WORKSHOP ON MOON IN TRANSITION: APOLLO 14, KREEP, AND EVOLVED LUNAR ROCKS

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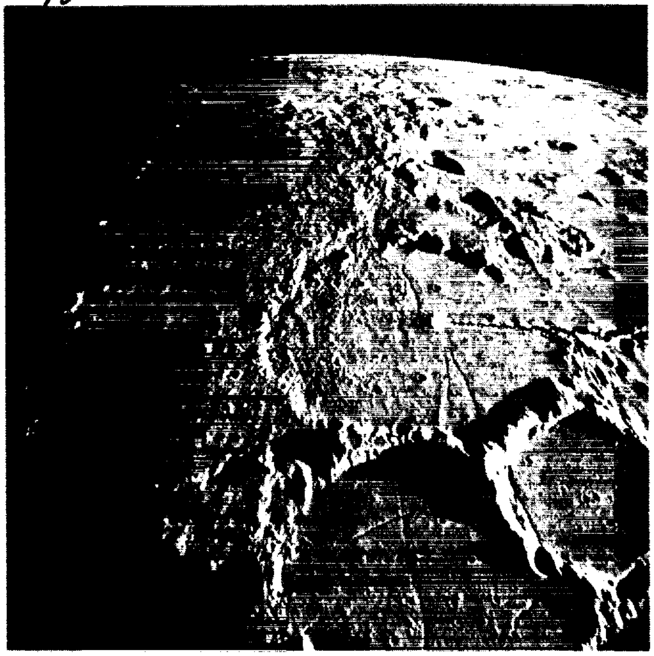

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WORKSHOP ON MOON IN TRANSITION: APOLLO 14, KREEP, AND EVOLVED LUNAR ROCKS

Edited by

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Cover photo: A north-looking oblique view of the region surrounding the Apollo 14 landing site. The landing site is about 600 km south of the Imbrium basin, which is just beyond the horizon. The large crater near the center is Fra Mauro, 95 km in diameter. NASA photo number AS16-1420M.

Contents

Preface

This report documents the "Workshop on Moon in Transition: Apollo 14, KREEP, and Evolved Lunar Rocks," held at the Lunar and Planetary Institute on November 14–16, 1988. This workshop was one of a series of meetings organized by the Lunar and Planetary Sample Team (LAPST) to spur progress on various specialized topics of lunar and planetary science. The samples from Apollo 14, i.e., the Fra Mauro highlands, are entirely unlike those acquired from any other lunar site. Evolved rock types such as KREEP, alkali anorthosite, and granite are relatively abundant, and alkali-poor or ferroan anorthosite (widely suspected to be the most common type of pristine rock in the crust as a whole) is nearly absent. A subordinate but still abundant rock type at the site is mare basalt, the samples of which also exhibit many distinctive traits. Efforts to unravel the history of the region have been complicated by the thoroughly brecciated nature of the rock samples, but recent years have seen much work aimed at isolating individual clasts within the breccias. Mare glasses from regolith samples are also targets of considerable ongoing research. The purpose of this workshop was to utilize the latest constraints for a new evaluation of the history of the Fra Mauro highlands, a new evaluation of the nature and history of KREEP, granite, and other evolved lunar rock types, and ultimately a fresh evaluation of the transition of the Moon from its early anorthosite-forming (magma ocean?) period to its later stages of KREEPy, granitic, and mare magmatism.

The Organizing Committee appointed by LAPST consisted of G. Jeffrey Taylor, University of New Mexico, and Paul H. Warren, University of California, Los Angeles, chairmen; B. Ray Hawke, University of Hawaii; Graham Ryder, Lunar and Planetary Institute; Paul Spudis, U.S. Geological Survey, Flagstaff; and Lawrence A. Taylor, University of Tennessee. Logistics and administrative support were provided by the Projects Office of the Lunar and Planetary Institute—we are deeply grateful to Pam Jones, LeBecca Turner, and their coworkers for their usual diligent and efficient organizational work.

G. Jeffrey Taylor and Paul H. Warren

Program

Monday Morning, November 14, 1988

8:00 a.m. Registration

9:00 a.m. Introduction to Workshop: *G. J. Taylor and P. H. Warren*

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Chairman: P. Spudis   Summarizer: B. R. Hawke

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B. R. Hawke

Telescopic Measurements of SiO_2 Abundances of Suspected Lunar Silicic Regions: Red Spots Are Not Granite
P. Lucey and B. R. Hawke

Elemental Abundances Around Apollo 14 and Other Selected Lunar Regions from the Apollo Gamma-Ray Spectrometer Experiment
R. Reedy

Where is the KREEP?
P. E. Clark

The Absence of a Heavy Early Lunar Bombardment, the Presence of a 3.85 Ga Cataclysm, and the Geological Content of Apollo 14 Rock Samples
G. Ryder

Monday Afternoon, November 14, 1988

Topic 2 - BRECCIATED NATURE OF THE APOLLO 14 SUITE
Chairman: W. C. Phinney   Summarizer: O. B. James

Brecciated Nature of the Apollo 14 Suite
D. Stöffler

^{40}Ar - ^{39}Ar Ages of Apollo 14 Rocks
F. J. Stadermann, E. Heusser, and E. K. Jessberger

Fra Mauro Formation, Apollo 14: I. Composition and Frequency Distribution of Igneous and Impact Metamorphic Rocks
S. Lingner, K. Bobe, H. Palme, B. Spettel, D. Stöffler, and H. Wänke

Fra Mauro Formation, Apollo 14: III. Calculated Composition of the Primordial Lunar Crust in the Imbrium Region
S. Lingner, B. Spettel, and D. Stöffler

Fra Mauro Formation, Apollo 14: IV. Synopsis and Synthesis of Consortium Studies
D. Stöffler, K. Bobe, E. K. Jessberger, S. Lingner, H. Palme, B. Spettel, F. Stadermann, and H. Wänke

Topic 3 - WHAT IS KREEP?
Chairman: G. J. Taylor   Summarizer: P. H. Warren

KREEP: Major-Element Diversity, Trace-Element Uniformity (Almost)
P. H. Warren

Highly Evolved Liquids from the Fractionation of Mare and Nonmare Basalts
P. C. Hess

The Splitting of KREEP into Identifiable Components: The "K-Frac" and "REEP-FRAC" Hypothesis
C. R. Neal and L. A. Taylor

Silicate Liquid Immiscibility and Crystal Fractionation in a Highly Evolved KREEPy Magma
R. W. Morris, G. J. Taylor, and H. E Newsom

Lunar Crustal Strength and the Large Basin-KREEP Connection
H. H. Schmitt

Tuesday Morning, November 15, 1988

Topic 4 - APOLLO 14 PLUTONIC ROCKS
Chairman: O. B. James Summarizer: M. M. Lindstrom

Highland Crust at the Apollo 14 Site: A Review
J. W. Shervais

Lunar Granite Petrogenesis and the Process of Silicate Liquid Immiscibility: The Barium Problem
C. R. Neal and L. A. Taylor

Compositional Survey of 2-4 mm Soil Particles from 14161 and Implications Regarding KREEP and Igneous Components in Apollo 14 Regolith Breccias
B. L. Jolliff, R. L. Korotev, and L. A. Haskin

Pink Spinel Troctolites in Apollo 14 Breccias
D. T. Collins and A. M. Reid

Tuesday Afternoon, November 15, 1988

Topic 5 - APOLLO 14 MARE BASALTS
Chairman: J. W. Delano Summarizer: T. Dickinson

Apollo 14 Basalt Petrogenesis: Generation from an Olivine-Opx Dominated Mantle, Followed by Crustal Assimilation and Fractional Crystallization
C. R. Neal and L. A. Taylor

Understanding Lunar Mantle Metasomatism: The Terrestrial Mantle Analogy
W. I. Ridley, J. E. Nielson, and H. G. Wilshire

Apollo 14 Pristine Mare Glasses
J. W. Delano, S. S. Hughes, and R. A. Schmitt

An Ion Microprobe Study of Trace Elements in Apollo 14 "Volcanic" Glass Beads and Comparisons to Mare Basalts
C. K. Shearer, J. J. Papike, S. B. Simon, N. Simizu, H. Yurimoto, and S. Sueno

Wednesday Morning, November 16, 1988

Topic 6 - ISOTOPIC CONSTRAINTS ON EARLY LUNAR DIFFERENTIATION
Chairman: L. E. Nyquist Summarizer: J. Dasch

Isotopic Constraints on the Petrogenesis of Apollo 14 Igneous Rocks
C.-Y. Shih and L. E. Nyquist

Zircon-Containing Rock Fragments Within Apollo 14 Breccia Indicate Serial Magmatism from 4350 to 4000 Million Years
C. Meyer, I. S. Williams, and W. Compston

Topic 7 - RELATION OF EVOLVED LITHOLOGIES TO THE MAGMA OCEAN OR OTHER EARLY LUNAR DIFFERENTIATION EVENTS

Chairman: P. H. Warren Summarizer: J. H. Jones

The Petrogenesis of Evolved Pristine Rocks
J. Longhi

Discussion

12:00 Noon ADJOURN WORKSHOP

Summary of Technical Sessions

This summary of presentations and discussion is based on notes taken by the respective summarizers during the workshop. These narratives are not intended to approximate a transcript of everything said at the workshop, but rather to sketch briefly the concepts that were discussed, giving some indication of where significant gaps remain in our collective perception, and noting where revisions of interpretation were suggested. In most cases we have identified those participants who asked questions or made comments, but this has not always been possible. We apologize to anyone who might be misidentified, misquoted, or misinterpreted.

TOPIC 1:
REGIONAL GEOLOGY AND THE ROLE OF IMPACTS

Summarized by B. Ray Hawke

Five papers were presented in this session, which dealt with geologic and remote-sensing studies of the Fra Mauro region. These talks provoked lively discussions that were channeled into four areas by the session chairman (P. Spudis). The first of these was the question of what pre-Imbrian events contributed to the regional geology of the Apollo 14 site.

In his keynote talk on the geologic and bombardment history of the Apollo 14 region, B. Hawke attempted to answer this question. He divided pre-Imbrian (Phase 1) time into three subdivisions (Phase 1A, 1B, and 1C) on the basis of the inferred relative ages of the various Phase 1 impact structures. The earliest events occurred during Phase 1A. The first impact event to have influenced the Apollo 14 region may have been the Procellarum (or Gargantuan) basin. Several workers (Cadogan, Whitaker, and Wilhelms) have proposed the existence of this huge basin to explain the lunar nearside-farside asymmetry, the localization of KREEP in the Oceanus Procellarum-Mare Imbrium region, and several proposed ring segments. During the discussion, D. Stöffler spoke in favor of the existence of Procellarum basin. In response, Spudis briefly summarized the evidence for and against Procellarum. He concluded that the bulk of the evidence cast doubt on the reality of the proposed "Procellarum basin." Spudis believes that Imbrium is a six-ring basin and that many of the features attributed to Procellarum were actually formed by Imbrium. Most workshop attendees apparently agreed with Spudis; no one else presented arguments in favor of Procellarum basin. Still, the reality of Procellarum must be considered an unresolved question. The existence of this very large basin has important implications not only for the Apollo 14 site but also for the structure of the nearside crust and the impact cratering process. Additional experimental, theoretical, and observational studies of both terrestrial and lunar impact structures will be necessary to resolve this problem.

Hawke noted that in addition to Procellarum, three other very old basins are near enough to have affected the Apollo 14 region. These are (1) Insularum basin, (2) Flamsteed-Billy basin, and (3) Nubrium basin. In addition, a large number of pre-Imbrian impact craters have been identified in the Fra Mauro region by B. R. Hawke and J. Head. Many of these Phase 1 craters are superposed on preexisting impact structures and therefore must have ejected deposits related to the older structures. Several of these craters could have contributed impact melt to the site. The workshop attendees seemed to be in agreement that the material delivered to the Apollo 14 site was involved in several previous impact events.

Other discussion questions asked by Spudis were: What is the geologic setting of KREEP in the Apollo 14 region? Is the Apollo 14 KREEP volcanic and, if so, when and where was it erupted? If KREEP was excavated by impact, which impact or impacts and when? These questions were addressed by two contributed papers that utilized the Apollo orbital geochemistry data sets. P. Clark presented a summary of the results of a number of ongoing analyses of the available lunar orbital geochemical data. These studies are being conducted at the global, regional, and local scales. On the basis of these studies, Clark concluded that while KREEP volcanism appears to have occurred principally in the Imbrium area, smaller-scale outbreaks of such early volcanism possibly occurred in other areas of the nearside and farside as well.

R. Reedy also presented a very interesting paper that reviewed the Apollo orbital geochemical experiments and discussed some of the results from Apollo Gamma-Ray Spectrometer (AGRS) mainly for regions around Apollo 14. In response to a question, Reedy pointed out that the uncertainities for the elemental abundanaces determined by the AGRS data are typically ~20% (higher for the lowest concentrations), but that this range of uncertainties is quite adequate for most lunar investigations. The results of the AGRS show that the regions of high radioactivity around Fra Mauro are fairly limited in extent, with the highest radioactivities being near and somewhat east (the Lalande-Davy region) of Fra Mauro. Reedy pointed out that further east, highland-like material dominates, although some radioactive material is mixed into the western parts of the central highlands. To the west, mare basalts with relatively high titanium dominate in Oceanus Procellarum, with typical lunar highland material present west of Oceanus Procellarum. In summary, Reedy noted that the "standard interpretation" of the orbital results is that the highly radioactive material (most likely KREEP) is somehow related to the formation of Imbrium basin (and possibly other basins near Imbrium now covered by Oceanus Procellarum) and that later emplacement of mare basalts left large amouts of KREEP present only on higher lunar features not flooded by mare basalts, such as Fra Mauro, Aristarchus, and Archimedes.

Reedy was questioned about the origin of the geochemical anomaly associated with Van de Graaff crater. He noted that the elemental concentrations in the Van de Graaff region are similar to those in a mixture of mare basalts and typical farside highlands material. Hawke pointed out that the preliminary results of Th deconvolution studies of the Van de Graaff region indicated that there was a direct correlation between the high Th values and the mare material in the floor of Van de Graaff.

During the discussion, three hypotheses were advanced to account for the existence of KREEP-rich material in the Apollo 14 region: (1) KREEP basalts were emplaced as surface flows in the Apollo 14 region, were extensively reworked by pre-Imbrium impacts, and were incorporated in the Fra Mauro formation by Imbrium secondary cratering events in the vicinity of the site. (2) KREEP was erupted in the Imbrium target site and was reworked by pre-Imbrian craters. Later, it was excavated and transported to the Apollo 14 site as Imbrium primary ejecta. (3) KREEP was excavated from some deep layer beneath the Imbrium target site and was transported to the site as primary ejecta.

In his review paper, Hawke used the orbital geochemistry data to argue for a local volcanic origin for Apollo 14 KREEP basalts. He noted that there were major changes in chemical composition occurring between the highland region just east of Ptolemaeus and the Bonpland-Parry area just south of the Apollo 14 site. In particular, there is a dramatic rise in the net radioactivity values due to increases in the concentrations of K, U, and Th and the changes appear to be most pronounced around the topographic inflection that forms the east rim of Ptolemaeus. The correlation of the change in geochemistry and KREEP abundance with the decline in elevation at the western edge of the central highlands (about 4.4 km from the area east of Ptolemaeus to Mare Nubium) suggests that KREEP emplacement was controlled by a process sensitive to topographic variations. The deposition of the Imbrium ejecta blanket would have been subject to only minor topographic influences whereas the distribution of lunar volcanic deposits has been strongly influenced by preexisting topography. The Fra Mauro region is a topographic low, at least in part due to the large pre-Imbrian craters and basins, and such low regions would have provided ideal sites for the early accumulation of KREEP basalt. Early (>4.0 b.y.) mare volcanism may have occurred in the low region west of the central highlands.

The occurrences of spectrally distinct premare ("red spots") materials of possible volcanic origin in southeastern Procellarum, Mare Cognitum, and northern Nubium have often been cited as evidence for pre-Imbrian volcanism in the Apollo 14 region. These "red spots" have been identified elsewhere on the west side of the Moon and some workers have suggested that they are composed of KREEP or more evolved lunar rocks (QMD, granites, rhyolites, etc.). P. Lucey and B. R. Hawke presented the preliminary results of an effort to determine whether lunar "red spots" are indeed composed of SiO_2-rich rocks. Thermal emission spectra (7–11 μm) were obtained for a variety of "red spots" as well as standard lunar terrain. The preliminary results appear to rule out a granitic composition; however, additional work is necessary.

The most controversial and perhaps the most important questions raised during this session concerned the nature of the Fra Mauro Formation. Is the Fra Mauro Formation composed exclusively of primary ejecta from the Imbrium basin or does it consist of a mixture of local material and primary basin ejecta? The workhop attendees generally agreed that the Apollo 14 mission had indeed sampled the Fra Mauro Formation. The discussion indicated that most participants thought that the Fra Mauro is a mixture. However, there was no agreement concerning the proportions of local material and Imbrium primary ejecta. Opinions varied widely on this issue. In response to direct question, G. Ryder indicated that he thought that there was "zero" Imbrium primary ejecta at the site. When F. Hörz asked Ryder what he meant by "zero" percent Imbrium ejecta, M. Cintala interjected that Ryder meant "a little." Ryder appeared to agree with Cintala's comment. Other attendees (e.g., Hawke, Hörz, Lucey) expressed the view that while the Fra Mauro Formation at the site was overwhelmingly dominated by local material, ~15–20% Imbrium primary ejecta was probably present. Spudis appeared to speak for several lunar scientists at the workshop (as well as a few who were absent) when he pointed out that recent studies of clustered impactors by P. Schultz and D. Gault indicated that much larger amounts (~45–55%) of Imbrium primary material might be present at the site. Finally, a few attendees expressed the view popular during and immediately after the mission, that the Fra Mauro Formation was composed exclusively of Imbrium primary ejecta.

During his review talk, Hawke presented the history of this important controversy. Premission studies indicated that the Fra Mauro Formation was a portion of the Imbrium ejecta blanket and was composed of material derived from the Imbrium target site. The results of preliminary sample studies were thought to be consistent with a primary ejecta origin and the range of thermal effects in the samples was attributed to autometamorphism in a "hot," thick ejecta deposit. However, some workers disagreed with this interpretation. While they considered the Fra Mauro Formation to be composed of Imbrium primary ejecta, they indicated that the deposit was emplaced in a "cold" mode and that the thermal effects were caused by pre-Imbrian impacts in the Imbrium target site.

In later years, V. Oberbeck and coworkers pointed out the importance of secondary cratering in the formation of impact crater and basin deposits. Their results demonstrated that the impact of ballistically transported primary ejecta excavates considerable volumes of underlying local material and incorporates this material into an ejecta deposit. The resulting mixture of primary ejecta and local material moves radially away from the parent crater or basin as a surface flow or debris surge. Detailed mapping of the Fra Mauro region by Hawke and Head revealed the presence of a large number of secondary crater chains and clusters that are radial and subradial to the Imbrium basin. Secondary crater chains in this region attributed to the impact of Imbrium ejecta range from about 0.5 to 12 km in width and are commonly tens of kilometers in length. Mixing calculations indicated that at the radial range from Imbrium typical of the Apollo 14 region, over 70% of the deposit that resulted from the impact of Imbrian secondary-forming projectiles was composed of locally-derived material.

In recent years, the local-mixing (secondary-impact) hypothesis has been under increasing criticism. Schultz and coworkers have presented experimental evidence that clustered impacts significantly affect crater morphology and reduce cratering efficiency. These workers have suggested that the continuous ejecta facies of large lunar impact structures could contain a much larger percentage of primary material. D. Wilhelms, who was unfortunately unable to attend the workshop, has also raised objections to the local-mixing hypothesis. He maintains that the topography of the landing-site regions is dominated by ridges formed by the flow of a thick deposit that has obscured the secondary craters and that this flow originated either at the basin rim or at secondary-impact sites much closer to the basin than its present resting place. Wilhelms has pointed out that the local-mixing equations developed by Oberbeck and coworkers are model-dependent and he questioned many of the imput parameters. In addition, Wilhelms has presented evidence for the presence of abundant melt in basin-ejecta deposits. He noted that if Imbrium impact melt was a major component of the Fra Mauro Formation at the Apollo 14 site, this melt could have been responsible for the thermal effects in many of the Apollo 14 samples as well as the 3.82–3.84-b.y. age cluster in the returned samples.

The discussion of the nature of the Fra Mauro Formation and the local-mixing hypothesis was quite lively. Several attendees presented evidence from a variety of sources in support of the local-mixing model. P. Warren presented sample geochemical data that indicated that major differences in trace element abundances exist between east-side and west-side highland samples. He suggested that basin-forming impacts were not very effective at transporting large amounts of primary ejecta far across the lunar surface. In support, Ryder pointed out that the Apollo 15 highlands samples are very different from those returned from the Apollo 14 site. Many sample workers apparently feel that this difference is a clear indication that the Apollo 14 samples are dominated by local material. In response, Spudis pointed out that these lithologic and geochemical differences could be due to compositional variations in the Imbrium target site. Spudis also discussed the results of the clustered impact experiments conducted by Schultz and Gault and concluded that the amount of Imbrium primary ejecta at the site was probably greater than that suggested by the advocates of the local-mixing hypothesis. Hörz countered that the Imbrium secondary craters were not necessarily formed by clustered impacts. In support, he cited the results of his studies of the Reis impact structure. Large megablocks were ejected from the Reis crater and detailed investigations of the Reis continuous ejecta deposit by Hörz and coworkers conclusively demonstrated the importance of local mixing in producing this unit. In response, Spudis noted that some workers do not consider the Reis to be a typical impact structure.

Hawke pointed out that the reality of local mixing was demonstrated by studies of regolith material collected from the ejecta of the Central Crater Cluster, a group of Tycho secondaries, at the Apollo 17 site. Even less Tycho primary material was found in the Central Crater Cluster ejecta than was predicted by the local-mixing hypothesis. However, Cintala noted that while local mixing was apparently quite efficient at the Apollo 17 site, the Apollo 14 site was much closer to the parent impact structure and a direct comparison may not be valid.

During the course of the discussion of the nature of the Fra Mauro Formation, it was mentioned that there was abundant evidence that the Apollo 14 multibreccias evolved in a near-surface environment. Hence, regardless of whether the Apollo 14 samples are Imbrium ejecta or local material, the volcanic origin for KREEP basalt was supported.

It was clear that the nature of the Fra Mauro Formation at the Apollo 14 site was a very significant unresolved problem. It may not be quickly or easily solved. Additional studies of the efficiency of local mixing in the distal deposits of large impact structures are needed. Remote-sensing studies of lunar crater and basin deposits may provide some answers. Field investigations of terrestrial impact structures would be useful as would additional experimental cratering studies. The results of lunar sample studies have provided important evidence on this issue in recent years and continued investigations of the Apollo 14 breccias and melt rocks will be critical to the final solution of the problem.

In the final paper of the session, Ryder presented what he termed a radical interpretation of the early bombardment history of the Moon. Based on lunar sample data as well as the "new" paradigm for the origin of the Moon (major impact into the Earth that produced an orbiting disk), Ryder argued that there was no heavy bombardment of the Moon after about 4.4 b.y.; accretion was rapid but did not linger, and then that much endogenous activity occurred with little external disturbance. He concluded that there was a late (~3.85-b.y.) cataclysmic bombardment of the Moon that had major implications for both exogenous and endogenous processes. Ryder argued that all of the 3.85-b.y. sample ages cannot be ascribed to the Imbrium impact and that the rate of material addition around 3.85 b.y. demonstrated the reality of a late cataclysm that produced almost all of the presently observable landforms in the lunar highlands. This interpretation contrasts sharply with the canonical view of a continuing heavy bombardment with no late cataclysm. Ryder pointed out that his interpretation was consistent with (1) the absence of impact melts older than 3.9 b.y., (2) the existence of mare basalts more than 4.2 b.y. old, (3) the lateral and vertical heterogeneity of the lunar highlands crust on local and regional scales, and (4) the properties of meteorites of lunar origin. According to Ryder, the Apollo 14 breccias and impact melts were produced during impact events that occurred during the late cataclysm.

Needless to say, Ryder's talk resulted in considerable discussion among the attendees. Stöffler pointed out that some workers have presented data indicating that there are impact melts older than 3.9 b.y. Ryder responded that in the few instances where an old age had been published for impact melt rocks, shocked plagioclase grains were present in the melts and probably affected the age determinations. Spudis stated that it really did not make any difference if there were a few melts older than 3.9 b.y. According to the interpretation presented by Ryder, a few precataclysm melts might be expected. Hörz raised the question of what percentage of the highland sample collection was actually composed of impact melt. It was pointed out during the general discussion that many of the Apollo 14 impact melts and melt-rich breccias are KREEP rich. Some attendees were uncertain that an early episode of KREEP volcanism in the Fra Mauro region was consistent with the bombardment model proposed by Ryder.

The reality of the bombardment model proposed by Ryder is an extremely important question. It is critical to the proper understanding of lunar surface history and processes and has important implications for the cratering history of other solar system objects. More work needs to be done on the Apollo 14 melt samples to better establish the range of compositions (from coarse fines and rocks), including trace siderophile elements, and to establish their ages. Could these melts have all been generated by the Imbrium impact event as suggested by Wilhelms? Do melts older than 3.9 b.y. exist at the site? Answers to these questions are urgently needed.

The final major discussion question raised by Spudis was: What post-Imbrium events have affected the geology of the Apollo 14 site? Hawke noted that subsequent to the formation of the Imbrium basin and the emplacement of the Fra Mauro Formation, the surface deposits at the Apollo 14 site continued to undergo bombardment and additional small primary and secondary craters were formed, although the major preexisting topographic features were not destroyed. A number of post-Imbrium craters in the 10^2–10^3-km-diameter range have been mapped at the Apollo 14 landing site. Four of these craters were of significance in producing the near-surface stratigraphy in the Cone crater target area and they range from 230 to ~1000 m in diameter. Cone crater lies on a ridge crest near the rims of the three largest craters. A total ejecta contribution of ~15 m could be expected from these craters at the Cone crater target site. Even though Cone crater is ~65 m deep, laboratory impact experiments have indicated that the Cone crater maximum excavation depth was ~32 m. Hence, it appears that the ~15-m post-Imbrium crater ejecta comprised almost 50% of the section excavated by Cone crater. Based on the estimated depths of excavation of these post-Imbrium craters, at least some pre-Fra Mauro material could have been present in this 15-m-thick deposit. In addition, this surface material had probably been subjected to considerable impact reworking prior to the formation of Cone crater.

In another session, J. Delano presented a very interesting talk concerning the pristine mare glasses observed to be common in most Apollo 14 regolith breccias. Hawke noted that major deposits of high-titanium pyroclastic debris have been identified north of the Apollo 14 site. Spudis pointed out that the eruption mechanisms proposed by Head and L. Wilson could have transported material for hundreds of kilometers across the lunar surface. Detailed spectral reflectance studies of the Fra Mauro region, comparable to those conducted for the vicinity of Apollo 15, would probably yield important information.

TOPIC 2: BRECCIATED NATURE OF THE APOLLO 14 SUITE

Summarized by Odette James

All the material presented at this session represents the work of the Cone crater consortium, a collaborative effort involving D. Stöffler and his coworkers at the University of Münster, H. Wänke and his coworkers at the Max-Planck-Institut für Chemie at Mainz, and E. Jessberger and his coworkers at the Max-Planck-Institut für Kernphysik at Heidelberg. The Cone crater consortium has done an admirable job in characterizing a very large suite of Apollo 14 samples and in interpreting the results of their work.

Stöffler began the session with an invited talk summarizing the petrology and chemistry of the Apollo 14 breccais (see review abstract by D. Stöffler). In brief, there are four types of breccias: (1) regolith breccias, rocks that are consolidated soils and are derived from the uppermost part of the landing site stratigraphy; (2) highly feldspathic fragmental breccias ("white rocks"); (3) subophitic impact melt breccias, typified by 14310; and (4) a gradational series of rocks ranging from fragmental breccias to fragmental breccias containing large clasts of melt rocks to homogeneous crystalline melt breccias (the rocks of this series are commonly termed "Fra Mauro" breccias). Stöffler interprets all but the regolith breccias as derived from the Fra Mauro Formation, the impact deposit that underlies the regolith at the site. This formation is generallly considered to be a deposit of impact debris emplaced by the Imbrium impact.

In the discussion following Stöffler's talk, P. Spudis commented that complex breccia-in-breccia textures, as seen in some of the "Fra Mauro" breccias, can be produced in single large impact events. He cautioned the audience against interpreting such textures as evidence of a multiple impact history. Stöffler agreed. G. Ryder questioned Stöffler's interpretation that the 14310-type melt breccias are from the Fra Mauro Formation. He pointed out that these melt breccias appear to occur in the regolith only away from Cone crater; this type of distribution would suggest that these rocks are not derived from the Fra Mauro Formation but instead represent a later addition to the site. Stöffler responded that there is no suitable post-Imbrium crater nearby that could be the source of such melt rock.

Following Stöffler's introductory talk, S. Lingner presented petrographic and chemical data on numerous samples of the various lithologies found at the site (see abstract I by Lingner et al.). In brief, Lingner found that the "white rocks" contain distinctive melt-breccia lithologies not found in other breccias at the site. Clasts of plutonic igneous rocks in all but the regolith breccias are exclusively of Mg-suite and alkali-suite rocks; ferroan-anorthosite suite clasts are absent. Granulitic breccias are very rare at the Apollo 14 site, in contrast to most other lunar landing sites.

Following Lingner's talk, F. Stadermann presented the results of ^{40}Ar–^{39}Ar age determinations (see abstract by Stadermann et al. and abstract IV by Stöffler et al.). Ten clasts from "white rock" 14063, most of which are impact melt breccias, showed plateau ages of 3.86 Ga or greater; one of the clasts showed a high-temperature plateau at 4.09 Ga as well as an intermediate-temperature plateau at 3.87 Ga. The data suggest that these rocks experienced a common heating event about 3.87 Ga ago or more recently, but some of them retain an Ar memory of prior events; the 4.09-Ga age is the oldest ^{40}Ar–^{39}Ar age thus far reported for an Apollo 14 rock. Nine fragments of impact melt from "Fra Mauro" breccias and 14310-type impact melt rocks showed consistently younger ages than clasts from the "white rocks," from 3.73 to 3.85 Ga; the youngest ages have the largest uncertainties. Exposure-age data on the 14063 clasts confirm that this breccia is Cone crater ejecta; most of the other samples have older exposure ages.

In the discussion following Stadermann's talk, Stöffler emphasized the usefulness of the data for determining the times of formation of the various types of breccias found at the site. As the "white rock" breccia was deposited as a relatively cold aggregate of fragments and not subsequently heated, the age of the youngest clast found in this rock, about 3.85 Ga, should set an upper limit on the time of formation of the aggregate. J. Delano suggested that the laser technique of Ar release might be profitably applied in ^{40}Ar–^{39}Ar studies of such small clasts.

Stöffler continued the consortium presentation with a discussion of mixing calculations that were used to try to determine the composition of the Apollo 14 crust in terms of the proportions of pristine igneous rocks (see abstract III by Lingner et al.). Stöffler concluded that the source crust for the "white rocks" was dominated by alkali anorthosite and troctolite, whereas the source crust for the "Fra Mauro" breccias was dominated by alkali anorthosite, norite, and gabbronorite. In the discussion following Stöffler's talk, R. Korotev commented that the mixing calculations had not used data for Eu; he suggested that Eu be incorporated in the calculations because the abundance of this element can distinguish different types of anorthosite.

The final formal consortium talk was given by Stöffler and consisted of a synthesis of the results of the group (see abstract IV by Stöffler et al.). Some of the points Stöffler emphasized were as follows. He accepts the interpretations that (1) the Fra Mauro Formation is part of the continuous ejecta blanket of the Imbrium basin and (2) the formation at the Apollo 14 site contains a large proportion of local rocks, as secondary ejecta. The consortium data suggest that the Fra Mauro Formation at the Apollo 14 site consists of two lithological units: (1) a unit consisting of "white-rock" feldspathic fragmental breccias such as 14063; and (2) a diverse unit relatively rich in melt rocks (includes "Fra Mauro" breccias and 14310-type impact-melt breccias). Stöffler suggested two possible interpretations of the site geology: (1) the material underlying the regolith is layered, with the "Fra Mauro" breccias and 14310-type melt rocks coming from a relatively thin Fra Mauro Formation directly underlying the regolith and the "white-rock" breccias coming from a deeper, older formation; or (2) the "white rocks" form large blocks of older breccia included within the Fra Mauro deposit. Stöffler favors the latter interpretation.

Stöffler further pointed out that the two lithological types show different ranges of $^{40}Ar-^{39}Ar$ ages. The "white-rock" breccias contain only clasts older than about 3.85 Ga, whereas fragments of melt rocks from "Fra Mauro" breccias and 14310-type melt rocks are all younger, ranging from 3.73 to 3.85 Ga. Stöffler proposed that the "white-rock" breccias are blocks of pre-Imbrian (Nectarian?) breccia included within the Fra Mauro formation; if these breccias are truly Nectarian, the 3.85-Ga age of their clasts is an upper limit to the age of the Nectaris basin-forming impact. He further proposed that the 3.75–3.77-Ga minimum age of the "Fra Mauro" melt breccias and 14310-type melt rocks represents the age of the Imbrium basin-forming event. In discussing the history of the lunar crust in the Apollo 14 area, Stöffler ascribed an important role to the proposed impact that formed the giant Procellarum basin. He favored the idea that this impact stripped off the uppermost, ferroan-anorthosite part of the crust and exposed deeper, more mafic, more KREEP-rich parts of the crust.

During the discussion after Stöffler's presentation, P. Warren commented that the Apollo 14 sample suite may be more heterogeneous than generally thought. Some unique rocks found at the site are breccia 14315, which is very aluminous and contains abundant particles similar to chondrules, and breccia 14076, which is similar to a typical Apollo 16 regolith breccia.

After Stöffler's presentation, H. Wänke gave a brief informal presentation on the calculated trace-element compositions of highlands magmas. His group has analyzed nearly pure plagioclase separates from pristine highlands igneous rocks and has calculated the compositions of liquids in equilibrium with these plagioclases, using measured partition coefficients. He finds a consistent progression of the chondrite-normalized abundances of the elements Sr, Eu, Na, Ba, and La for all the calculated liquids, with the liquid in equilibrium with ferroan anorthosite 15415 being the most primitive (all five elements about 10× chondritic) and liquids in equilibrium with Apollo 14 samples being the most evolved. The C1-normalized concentrations in the most evolved liquid range from 28 times chondritic for Sr to 1100× chondritic for La. The absolute concentrations of Sr, Eu, Na, Ba, and La in a KREEP-rich sample from breccia 14321, in which La is 360× chondritic, fall well on the fractionation lines for these elements. The observed progression suggests that all the samples may be related to an evolving liquid or that liquids from the onset of plagioclase crystallization to the very last residual liquids furnish the widely distributed lunar KREEP component. Following Wänke's presentation, P. Hess commented that partition coefficients can be temperature dependent and, because the calculations of parent magma composition had assumed constant partition coefficients, the calculated equilibrium liquid compositions might not be realistic. Wänke agreed that there might be uncertainties for Ba and La in the equilibrium liquid because of possible temperature dependence of the partition coefficients but stated that there should be little effect on Na, Eu, and Sr.

Spirited discussion at the end of the session was devoted to Stöffler's proposed age of about 3.75 Ga for the Imbrium basin impact. This age is 100 m.y. younger than currently favored by most other workers. L. Nyquist commented that assigning the youngest of the measured ages to Imbrium left no dates for later craters, and he suggested that it might make more sense to assign the peak in the age frequency histogram, at about 3.87 Ga, to formation of the Imbrium basin. In response, Stöffler reiterated that an upper limit to the age of an ejecta unit is determined by the age of the youngest rock in that unit, provided that no significant resetting occurred after the unit formed. Therefore, as the Fra Mauro Formation contains abundant melt breccia having ages in the range 3.73–3.85 Ga, the unit must have formed about 3.75 Ga ago or more recently. H. Schmitt asked Stöffler how he explained the fact that some mare-basalt samples, collected from mare surface not far outside the edge of the Imbrium basin, have ages much older than 3.75 Ga; one would have expected such basalts to have been buried by a thick layer of Imbrium ejecta if the Imbrium event postdated their extrusion. Stöffler responded that he felt the old basalts had indeed been buried by Imbrium ejecta, the ejecta had been covered by later basaltic flows, and rocks from the old flows had been exhumed by local impacts. P. Spudis commented that Apollo 15 KREEP basalt, which comes from the Apennine Bench Formation, has an age of 3.85 Ga; as the Apennine Bench Formation embays and fills in low spots in the basin, it must be younger than the basin, so that the basin must be 3.85 Ga old or older. Stöffler disagreed with several aspects of Spudis' interpretation. Stöffler interprets the Apennine Bench Formation as a huge megablock that predates rather than postdates the basin. He added that Apollo 15 KREEP basalt has not been demonstrated to represent the Apennine Bench Formation because the MgO content of the formation, as measured from orbit, is not the same as that of KREEP basalt. Spudis responded that MgO contents are the same within error, and all other elements are identical. B. R. Hawke added his voice to Spudis' with an emphatic assertion that the surface composition of the Apennine Bench Formation is the same as that of Apollo 15 KREEP basalt. Spudis also objected to Stöffler's suggestion that formation of the proposed Procellarum basin stripped off a preexisting ferroan-anorthosite crust in the area. He pointed out that ferroan anorthosite is present at the Apollo 15 site, which is even closer to the center of the Imbrium basin than the Apollo 14 site. He suggested lateral heterogeneity of the crust would be a better explanation for the absence of ferroan anorthosite at the Apollo 14 site.

Although little time was spent during the session outlining possible directions for future research, the discussion revealed several areas where additional work is highly desirable. Studying unique samples such as those mentioned by P. Warren and determining their provenance should add significantly to our knowledge of the geology of the site. The most profitable line of research, however, would be studies aimed at resolving the controversy concerning the interpretation of the age data. Are the measured ages that are younger than 3.85 Ga true ages? The measured ^{40}Ar–^{39}Ar ages younger than 3.8 Ga all have relatively large uncertainties, suggesting they might be affected by Ar loss, but there are also measured Rb-Sr ages younger than 3.85 Ga. Which ages truly represent the ages of material contained within the Fra Mauro Formation? The ages younger than 3.85 Ga with small uncertainties are mostly from 14310-type impact melt rocks, whose presence in the Fra Mauro Formation is controversial. How should the age data be interpreted in terms of dates of major basin-forming impacts? To help answer these questions, additional age data on samples from "Fra Mauro" breccias would be very useful. There is no controversy concerning geologic occurrence of these rocks, so their ages would help define the dates of events that have affected the Fra Mauro formation. Also, attempts to resolve the geologic occurrence of the 14310-type melt rocks at the site would aid interpretation of the age data.

TOPIC 3: WHAT IS KREEP?

Summarized by Paul Warren

P. Warren opened the session with a review on the composition and origin of KREEP. Warren emphasized that KREEP lithologies exhibit considerable diversity in their overall enrichments in incompatible elements, although no other common lunar rock type is nearly so incompatible-element-enriched, and among KREEP rocks the incompatible elements occur in remarkably uniform proportions to one another. A typical pristine KREEPy rock is a basalt with roughly equal proportions of low-Ca pyroxene and plagioclase, but the class also includes a monzodiorite, and arguably even one granite. KREEPy rocks are also diverse texturally, ranging at least from glassy to subophitic. Warren has compiled a database for bulk compositions of KREEPy rocks in an effort to refine the average high-K KREEP composition. The average composition is derived by plotting data for each element vs. an average of data for a number of archtypically-KREEPy elements (e.g., light REE, U, Th) in the same sample, the average having been normalized to a previous estimation of the average high-K KREEP composition. For incompatible elements, plotting large numbers of KREEPy samples on such a diagram generally results in linear correlations, which Warren uses to refine the average high-K KREEP composition and to search for possible systematic diversity of incompatible element ratios among KREEPy rocks. Concerning the origin of KREEP, Warren drew attention to two salient features of its composition: First, the diversity of incompatible element concentrations is accompanied by remarkably little diversity for the ratios among these elements, an observation that suggests derivation of all KREEP by a process involving dilution of a common parent (presumed to be the residual liquid of the magma ocean, a.k.a. "unKREEP"), and not as a series of localized partial melts. Second, despite appearing extremely "evolved" in their concentrations of incompatible elements, most pristine KREEP rocks have remarkably moderately-high *mg* ratios, an observation that suggests derivation by some form of mixing between Mg-rich magmas and magma ocean residuum.

During discussion after Warren's talk, J. Taylor noted that numerous mare basalts from Apollo 14, and at least one from Apollo 15, have KREEP-like REE patterns, consistent with Warren's point about the major-element diversity of KREEP. C. Neal asked Warren for more specifics regarding the major-element composition of urKREEP. Warren suggested that urKREEP probably never had a unique major-element composition, as the magma ocean residuum was most likely subjected to mixing with uprising Mg-rich magmas even as it collected between the bottom of the crust and the top of the mantle. C. Meyer and J. Papike asked why KREEP could not have formed by a series of partial melting episodes, with no magma ocean. Warren said that many separate partial melting episodes would have engendered many distinct incompatible-element-ratio patterns, and would not generally have engendered high *mg* ratios.

The next talk, by Paul Hess, was an invited review on the phase equilibria involved in the production of highly evolved lunar magmas. Hess employed the system $CaAl_2Si_2O_8$-Mg_2SiO_4-SiO_2-$CaSiO_3$ as a basic reference, but he also considered the effects of adding Fe, Na, K, Ti, Zr, and P. He pointed out that enrichment in FeO relative to MgO tends to displace the low-Ca pyroxene-silica boundary away from SiO_2, and thus tends to limit the degree of Si enrichment in late-stage melts. However, enrichment in K_2O tends to have the opposite effect. Normative $FeTiO_3$ probably plays a crucial role in the evolution of Si-rich lunar melts. Crystallization of ilmenite tends to increase the SiO_2 content of the residual melt. However, as long as ilmenite does not crystallize, TiO_2 acts like K_2O to diminish the SiO_2 contents of the residual liquids. TiO_2-enriched lunar liquids undersaturated with respect to ilmenite tend to undergo little SiO_2 enrichment, but eventually produce granites by silicate liquid immiscibility. KREEP basalts, however, are relatively rich in SiO_2, MgO, and K_2O, which should in principle make them more prone to follow the Bowen trend, i.e., steady enrichment of SiO_2 as crystallization proceeds. However, experiments with KREEP basalts 14310, 15382, and 15386 tend to indicate that even KREEP-basaltic magmas generally undergo only mild SiO_2 enrichment (accompanying much stronger FeO enrichment) as they crystallize. Hence, production of lunar granites from KREEPy initial magmas may also require liquid immiscibility. Hess inferred that the residual melt of the magma ocean was probably a ferrobasalt with low SiO_2, high TiO_2, and low Al_2O_3. This melt may have undergone liquid immiscibility, but only on a relatively localized basis, due to its still modest K_2O content. In addition, the last dregs of the magma ocean probably underwent phosphate and possibly also zircon fractionation. Hess suggested that this ferrobasaltic material was ultimately tapped to produce KREEP basalts, although he also acknowledged that the ferrobasaltic residuum may have been susceptible to contamination by Mg-rich melts intruding from below.

During the ensuing discussion, Papike asked if ilmenite fractionation might help to account for the high *mg* ratios observed among KREEP basalts. Hess answered that although ilmenite fractionation tends to stabilize *mg* during late-stage crystallization, it could not be expected to significantly reverse the *mg* diminution implied by the earlier fractionation necessary to produce high incompatible element contents. Warren noted that sample 12033,547, which is a crystalline granite criss-crossed by veins of an extremely FeO-rich glass, has been interpreted as an example of mingling of both the SiO_2-rich and the FeO-rich products of liquid immiscibility (see also the abstract by R. Morris). Several persons asked why ferrobasalt such as Hess described seems relatively rare among lunar samples. Hess reiterated that most of his talk addressed idealized, closed-system petrogenesis, whereas complexities such as magma mixing appear to have been common in the real Moon.

The next speaker was Neal, who proposed a model for the origin of KREEP involving its division into K-rich and REE-rich fractions ("K-Frac" and "REEP-Frac," respectively). Neal suggested that a subordinate portion of the magma ocean residual melt (urKREEP) underwent liquid immiscibility, after which the viscous granitic (K-Frac) melts remained nearly in place, but the low-viscosity FeO-rich (REEP-Frac) melts percolated upward through the crust, and locally metasomatized it. Besides metasomatic reactions with the crust, the REEP-Frac is inferred to have undergone further crystallization involving fayalite, which Neal suggests would reduce the density of the residual melt, thereby increasing its buoyancy relative to the overall crust. Neal suggested that the REEP-Frac was crucial to the origin of the widespread low-K Fra Mauro "basalt" materials, while the K-Frac was a precursor to lunar granites and was assimilated during the genesis of VHK basalts.

J. Shervais led off the discussion by asking Neal for more details as to how the dense, FeO-rich REEP-Frac melts could possibly rise instead of sinking. Neal reiterated that he assumes that ongoing crystal fractionation lowered the density of the REEP-Frac. T. Dickinson said she shared Shervais' doubts. Warren commented that although REE and K do not correlate well among Apollo 14 rocks, neither do REE and P, yet Ba correlates strongly with REE. He noted that H. Palme long ago interpreted the scatter in the alkali/REE ratios as a product of alkali volatilization (both K and P are volatile). G. Ryder questioned the wisdom of assuming that lunar granites are compositionally identical to their parent melts, when instead some crystal accumulation might have been involved in their genesis. Neal responded that the relatively small scales of the granitic magma chambers would not be conducive to efficient crystal/melt separation processes.

Morris gave the next talk, which was on petrographic evidence for liquid immiscibility and crystal fractionation among KREEPy magmas as recorded by three Apollo-14 rocklets. These rocklets each consist of two lithologies: (1) brown, FeO-rich glass and (2) shocked, granophyric granite. The bulk-rock REE patterns of these rocklets are roughly intermediate between average lunar granite and a "superKREEP" pattern (the "superKREEP" composition has REE at roughly twice their levels in the average high-K KREEP composition commonly cited as "KREEP"; e.g., super KREEP has La ~1280× chondritic). Morris et al. interpret these rocklets as products of separation of immiscible melts followed by remixing through impact-remobilization. Crystal fractionation surely preceded the liquid immiscibility, with phosphate (apatite?) and zircon probably among the phases involved. Morris et al. also interpret the moderate FeO contents of the glasses (~25 wt.%) as evidence that some crystal fractionation occurred after the immiscibility. The REE patterns can be modeled satisfactorily by this model, but only if the parent melt before immiscibility is assumed to have extraordinarily high, superKREEP-like REE abundances. Morris suggested that these processes may have occurred during the last stages of magma ocean crystallization.

In the discussion afterward, J. Longhi asked if the compositions of the minerals found in the crystalline-granitic portions of the rocklets appear consistent with equilibrium with the brown glass as a melt. Morris said he was not sure. Warren commented that the composition of urKREEP was probably roughly 1.5–2× richer in REE than the KREEP composition used as a reference by Morris et al., making the usage of "superKREEP" in their model completely justifiable. H. Wänke agreed, citing some new analyses of Cone crater samples from his laboratory.

The final talk of the session was by H. Schmitt on the role of gradual strengthening of the crust, as it cooled and otherwise evolved after the primordial melted shell era, in controlling the distribution of mass concentrations associated with lunar basins. Schmitt noted that the older multiring basins tend to be isostatically fully compensated, whereas those younger than about 4.2 Ga are associated with mascons and have retained sharply circular forms. Schmitt suggested that this difference may be a consequence of gradual crustal strengthening, caused largely by the evolution of KREEP from a residual melt layer below the crust, into mainly a network of interlocking solid dikes within the crust. Schmitt suggested that the observed distribution (largely associated with Imbrium basin ejecta) and ages of KREEP are consistent with this model.

Discussion after this talk was brief. There seemed to be a general consensus that Schmitt's hypothesis makes good sense as an extrapolation from current models for the origin and evolution of KREEP, albeit the more novel aspects of the hypothesis will be difficult to test until we obtain data from a future sophisiticated lunar orbiter mission.

TOPIC 4:
APOLLO 14 PLUTONIC ROCKS

Summarized by Marilyn Lindstrom

J. Shervais opened the session with an invited talk on highland crust at the Apollo 14 site. He described the unique character of the Apollo 14 samples and combined them with Apollo 12 highland rocks to describe a distinct Western Highland Province. The rocks of the western province fall into three major groups: magnesian suite, alkali suite, and evolved lithologies. An unfortunate problem in deciphering petrogenetic relationships among these samples is that no large samples are found; they occur only as clasts in impact and regolith breccias.

Using a diagram of Mg′ in mafics vs. An in plagioclase, the Mg-suite samples can be divided into a magnesian troctolite association (dominated by troctolites with high Mg′ and An compositions, but including anorthosites and dunites with similar mineral compositions) and a diverse group of magnesian norites. Tha alkali suite is dominated by anorthosites, but also includes norites and gabbronorites. These have low Mg′ and An mineral compositions and an abundance of accessory minerals. Evolved lithologies are mostly lunar granites.

The geochemistry of the Western Highland Province is unusual. REE concentrations are significantly higher than in other lunar suites and vary widely within both magnesian and alkali suites (15–700× chondrites). These extreme variations are largely due to modal variations in accessory minerals, especially in whitlockite, in these very small samples. A plot of Sm vs. Eu clearly distinguishes the Western Suite samples from other highland rocks. Ferroan anorthosites and Eastern Mg-suite rocks vary widely in Sm yet have fairly constant low Eu concentrations. Western Mg-suite rocks overlap with their Eastern counterparts in Sm but extend to higher concentrations and have distinctly higher Eu concentrations. Alkali suite rocks show much the same range in Sm as Western Mg-suite rocks, but have distinctly higher Eu concentrations. These geochemical distinctions are what led Warren to define the Western Highland Province.

The petrogenesis of Apollo 14 plutonic rocks is complicated and still unresolved. Because of the high REE concentations and subchondritic Ti/Sm and Sc/Sm ratios it is likely that KREEP was involved in their petrogenesis. Shervais outlined several scenarios to explain the wide variety of rock types: (1) Both magnesian and alkali suites are derived from a single parent magma with variable degrees of KREEP or urKREEP assimilation. (2) The magnesian and alkali suites represent two parental magmas, each of which has assimilated KREEPy material. (3) The two parental magmas include the magnesian suite and KREEP that was parental to the alkali suite. (4) Metasomatism of REE-rich fluids and assimilation of ferroan anorthosites are responsible for the compositional variation of Apollo 14 rocks. Shervais admitted that there are problems with several of these hypotheses and that they serve only to guide our thoughts. He proposed some areas for further study that might clarify some problems: Detailed studies on the origin of KREEP could clarify relationships to other rocks. Age data need to be obtained for various Apollo 14 highland rocks in order to evaluate relationships and possible links with ancient highland rocks.

The discussion that followed included the question of whether the Mg-anorthosites and dunites might be unrepresentative samples of troctolites. This is a possibility, but they could also represent different layers in the same intrusion. Further discussion centered on the origin of KREEP, with questions asked about just how much we know about the range of variation in pristine KREEP, but no answers or real plans of research were offered. D. Stöffler added that his consortium had measured some ages for Apollo 14 plutonic rocks. A Mg-anorthosite was dated at 3.8 b.y.

A. Reid then presented a talk on pink spinel troctolite in Apollo 14 breccias. D. Collins and Reid have done an extensive search of JSC library thin sections for pink pleonaste spinels and found them to occur both as isolated grains and as part of polymineralic clasts containing plagioclase and/or olivine. These clasts vary in texture from cataclastic cumulates to breccias. Compositions of major minerals show considerable variation of Mg′ in olivine and less variation of An in plagioclase. Compositions of spinels generally exhibit continuous normal zoning from core to rim, but sometimes show reaction coronas in contact with matrix. Reid concluded that the spinels originated in several spinel troctolite cumulates with various mineral compositions. Discussion suggested that cumulate fractionation need not produce large changes in plagioclase composition and that the spinels could be in a reaction relationship in various intrusions.

A general discussion of Apollo 14 plutonic rocks followed. The relationships of alkali anorthosites to other samples was a major topic. The much broader alkali suite from all sites was used to argue against a close relationship to the Mg suite. However, regional diversity within the suite, especially in Sm-Eu systematics, argues against a single alkali suite. It was agreed that detailed studies of Sm and Eu concentrations in plagioclases are required to solve the problems. C. Meyer said that he had obtained a variety of ages for Apollo 14 plutonic rocks ranging from 4.0–4.3 b.y. Further discussion centered on KREEP: whether KREEP ages fit with plutonic rocks, the absence of pristine KREEP at Apollo 14, and whether assimilation would be bulk KREEP or selective partial melts. J. Papike raised the issue of the validity of the magma ocean hypothesis, finding it hard to fit the many separate magmas required into such a model. The model was defended by several people, but the issue was left unresolved and the discussion continued in later sessions.

B. Jolliff presented a talk on a compositional survey of 2–4 mm soil particles from 14161 and implications regarding KREEP and igneous components in Apollo 14 regolith breccias. In this survey of 281 particles they found that most of them were impact melts and microbreccias or regolith breccias whose compositions closely resemble that of the local soil. In general, incompatible element correlations are very tight and REE patterns are KREEPy. They found very few igneous rocks; these included ferroan anorthosites, basalts, a granite, and a few troctolites and norites. They also found two super-KREEPy melt rocks. The impact melts seem to be the dominant soil component. The meaning of differences between the soil particles and Fra Mauro breccias was the topic of discussion.

C. Neal then gave a talk on lunar granite petrogenesis and the process of silicate liquid immiscibility. The lack of rock types intermediate between basalts, even KREEP basalts, and granites led several workers to consider silicate liquid immiscibility in the origin of granite. Late-stage silica-rich glasses have been found in lunar samples and experiments have been done to set constraints on the process. Neal modeled silicate liquid immiscibility taking place after 90–98% crystallization of a basic magma and used experimental data to partition elements between basic and acidic melts. Most elements show good agreement between actual and theoretical partitioning, but Ba is present in acidic melts rather than the basic melts as experiments predicted. Neal explained that Ba partitioning depends on the alkali/Al ratio, which differed in lunar and experimental conditions. In high K and Na melts Ba has a strong affinity for sites associated with tetrahedral Al and is needed for charge balance.

The discussion showed that, especially after P. Hess's talk in an earlier session, silicate liquid immiscibility is growing in acceptance, but considerable reluctance still exists regarding using it to account for the origin of granite. Partitioning of Eu, U, and Th were raised as potential problems. Other problems concern the physical process. Hess had convinced most of us that silicate liquid immiscibility would take place very late in the crystallization process. He added that the system would proceed through the immiscibility gap back to fractional crystallization. The reluctance to accept silicate liquid immiscibility stems mostly from problems with separating such late-stage liquids to concentrate them as granite and questions of what happened to the complementary basic melt.

TOPIC 5:
APOLLO 14 MARE BASALTS

Summarized by Tammy Dickinson

In the Apollo 14 collection, mare basalts occur mainly as clasts in breccias. The Apollo 14 mare basalt suite is dominated by aluminous and very high potassium (VHK) basalts. Aluminous basalts contain 11–14 wt.% Al_2O_3, <0.3 wt.% K_2O, and K/La ratio >100. VHK basalts contain >0.3 wt.% K_2O, K_2O/Na_2O ratio >1, and K/La ratio >150.

C. Neal gave a keynote talk on Apollo 14 basalt petrogenesis, focusing on generation from an olivine-opx dominated mantle, followed by crustal assimilation and fractional crystallization. Based on La-Hf systematics, Neal argued that the Apollo 14 aluminous mare basalt compositions define a continuum rather than distinct groups. There was considerable debate about this point, led by J. Shervais. There is still no consensus as to whether the Apollo 14 aluminous basalts define distinct compositional groups or whether they represent a continuum of compositions as suggested by Neal et al. (see paper in *Proc. Lunar Planet. Sci. Conf. 18th*, pp. 139-153). Some of the scatter in the data is probably due to sample heterogeneity of small fragments of a single flow. However, the question remains: Is sample heterogeneity the cause of smearing of data between distinct groups or is there a continuum of compositions? Whether the samples represent distinct groups or a continuum may be irrelevant with respect to their petrogenesis.

Neal has modeled the major, trace, and REE variations in these aluminous basalts by the combined effects of fractional crystallization of liquidus phases and assimilation of KREEP. In the model "r," defined as mass assimilated/mass crystallized, is estimated to be 0.22. The assimilant composition used is that of KREEP basalt 15386. The AFC model can produce the observed aluminous basalt compositions by 5% to 70% fractional crystallization of LREE-depleted parental magma and 1.1% to 15.4% assimilation of KREEP.

Neal has modeled the petrogenesis of VHK basalts by a similar AFC process, but in this case the parent magma is an aluminous basalt and the assimilant is granite. Three parental aluminous basalt magmas are required to generate all the observed VHK compositions. The modeling suggests that there is a KREEP component in the VHK compositions. The "r" value used in this model is 0.5.

Shervais pointed out numerous problems with the AFC model. Neal proposed a LREE-depleted parental magma for his AFC process for the aluminous mare basalts. All other models for mare basalt genesis require a LREE-enriched, not a LREE-depleted, parental magma. The basalts with the highest La content do not have the lowest MgO as necessitated by fractional crystallization of mafic phases. The AFC model for the formation of the VHK basalts needs to be reevaluated with respect to the thermal constraints for melting and assimilation of granite by a basaltic magma (a "r" value of 0.5 is unreasonably high). The AFC process is modeled as a bulk assimilation process, which is probably not the case. I. Ridley noted that in acid-base complexes on Earth magmas do not appear to mix. Therefore, it may be difficult to produce the hybridized magmas required by the AFC model. Also, the initial Sr concentrations do not increase in the more evolved basalts as required by AFC with KREEP assimilant.

Shervais believes that the three groups of aluminous mare basalts with the lowest REE abundances are best modeled by varying degrees of partial melting of a common source, and the two REE-enriched groups by assimilation of KREEP.

Further work needs to be done on the petrogenesis of Apollo 14 aluminous mare basalts. It would be enlightening to attempt to integrate the basalt data with the glass bead studies when doing further modeling. Also, the AFC model needs to be refined to include the available isotopic data for these samples.

Ridley presented intriguing information on terrestrial mantle metasomatism. Partial melts rise through fractures in the lithosphere, with only some of the melts reaching the surface. Those that do not reach the surface lose heat and fractionate in the mantle. Volatiles may separate from these melts and transport trace elements into other areas of the mantle. Because the Moon underwent massive differentiation, Ridley suggested that it might be inevitable that the lunar mantle underwent metasomatic processes similar to the terrestrial mantle. There is mounting evidence that volatiles were present on the Moon. However, we do not know which volatiles and in what concentrations. It is possible that complexities in mare basalts may be inherited from the mantle and may have nothing to do with the lunar crust. Ridley suggested that on our next trip to the Moon, we look for samples of the lunar mantle. Without them, it may be impossible to understand mantle metasomatism on the Moon.

The next presentation was by J. Delano on Apollo 14 pristine mare glasses. Six varieties of primary glasses occur at the Apollo 14 site, ranging from low-Ti green glasses to very high-Ti red/black glasses. Many Apollo 14 glasses have high P, and P correlates with La abundance. These glasses are enriched in LREE and depleted in Eu. The red/black glasses show a wide range in alkali abundances, with a covariance between Na and K and constant Ca/Al ratios. This alkali enrichment causes virtually no change in the proportions of Ca, Mg, and Ti.

Many questions remain with regard to these glasses. What was the eruptive mechanism? What was the importance of volatiles and what volatiles were these? What is the cause of the observed alkali enrichments?

The last talk of the session, given by C. K. Shearer, was on an ion microprobe study of trace elements in Apollo 14 volcanic glass beads and comparison to mare basalts. This is one of the first studies of trace element abundances in glass beads, analyzed *in situ* in thin section. The emphasis of this study was the Mg-rich end members of glass compositions present at the Apollo 14 site. The Apollo 14 glasses show a wide range in major element composition, but all have a KREEP component. Green B, Green A, and VLT glasses are LREE-enriched, with Green A and VLT compositions overlapping each other. Shearer has evaluated the possibility of a genetic relationship among the picritic glasses, between the picritic glasses and the

Apollo 14 aluminous basalts, and between the picritic glasses and other mare basalts. The black, orange, Green A, Green B, and VLT glasses are not related by low-pressure fractional crystallization, nor are they related to the mare basalts at the Apollo 14 site. It was suggested that this may indicate that the mantle at the Apollo 14 site is different from other mare basalt source regions. The Apollo 14 source may be intermediate between low- and high-Ti sources and may have highly evolved material mixed in. Ridley noted that in the Skaargard intrusion, contamination and assimilation occur in feeder dikes, not in large magma chambers. Fluids move through rather rapidly and scavenge elements from depth, transporting them to the surface. A similar process may have been in effect on the Moon.

More trace element data, including P, age dates, and isotopic data, are needed for the range of Delano glasses in order to further evaluate the relationship, if any, between picritic glases and mare basalts.

Although we have answered many questions concerning the Apollo 14 mare basalts, this session indicated that there is still much work to be done. Isotopic data and data for the glass beads all need to be incorporated into models for the petrogenesis of Apollo 14 aluminous mare basalts.

TOPIC 6: ISOTOPIC CONSTRAINTS ON EARLY LUNAR DIFFERENTIATION

Summarized by E. Julius Dasch

An understanding of the unique and most significant geologic aspects of the Apollo 14 Western Highlands site—the wide variety and KREEPy character of its intrusive and extrusive rocks and the oldest (pre-"terminal cataclysm") ages of lunar volcanism—has been and will continue to be elucidated by precise isotopic analyses of carefully selected rocks, minerals, and glasses.

The recent discovery of Apollo 14 crystallization ages near 4.3 Ga (reviewed herein by C. Shih and L. Nyquist) conflicts with the widely held theory that lunar volcanism did not commence until after major crustal formation and, later, the impact "cataclysm," near 3.9 Ga. Instead, periods of lunar plutonism and volcanism apparently overlapped. A careful time framework for this important transition requires additional work, especially Rb/Sr and Sm/Nd internal (mineral) isochrons for carefully selected plutonic and volcanic rocks, and U/Pb ages for granitic zircons. The added constraint provided by isotopic composition of Sr, Nd, and Pb, at the time of rock formation, will aid the further understanding of the earliest magmatic history of the Moon. The question of a lunar magmasphere or magma ocean and its characteristics may be addressed with a larger data bank of age dates and initial isotopic compositions; anaylses of Apollo 14 alkalic anorthosites and norites should be included. (If a magma ocean did exist, its internal homogeneity or inhomogeneity might be addressed through the use of T. Barth's concept of residence times and mixing rates for individual chemical species.)

Recent, detailed petrographic and chemical work on numerous basaltic fragments separated from Apollo 14 breccias has shown that a surprisingly wide variety of basaltic rocks are present at this site (olivine basalt, tridymite ferrobasalt, etc.); a large number of the more numerous aluminous basalts analyzed, however, appear to be closely related petrogenetically, perhaps through partial melting or fractional crystallization processes. There is disagreement as to whether these chemically related basalts can be subdivided into natural chemical groups (an opinion discussed herein by J. Shervais) or if they are part of a chemical continuum (see discussion by C. Neal and L. Taylor, this volume). Isotopic information (internal ages and initial isotope ratios) on this question, though sparse, indicates that the chemically related aluminous basalts belong to at least three chemical groups, perhaps related by olivine fractionation and KREEP assimilation (C. Shih and L. Nyquist, this volume). The question needs to be addressed further in that it bears directly on the characteristics and peculiarities of earliest lunar volcanism.

The age of the oldest lunar crust and its relation to a possible magma ocean have yet to be defined. Recent and older analyses of lunar plutonic rocks, some from the Apollo 14 collection, have not yet provided an unequivocal answer to these questions. The *oldest* zircons from lunar granites (C. Meyer et al., this volume) and a precise Sm/Nd internal isochron on a pristine Apollo 16 ferroan anorthosite (see abstract by G. Lugmair in *Lunar and Planetary Science XVIII*) yield ages near 4.4 Ga and suggest to some that this is the time of the completion of crustal formation from a magma ocean. Other dates on Mg-suite plutonic rocks, several from the JSC laboratory, have yielded a range of ages from 4.2–4.6 Ga. The existence of crustal rocks with apparent ages of 4.4–4.6 Ga requires additional study. Based on time-of-crystallization isotopic composition and internal ages, Shih and Nyquist (this volume) suggest that norites may be parental to the grouped Apollo 14 basalts. Apollo 14 norites and anorthosites, including alkalic anorthosites, should be dated. These ages, and the chemical information provided by the parent-daughter and daughter isotopic compositions may provide important clues to proposed events in earliest lunar history, including the magma ocean and the giant impact theory of lunar origin.

The initial isotopic composition of Pb from the oldest lunar rocks is poorly known, owing to very low Pb abundances and a probable complex thermal history for these rocks, as discussed by W. Compston et al. (this volume). A precise knowledge for Pb isotopic composition also is needed for the most accurate U/Pb ages of lunar zircons. The available ion microprobe data from the Australian National University indicates that the highly evolved zircon-bearing granites formed between 4.1–4.4 Ga and originated from lunar source rocks that had very early been depleted in Pb. The earliest evolution of lunar Pb, as well as Sr and Nd, can be critical for a better understanding of a possible magma ocean and the earliest history of the Earth-Moon system. Available data for the earliest terrestrial evolution of Pb suggests to some that Earth underwent an "event" near 4.5 Ga, distinctly after the accepted time of Earth accretion at 4.56 Ga. Is this event the giant impact suggested for lunar origin? Can the "event" be discerned in the compositional data for the earliest lunar rocks, and does the Moon have an accretion date distinctly younger than 4.56 Ga? It is obvious that further work is required to determine if these fundamental questions can be isotopically constrained.

Several important lunar problems may be answerable through the continued isotopic study of lunar glasses. The first-order question of whether there was a lunar impact "cataclysm" near 3.9 Ga (an opinion promoted herein by G. Ryder) and, if such a "cataclysm" did occur, if it happened in discernible time intervals (for example near 3.75, 3.9, and 4.1 Ga; see papers in this volume by F. J. Stadermann et al. and D. Stöffler et al.), must be addressed with a well-chosen set of additional age determinations on lunar impact glasses, presumable by $^{40}Ar/^{39}Ar$ analysis. These glasses commonly are not chosen for analysis, owing to their lack of "pristineness." The age(s) of the largest impact basins, such as Imbrium (and the debated Procellarum) may be better understood as a result of such a survey.

Significant new information can be obtained from further isotopic analyses of the pristine volcanoclastic glasses that have been studied from the Apollo 14 and other lunar collections (reviewed herein by J. Delano et al). Delano and coworkers have shown that these glasses are the least-modified liquids from lunar source rocks and thus offer the least-equivocal evidence for the composition of the lunar mantle. Age data, perhaps by $^{40}Ar/^{39}Ar$ laser analysis, should be obtained for these important but small spherules. Isotopic analysis for Sr and Nd on these spherules, difficult at best, can be used with the cooling ages to determine initial isotopic compositions for use in further constraining the lunar mantle and subsequent volcanic processes.

Though not specifically related to the Apollo 14 materials, significant unresolved problems in the isotopic analysis of lunar materials should continue to be addressed. An accepted value for the precise decay constant of ^{87}Rb has not yet emerged. Differences in the diffusional characteristics of parent-daughter nuclides among the several chronologic systems may result in different formational "ages" for the same event. Reheating of material, perhaps as a result of impacting (currently under study at JSC) or burial, may reequilibrate phases differently or to different degrees. Assimilation (or "contamination," depending on viewpoint) of pristine magma by meteoritic debris, wallrock or crustal rocks, including KREEP and granite, or metasomatized mantle rock (discussed herein by I. Ridley et al.) can affect initial isotopic compositions and, where equilibration after contamination was not complete, alter the resulting age determinations.

Lively debate at the workshop insures that further analysis of the unique Apollo 14 materials, perhaps the least understood of the several Apollo collections, offers significant opportunities for a better understanding of these lunar and isotopic problems.

TOPIC 7:
RELATION OF EVOLVED LITHOLOGIES TO THE MAGMA OCEAN

Summarized by John Jones

The only speaker in this session was J. Longhi. Longhi gave the details of a model calculation that he had performed in which he fractionated a liquid in equilibrium with FAN-suite lithologies until the magma became very KREEP-like. Longhi emphasized that the global uniformity of the KREEP signature implied that the same amount of crystallization had occurred everywhere. This is difficult to achieve and implies in turn that some mechanism is necessary to retard the crystallization of the last dregs of the magma ocean, if such existed. Although not explicitly mentioned, it is possible that volatile elements, which also act as incompatibles, could become enriched enough to substantially lower liquidus temperatures and help to slow down crystallization. As an aside, Longhi used arguments based on REE abundances in mare basalts to support the idea of a magma ocean and concluded that the negative Eu anomalies are indeed due to the removal of solid plagioclase and not to an inherent capacity of olivine and pyroxene to exclude Eu^{2+}, as argued by J. Papike. Finally, Longhi used the fractionation trends of various mantle-derived magmas to hypothesize that the earliest magmas were hotter and assimilated more crustal plagioclase than later, cooler magmas. In this scenario, the oldest magmas, precursors of the Mg-suite, assimilated enough plagioclase to produce troctolites, containing olivine and plagioclase; the younger KREEP basalts show nearly simultaneous crystallization of pyroxene and plagioclase after olivine; and the youngest mare basalts crystallzie olivine and pyroxene before plagioclase.

In detailing his models, Longhi described how, for most of their fractionation sequence, magmas produce steep trends on a Mg# vs. An diagram. This led into a natural discussion of how alkali-suite lithologies were produced and whether high-level (?) assimilation of KREEP-rich lithologies by mantle-derived magmas could be the ultimate source of the alkali-suite.

ABSTRACTS

WHERE IS THE KREEP? P.E. Clark Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Analyses of available lunar orbital geochemical data done during the last decade have led to a greater understanding of the distribution of KREEP on the lunar surface. The results of some of these ongoing studies, done at global, regional, and local scales, are summarized below. The most recent work includes close examination of remote sensing data available for landing sites, as described below.

Multi-dimensional supervised and unsupervised classification techniques, including cluster analysis, were used to correlate (1)(2) orbital XRF Al/Si and Mg/Si(3) and GRS Fe, Ti, and Th (4)(5) concentration data. Regional scale units representing major rock components which could be identified included four basalt types (consisting of a KREEP unit primarily associated with the Imbrium basin, and three basin age-correlated mare basalt units) and five highland units dominated by ANT suite material but obviously contaminated by varying amounts and/or different types of basaltic materials including KREEP-rich basalt.

Three highland regions have been studied in detail, particularly in regard to geochemical heterogeneity resulting from Fra Mauro or highland basalt distribution(3)(6)(7). Data from the Hadley Apennine region are consistent witht he presence of a mixture of ANT suite and Fra Mauro basalt components, dominated by KREEP basalt west of the Apennine front(3)(8). The composition of the Apennine Bench is within the KREEP compositional field and appears to be the source for KREEP here. A more noritic component, possibly low-K Fra Mauro basalt, is concentrated along the northern Apennine crest and backslope and in part of Palus Putredinis. The region nestled between Crisium, Fecunditatis, and Smythii, including the Balmer basin, has been studied in detail as well(6)(8)(9). Results of the studies have indicated the presence of a basalt component, showing considerable variation and associated with mare and plains deposits, in a region otherwise dominated by ANT suite material. A basalt intermediate in composition between mare basalt and KREEP basalt, has been proposed as a probably component of the Balmer plains region. In the region east of Smythii, consisting of farside highlands, a few geochemical anomalies indicating the presence of buried basalt have been found, particularly in the vicinity of Pasteur(7)(9), in a region also largely dominated by ANT suite maerial. In a few places, particularly south and west of Pasteur, mapped plains deposits may have a KREEP basalt component.

In the most recent study, elemental concentrations from landing site soil sample data and orbital data were compared. Orbital XRF (Al and Mg) data were averaged within 1 degree by 1 degree bins representing the effective resolution of the data(3)(10). In the case of GRS data, resolution was effectively 300 km for the Fe and Ti data (4), and 60 km for the Th(5) and K(11) data. Published averages of soil sample data were made available by Basu(12). One interpretation of the differences between remote and in situ data is that local versus regional differences in typical rock components, in some cases KREEP, are responsible for the differences in elemental concentrations between the two datasets. The differences will now be discussed assuming that is the case. At the Apollo 12(Procellarum) landing site, lower Th and slightly higher Fe concentrations from the remote sensing data indicate that the area around the landing sites has a smaller basalt component that the landing site itself. However, at the Apollo 14 (Fra Mauro) landing site, Th and K concentrations acquired remotely are highler, and indicate a greater KREEP component in the soil of eastern Procellarum than at the landing site. The KREEP component for the Apollo 15 (Hadley Apenning) landing site itself, from in situ data, is seen to be smaller than for the region as a whole, as evidenced by elevated Th and K, and decreased Al and Mg from remote experiments. The Apollo 17 (Taurus Littrow) site may have a smaller basalt component, than the the surrounding area, which would include part of Serenitatis. Th, K, and Fe concentrations acquired from the low resolution remote sensing data are slightly elevated for Lunas 16 and 20 (Fecunditatis) and Luna 24 (Crisium), possibly due to the presence of KREEPy basalt in the Balmer basin.

On the basis of these studies, although KREEP volcanism appears to have occurred principally in the Imbrium area, smaller-scale oubreaks of such early volcanism possibly occurred in other areas on the nearside and farside as well.

The research described in this paper was partly carried out at Jet Propulsion Laboratory, California Institute of Technology.

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PINK SPINEL TROCTOLITES IN APOLLO 14 BRECCIAS

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Apollo 14 soils and breccias contain distinctive pink-purple pleonaste spinels as isolated grains and as a component of breccia clasts. Several studies have been made of spinel compositions (e.g. 1-4) and some individual clasts have been described. We searched the thin section collection in the Curatorial Facility at JSC for Apollo 14 breccias with polymineralic clasts containing pleonaste spinel. The collection allows a comprehensive reconnaissance of the important breccia samples: however breccia sample 14063, known to contain significant pleonaste spinel, is not well represented in the collection.

Spinel Compositions The pleonaste spinels are intermediate in composition between spinel and hercynite with significant chromium (Cr_2O_3 2.0-10.5 wt. pct.) and low titanium (TiO_2 0-1.5 wt. pct.). Many grains exhibit continuous zoning (primary zoning (3)) from magnesian cores to darker colored more iron-rich rims. Continuous symmetrical zoning patterns are consistent with crystal-liquid fractionation associated with primary growth. If this interpretation is correct, the pleonaste spinels have retained their primary compositions despite the complex evolution of the breccias. Superimposed on the gradational zoning, in some grains, are very dark to opaque outer rims where the spinel is much richer in Ti and Fe, approaching ulvospinel in composition. These narrow rims (5-20 microns wide) are a product of reaction with the matrix. The reaction has also produced, between the dark outer rim and the matrix, narrow clear coronae of anorthitic plagioclase. Pleonaste spinels in contact with other phases in polymineralic clasts show no evidence of this reaction relationship which is present only where the pleonaste is in contact with the matrix.

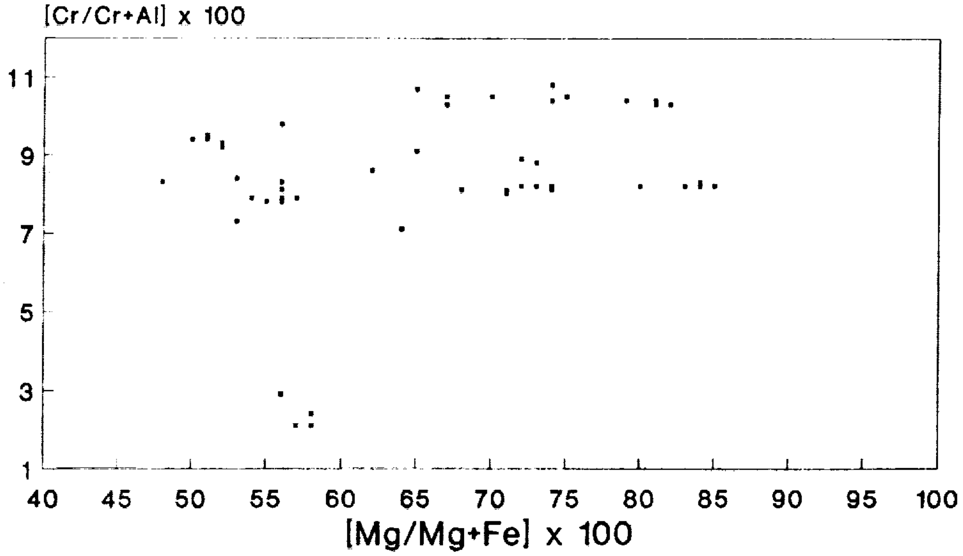

Figure 1: Range of pleonaste spinel compositions in Apollo 14 breccias

Polymineralic Clasts We have examined 15 polymineralic clasts which show the assemblages spinel + plagioclase (5); spinel + olivine (3); and spinel + plagioclase + olivine (7). Analyses of the major minerals yield a data set with no significant differences between mineral compositions in bimineralic assemblages and those in three-phase assemblages. The clasts are small and the data are consistent with comminution of an original three-phase spinel troctolite assemblage

The spinel-bearing clasts show a range of textures reflecting in part various deformational histories. Some clasts are themselves breccias: others appear to retain a primary texture partly obscured by later events that have resulted in cataclasis or partial recrystallisation. Within this range of textures the pleonaste spinels appear to be the most resistant to deformation and to recrystallisation, as evidenced by the persistence of symmetrical zoning patterns. In one extreme case relict rounded spinel grains occur in a fine-grained matrix that has, apart from the spinel, totally melted and quenched. Where original textures are preserved the primary association appears to be of spinel, plagioclase and olivine in a relatively fine-grained (few hundred micron) equigranular assemblage with smooth curving grain boundaries and with growth zoning in the spinel and some of the olivine.

Primary pleonastes show a wide range of Mg/Mg+Fe ratios: the new data extend the range of primary spinels in polymineralic clasts to much higher Mg/Mg+Fe values (Figure 1). The accompanying plagioclase is highly calcic (with one exception) with a restricted compositional range: olivine, occurring with pleonaste, exhibits a wide and sympathetic range of Mg/Mg+Fe ratios (Figure 2). Figure 3 shows the variations in composition of olivine and plagioclase that coexist with spinel. The consistent trends suggest that, if the spinel compositions are primary as argued above, the compositions of the coexisting phases have not substantially changed. The polymineralic clasts represent a possibly cogenetic suite of spinel troctolites where crystal-liquid fractionation has generated a wide range of Mg/Mg+Fe values with little complementary change in the Ca/Ca+Na ratio of the feldspar. Comparison with equivalent values for 'pristine' lunar highland samples (5), however, shows that the pink spinel troctolites cut across the 'magnesian' and 'ferroan anorthosite" trends (Figure 3) and therefore could be derived from mixtures of more primitive components.

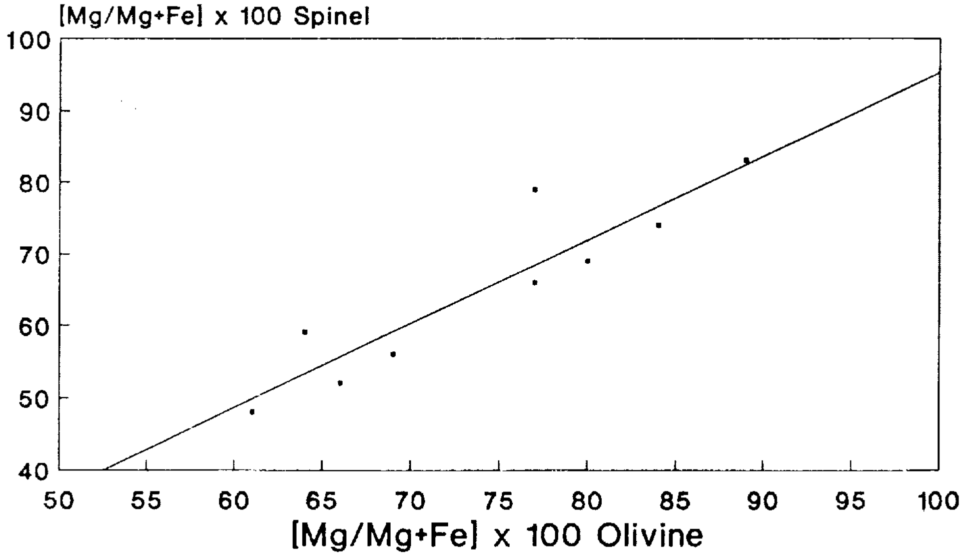

Figure 2: Mg/Mg + Fe in coexisting pleonaste and olivine in breccia clasts

Discussion The rather sparse mineralogical and textural evidence suggests that the pleonastes and related material derive from a suite of spinel troctolites that are cumulates from a highly magnesian, aluminous melt. The grain size and the zoning are more readily explained if these samples represent local cumulates from relatively small magma pockets, rather than from some large magma reservoir. The mineral data are consistent with crystal-liquid fractionation but with relative buffering of the feldspar composition. The presence of one clast with much more sodic plagioclase (Figure 3) raises the intriquing but unproven speculation that there may be other troctolite series e.g. more alkali-rich. In contrast, the data do not fit well with trends established for 'pristine' lunar highland assemblages and we cannot rule out the possibility that these are in part hybrid rocks.

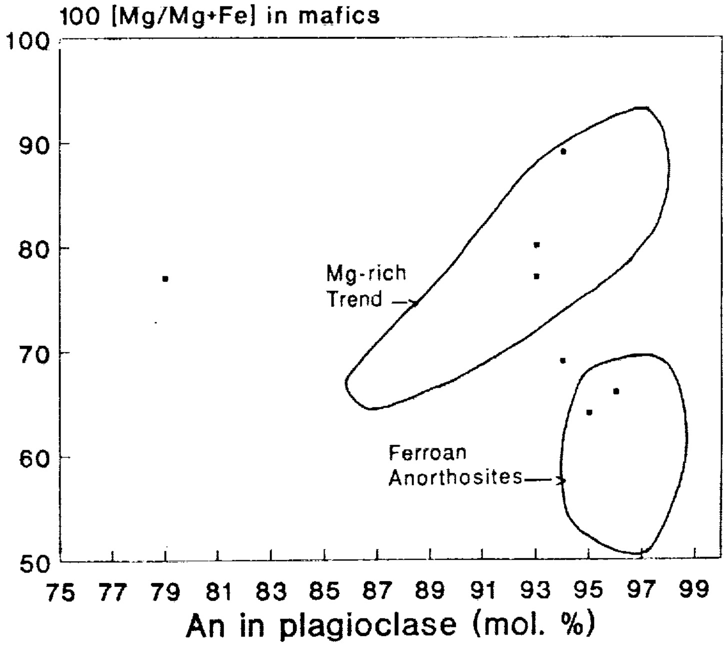

Figure 3: Mg/Mg + Fe in olivine versus An content of plagioclase for pleonaste-bearing clasts.

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The problem of lunar initial Pb

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The initial Pb isotopic compositions of the oldest-known lunar rocks are still not well defined, making it difficult to trace certain aspects of lunar geochemistry between 4.55 Ga and 4.4 Ga. The particular question is the Moon's earliest value for $^{238}U/^{204}Pb$ ('μ'). At some point during this time interval, the Moon as a whole or its antecedents lost Pb by volatilization and mineral fractionation, thus acquiring a high μ relative to the Earth (Silver, 1970; Tatsumoto, 1970). In addition, Pb loss from the Moon was not uniform: the deep source rocks for mare basalts have comparatively low μ (~30) whereas some of the anorthositic remnants of the oldest lunar crust have very high measured μ, as can be expected for volatile Pb loss from an outer magma ocean.

Direct measurement of lunar initial Pb is especially difficult because of the very low Pb contents of lunar highland rocks, and in addition, interpretation is complicated by their complex thermal histories due to meteoritic bombardment. It is known that highly radiogenic Pb was present in feldspars at ~3.9 Ga (Tera *et al.*, 1974). Was it wholly metamorphic in origin due to isotopic resetting during a 'terminal cataclysm', or was there radiogenic initial Pb at , say, 4.4 Ga generated in still older high-μ rocks?

We applied the ion probe to this question primarily in the course of U-Pb age determinations on lunar zircons. In principle, the precision for U-Pb ages by ion probe for old zircons can be as high as a few million years, but this cannot be realized without reliable knowledge of the initial Pb isotopic composition. There were internal indications from our first lunar zircon measurements of a high-μ initial Pb at 4.35 Ga (Compston *et al.*, 1984), but the particular zircons, being rounded grains in breccia, were not relateable texturally to adjacent minerals that might have enough initial Pb to measure. The later discovery of euhedral zircons that are evidently cogenetic with Pb-bearing K-feldspars within thin-sections of lunar granophyres (Meyer *et al.*, 1985) made direct *in situ* Pb isotope measurements of feldspars by ion probe worthwhile.

Figure 1 shows our Pb isotope measurements for two comparatively young granite clasts, from soil 12033 and breccia 14321, which crystallized at 3.90 ± .01 and 3.96 ± .02 Ga respectively, according to the ages of cogenetic zircons. The ilmenite data, which are successive scans during analysis of a single spot, merely illustrate the effect of surface-related Pb contamination, together with our need for cleanable lunar thin-sections. No lunar initial Pb is present in the ilmenite. Instead, there is terrestrial Pb contamination which is slowly removed as the sputtered hole in the target deepens, and eventually only radiogenic Pb produced *in situ* from the tiny U content of the ilmenite will remain. The K-feldspar analyses from 12033 show similar but much smaller effects: those having the lowest $^{208}Pb/^{206}Pb$ (Fig. 1) are the least contaminated.

K-feldspars from 14321 contain considerably more Pb than those from 12033 (Table 1) and give no sign of contamination whatever. None of the feldspars contain detectable U, so that the measured isotope ratios would not be changed significantly by *in situ* radiogenic Pb.

Table 1. Relative ^{206}Pb contents of lunar feldspars and other minerals
(units are observed counts per 10 seconds)

	14303	**12033**	**14321**		**15405**
K-feldspar	69	74	1450	**Si, K-feldspar intergrowth**	226
	188	78	1650		188
	765	514	1175		165
	924	590			176
	954				23
					22
Sulphide	303			**Plagioclase**	22
	85				17
					14

Isotopically, the K-feldspar Pb is characterised by high ^{207}Pb/^{206}Pb and low ^{204}Pb/^{206}Pb (Fig. 2), both of which require high-μ source rocks prior to 3.9 Ga, and by a value for ^{208}Pb/^{206}Pb that likewise demands a high-μ source when assigned the average lunar Th/U of ~3.8. For the 14321 clast, two-stage Pb isotope models are numerically possible only if the 1st stage extends from Canyon Diablo Pb at 4.55 Ga (t_1) to 4.34 Ga (t_2) or later. A comparatively low-μ 1st stage is required, followed by μ values exceeding 3200 for all 2nd stage models. If the 1st stage is prolonged further, μ for both stages must be increased e.g. if t_2 is taken as 4.0 Ga, μ_1 becomes 1269 and μ_2 7389. Similar modelling is possible for the 12033 clast, but t_2 in this case cannot be older than 4.18 Ga. Extremely high values for μ are required for the 2nd stage: 5.5×10^4 and greater, a consequence of the extremely low ^{204}Pb/^{206}Pb measured for the 12033 K-feldspar. Although there is no sign of technical fault in the ^{204}Pb measurement, the ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb ratios correlate both with each other and inversely with the count-rate (Table 1) suggesting terrestrial or meteoritic contamination, which should have produced a much higher ^{204}Pb/^{206}Pb. It would be prudent therefore to discount the extreme value for the modelled μ_2 at present.

Figure 3 shows the Pb isotope ratios for the two older granitic clasts from 14303 and 15405, both of which slightly exceed 4.3 Ga in age on the basis of their zircon ages. As before, the data broadly indicate the presence of three Pb components: terrestrial or meteoritic common Pb seen at very low concentration on the mineral surface, 4.3 Ga radiogenic Pb as concentrated in the zircons, and a highly radiogenic Pb in the feldspar characterised by high ^{207}Pb/^{206}Pb and low ^{204}Pb/^{206}Pb. The K-feldspar from 14303 contains measureable U and the Pb has been corrected for dilution by *in situ* radiogenic Pb by extrapolation to zero $UO^+/^{206}Pb^+$. This gives 1.54 for ^{207}Pb/^{206}Pb and 0.0043 for ^{204}Pb/^{206}Pb. However, there are no possible isotope evolution paths between this Pb composition at 4.30 Ga and Canyon Diablo Pb at 4.55 Ga: bigger values for $^{207}Pb/^{206}Pb$ at 4.3 Ga are required. If the feldspar is corrected for the assumed presence of unsupported 4.3 Ga radiogenic Pb, two-stage evolution becomes possible after the corrected $^{207}Pb/^{206}Pb$ exceeds ~1.62. For this and all higher values of corrected $^{207}Pb/^{206}Pb$, the second stage will have very high μ. Despite its extremely low Pb content (Table 1), the plagioclase from 15405 records very low $^{204}Pb/^{206}Pb$ and high $^{207}Pb/^{206}Pb$.

For the 4.3 Ga granites, although radiogenic initial Pb was very likely present in the magma, it is necessary also to postulate that additional radiogenic Pb (chiefly ^{206}Pb) was added to the feldspars during a later metamorphism. This need not represent isotope 'homogenisation' - the zircons plainly have not equilibrated - but the loss of a small fraction of radiogenic Pb from zircon or U-rich minerals, which is then absorbed by the K-feldspar, would be sufficient. Tera and others (1974) explained similar $^{207}Pb/^{206}Pb$ values in many feldspar-rich fragments as due to internal equilibration, during widespread lunar metamorphism at ~3.8 Ga, between U-rich and Pb-rich minerals that formed originally at 4.4 Ga. No radiogenic initial Pb at 4.4 Ga is required on this model. Our finding here is that it is not necessary to use their model for the 3.9 Ga granites, and that a much less drastic and a much younger metamorphism would suffice for the 4.3 Ga granites. We favour the hypothesis of radiogenic initial Pb at 4.3 Ga, because such Pb is registered by the internal systematics of 4.3 Ga zircons that appear to be totally preserved. The implication for lunar history is that there was **very early** Pb loss from large volumes of the Moon, and later production of lunar granite from this Pb-depleted material.

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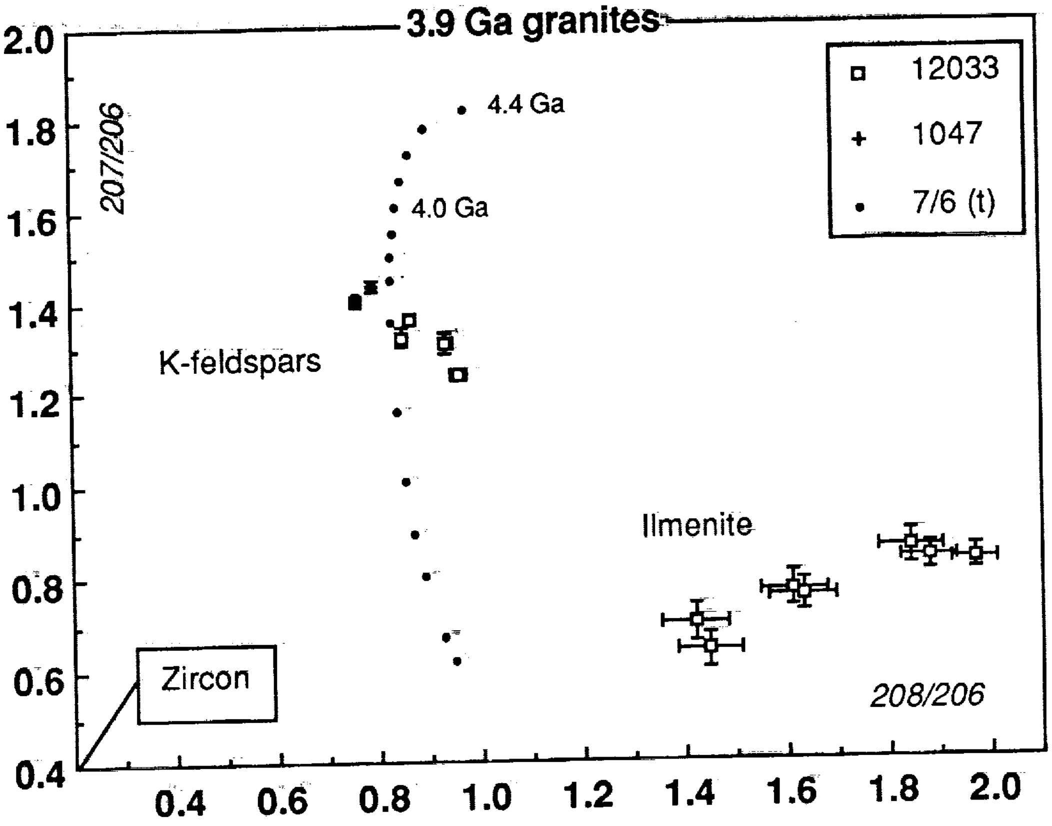


Figure 1

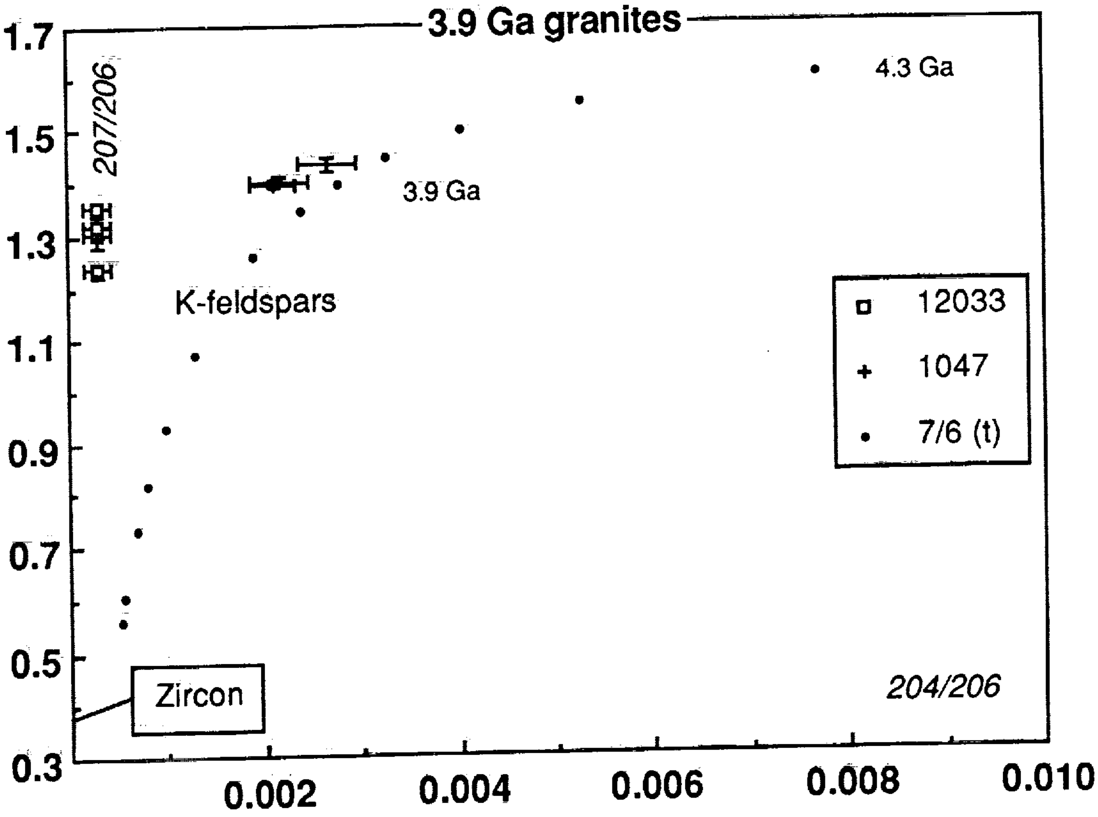
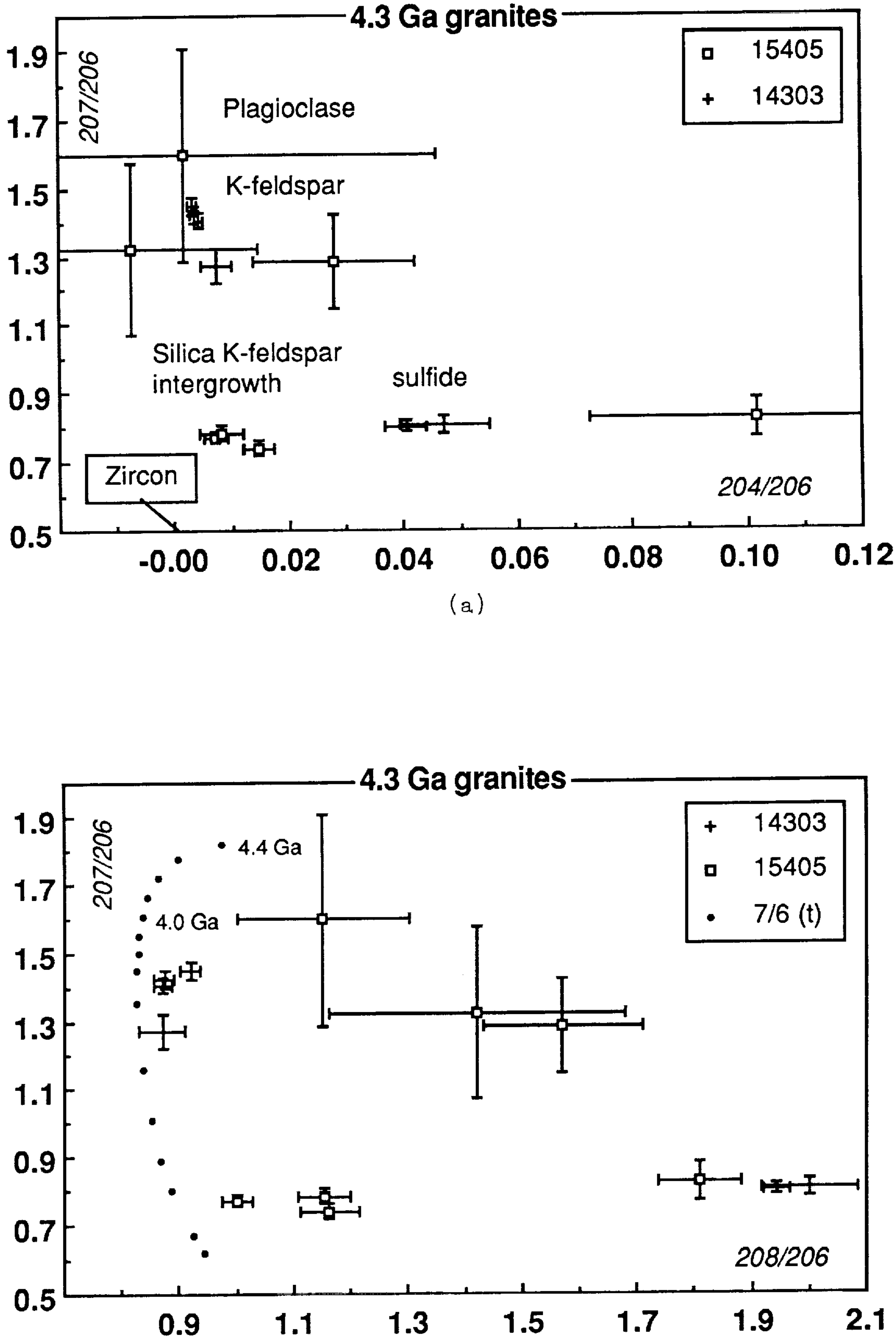


Figure 2


4.3 Ga granites
207/206
204/206
15405
14303
Plagioclase
K-feldspar
Silica K-feldspar intergrowth
sulfide
Zircon
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
-0.00
0.02
0.04
0.06
0.08
0.10
0.12
4.3 Ga granites
207/206
208/206
14303
15405
7/6 (t)
4.4 Ga
4.0 Ga
0.9
1.1
1.3
1.5
1.7
1.9
2.1

(a)

(b)

Figure 3

APOLLO 14 PRISTINE MARE GLASSES.

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Six chemical varieties of primary, mantle-derived magma in the form of pristine (i.e. volcanic) mare glass are presently thought to occur at the Apollo 14 landing site [1]. They range from low-Ti green glasses to intermediate-Ti yellow glasses to high-Ti orange glasses to very high-Ti red/black glasses (Table). In the same way that clasts of crystalline mare basalt are common occurrences at this highlands site, so to are the pristine mare glasses observed to be common in most Apollo 14 regolith breccias [2]. In addition to their abundance, the compositional variety in this suite of Apollo 14 pristine mare glasses is greater than that found at any other Apollo or Luna site. Although the causes of this large mare component at the Apollo 14 highlands site have not yet been determined, detailed spectral reflectance studies of the Fra Mauro region, comparable to those already conducted in the vicinity of Apollo 15 [3], would probably give important information.

Due to crystal/liquid fractionation during ascent and emplacement, most crystalline mare basalts do not appear to be samples of primary magmas [e.g. 4]. Studies of Apollo 14 basalts have also shown that crustal assimilation [5,6] can also significantly alter the composition of a mafic magma during its rise from the mantle source-region. In contrast, the picritic magmas represented by the pristine mare glasses seem generally to have escaped the ravages of crystal/liquid fractionation and crustal assimilation by having ascended rapidly from their source-regions. However, two of the six varieties of Apollo 14 pristine glass (VLT and red/black) have chemical variations that are suggestive of fractional assimilation. Most notably, the Apollo 14 red/black glasses display a large range of alkali abundances (wt.% K_2O + wt.% Na_2O) of 0.25 wt.% to 5.1 wt.%. This latter value is more than a factor of 2 greater than that observed even in the Apollo 14 VHK basalts [5,6]. Although crustal assimilation is a tempting explanation for these data, there is an important distinction to be made between these high-Ti glasses and the VHK basalts. Whereas in the VHK basalts, Na and K are decoupled from one another and are thereby consistent with experimental models of magma contamination [7,8], the high-Ti glasses show an apparent covariance between Na and K. Figure 1a shows that the 43 samples of Apollo 14 red/black glass define a strong linear trend toward the alkali corner of the ternary diagram with little-if-any change in the Ca/Al ratio. Figure 1b demonstrates that this alkali enrichment also causes essentially no change in the Ca/Mg/Ti ratio among the 43 samples. At present, the cause of this feature is unknown but under investigation.

Figure 2 shows an interesting relationship between FeO and Sc in the mare basalts and pristine mare glasses. Laul and Schmitt [9] were the first to note that a significant correlation existed among lunar samples between iron and scandium. Since then, a lunar FeO/Sc ratio of 5400 has become entrenched in the literature [10]. This value seems applicable to (a) all analyzed pristine glasses (regardless of titanium abundance) and (b) most low-Ti mare basalts from Apollo 12, Apollo 15, and Luna 24. However, about an equal number of mare magmas lie prominently off that ratio including: (a) Apollo 14 low-Ti groups 1-5 basalts [11]; (b) Apollo 17 VLT basalt [12]; (c) Apollo 11 high-Ti basalts [13]; (d) Apollo 17 high-Ti basalts; and (e) Apollo 12 feldspathic basalts. Contrary to an early view [14] that the high-Sc trend was occupied exclusively by high-Ti basalts, it is now obvious from the Apollo 14 data that the two trends in Figure 2 are essentially independent of Ti since both contain a wide spectrum of basalt compositions. Since experimental petrology suggests that olivine + low-Ca pyroxene were the sole residual phases in most, if not all, of the source-regions for these magmas, the bulk partition coefficients for Feo and Sc during partial melting are likely to have been near unity. If so, then the diachotomy evident in Figure 2 was inherited from the mantle-source regions. Perhaps this can result naturally from a scenario involving three ancient differentiated components [15] of a primordial lunar magma ocean: (a) early olivine ± orthopyroxene cumulates; (b) late-stage clinopyroxene + pigeonite + ilmenite + plagioclase cumulates; and (c) late-stage intercumulus liquid. It is of additional interest to note that a single landing site (e.g. Apollo 14; Apollo 17) can possess a suite of mare rocks and glasses where both FeO/Sc reservoirs are represented.

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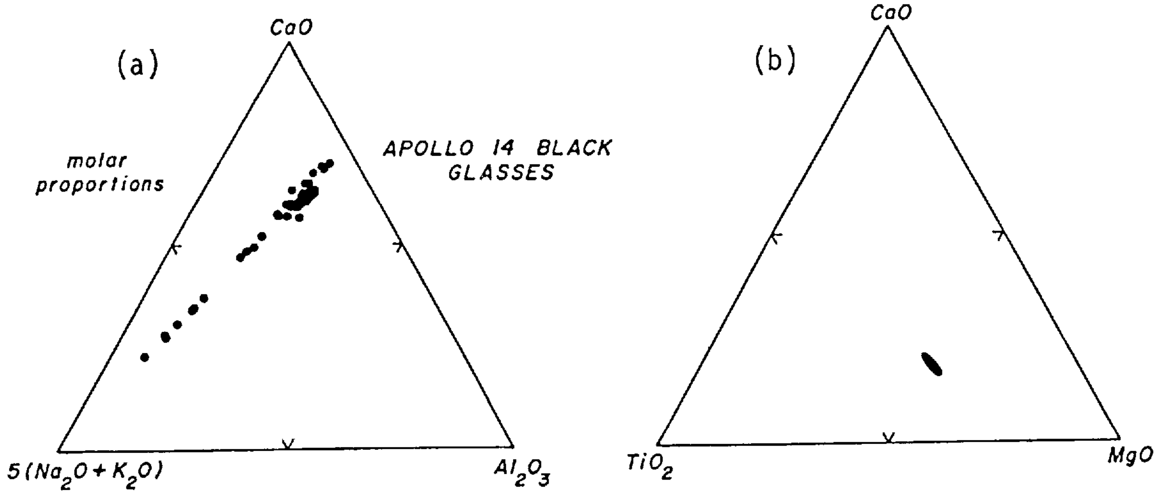
Table. Six varieties of Apollo 14 pristine mare glass.
(Asterisk indicates INAA data. All other values by electron microprobe)

(weight %)	GREEN A	GREEN B	VLT	YELLOW	ORANGE	RED/BLACK
SiO_2	44.1	44.8	46.0	40.8	37.2	34.0
TiO_2	0.97	0.45	0.55	4.58	12.5	16.4
Al_2O_3	6.71	7.14	9.30	6.16	5.69	4.6
Cr_2O_3	0.49 *	0.54	0.51 *	0.41	0.86	0.92
FeO	23.1	19.8	18.2	24.7	22.2	24.5
MnO	0.35 *	0.24	0.26 *	0.30	0.31	0.31
MgO	16.6	19.1	15.9	14.8	14.5	13.3
CaO	7.94	8.03	9.24	7.74	7.04	6.9
Na_2O	0.18 *	0.06	0.29 *	0.42	0.28	0.23
K_2O	0.05 *	0.03	0.11 *	0.10	0.29	0.16
(ppm)						
Ni	115	185	125	82	30	≤ 22
Sc	38 ± 1 *		36 ± 1 *			
V	210 ± 30 *		170 ± 8 *			
Co	68 ± 10 *		58 ± 2 *			
La	7 ± 1 *		12 ± 1 *			
Ce	--		31 ± 5 *			
Nd	27 ± 15 *		22 ± 4 *			
Sm	4.9 ± .2 *		7.0 ± .2 *			
Eu	0.8 ± .3 *		0.48 ± .07 *			
Dy	6.8 ± .5 *		9 ± 1 *			
Ho	1.5 ± .3 *		2.0 ± .2 *			
Yb	2.2 ± .5 *		4.9 ± .3 *			
Lu	0.6 ± .3 *		0.7 ± .2 *			
Hf	--		8.0 ± 1.2 *			

Estimated liquidus temperatures (± 10°C) at zero-pressure

T(°C)	1405	1440	1375	1375	1355	1330

FIGURE 1



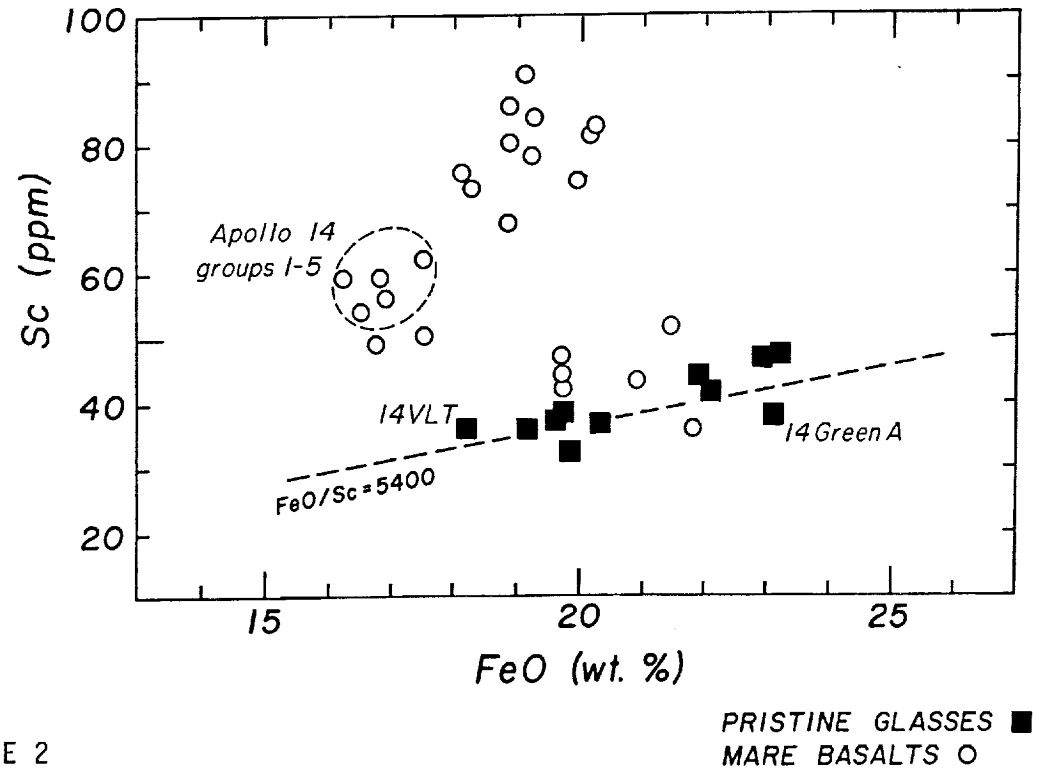


FIGURE 2

GEOLOGIC AND BOMBARDMENT HISTORY OF THE APOLLO 14 REGION.

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INTRODUCTION

A major objective of the Apollo 14 Mission was to sample material comprising the Fra Mauro Formation, a distinctive ridged and furrowed unit surrounding the Imbrium basin.[1,2] The Fra Mauro Formation has been interpreted to be a portion of the ejecta blanket deposited during the impact formation of the Imbrium basin.[1,2,3,4,5,6] Major controversy has centered on questions concerning the mode of emplacement of the Fra Mauro Formation, the provenance of materials with the unit, and the sources of the range of thermal effects exhibited by the returned samples. Early studies interpreted the major characteristics of the geology and petrology of the site in terms of the deposition of a blanket of Imbrium primary ejecta which largely originated from the area of the Imbrium crater and which was emplaced in a mode in which thermal metamorphism played a significant role.[7,8,9] The range of thermal effects observed in the Apollo 14 sample collection was attributed to autometamorphism in a hot, thick ejecta blanket. More recently, Hawke and Head[2,10,11,12,13] presented the results of a series of investigations of the processes and events dominating the history of the Apollo 14 region. It was concluded that the Fra Mauro Formation was formed by a process which included the erosion and excavation of local pre-Imbrian material by filaments of Imbrium primary ejecta and the mixing of this Imbrium ejecta with local crater deposits, to produce an ejecta blanket dominated by locally derived material. Similar conclusions were reached by other workers, based on laboratory cratering experiments, photogeologic analysis, studies of terrestrial craters, and lunar sample studies.[20,21,22,23,24,25,39,40] In recent years, this interpretation has been challenged by Wilhelms and co-workers.[5,45]

The history of the Apollo 14 region can be subdivided into three time intervals: Phase I (prior to the formation of the Imbrium basin; pre-Imbrian time); Phase II (the very short period of time associated with the formation of the Imbrium basin; earliest Imbrian time); and Phase III (the time period subsequent to basin formation and ejecta deposition; post-Imbrium events; Imbrian, Eratosthenian, and Copernican time). The purpose of this paper is to identify the events and processes associated with these three time periods and to assess their relative importance in the Fra Mauro region in terms of the provenance and mode of emplacement of the Fra Mauro Formation and the origin of the Apollo 14 samples.

REGIONAL GEOLOGIC SETTING

The Apollo 14 landing site is located on an elevated north-south trending expanse of highlands terrain surrounded by regional topographic lows. The site is located approximately 1230 km south of the center of the Imbrium basin, about 550 km south of the main basin ring (Montes Carpatus), and about 750 km south of the estimated rim of the Imbrium transient crater cavity.[2,10,14] The geology of the region has been mapped by Eggleton[3,15,16], Offield[17], Wilhelms and McCauley[18], and Hawke and Head.[2,10] The local site geology has been summarized by Swann et al.[1,6,19] and Head and Hawke.[2] The Apollo 14 LM landed near the outer edge of the Fra Mauro Formation. In this area, the formation grades southward from a ridged deposit to a complexly cratered one.[6,19] Ridges, the most characteristic feature of the formation, in the vicinity of the landing site are generally 1 to 4 km wide, a few to several tens of meters high, and five to ten times as long as they are wide.[19] These ridges are slightly sinuous and roughly radial and subradial to the Imbrium basin. Locally, somewhat flatter areas, typically measuring a few kilometers across, exhibit slightly lower albedos than those of the ridges.

The major geologic objectives of the mission were to describe, photograph, and sample the ejecta deposit of Cone crater, a 370-m-diameter impact structure situated on one of the ridges of the Fra Mauro Formation. This ridge is 50-100 m high.[63] Cone crater is 60-70 m deep and penetrates below the fine-grained lunar regolith into a blocky substrate.[5] The regolith thickness at the landing site was estimated to vary from 5 to 12 m based on observations of small craters in the area.[5,16,17] The active-seismic data indicate a regolith thickness of 8.5 m.[64,65]

IMPACT HISTORY OF THE FRA MAURO REGION

Phase I - This period of lunar history is defined as the time prior to the formation of the Imbrium basin and the emplacement of the Fra Mauro Formation (i.e., pre-Imbrian time).[2,4] The emplacement of the Fra Mauro Formation considerably altered the underlying terrain by erosion and burial. However, detailed studies of the region have provided considerable information on the characteristics of the pre-Imbrian topography and geology.[2,10,11]

Phase I time can be divided into three subdivisions (IA, IB, and IC) on the basis of the inferred relative ages of the pre-Imbrian impact structures. The earliest events occurred during Phase IA. The first recognizable impact event to have influenced the Apollo 14 region may have been the formation of Procellarum or Gargantuan basin. Cadogan[26] first proposed the existence of this basin, which he called Gargantuan, to explain the lunar nearside-farside asymmetry and the localization of KREEP-rich material in the Oceanus Procellarum-Mare Imbrium region. He described Gargantuan as being centered at 23°N, 29°W and having a diameter of 2400 km, and suggested an age of ≥ 4.3 b.y. Whitaker[27] and Wilhelms[5] described a very large (diameter = 3200 km) multi-ringed basin, which they called Procellarum, in the same region. If this basin exists, it would be the largest and probably the oldest recognizable impact structure on the Moon. The Apollo 14 site lies well within the rim of this proposed structure. An impact with sufficient energy to produce Procellarum basin must have had a profound effect on the lunar lithosphere in terms of the amounts of material melted, brecciated, fractured, and excavated. However, it should be noted that the existence of the basin has not been firmly established and it continues to be the source of a major lunar controversy. Hawke and Head[10] presented arguments against the Gargantuan basin model presented by Cadogan[26] and Schultz and Spudis [28] raised major objections to the proposed Procellarum basin.

In addition to Procellarum, three other very old basins are close enough to have affected the Fra Mauro region during Phase IA time. These are (1) Insularum basin (South Imbrium basin[10]), (2) Flamsteed-Billy basin (South Procellarum basin[10]), and (3) Nubium basin. The relative ages of the three impact structures are uncertain. Wilshire and Jackson[7] indicated that Insularum basin formed first, followed by Nubium, and finally by Flamsteed-Billy. Alternatively, Wilhelms[5] suggested that Nubium basin formed after Flamsteed-Billy.

Insularum is possibly the largest and oldest of the three post-Procellarum, Phase IA basins and may have played an important role in the early evolution of the Fra Mauro region.[10,11] The basin is centered near Copericus crater and its presence is inferred from a circular and concentric series of topographically high terra remnants surrounding a regional low which has subsequently been flooded by mare basalt.[2,10,29] Two partial rings have been identified by Wilhelms and McCauley.[18] The Apollo 14 site is located about 118 km south of the inner ring which is ~600 km in diameter and the site is just north of the 940-km-diameter outer ring. The site occupies a position with respect to Insularum that is roughly analogous to that of the Apollo 15 site with regard to Imbrium.[10] Ejecta thickness calculations[30] indicate that Insularum basin may have contributed ~580m of material to the Apollo 14 site.[10] Insularum ejecta at the Apollo 14 site was likely to have been emplaced as a unit consisting primarily of weakly shocked crustal material derived from depths generally in excess of 10 km. However, a thin layer of Insularum impact melt may have been emplaced on top of this weakly shocked material.

The Flamsteed-Billy basin lies west of the Fra Mauro region in the southern part of Oceanus Procellarum.[5,18,31] There is less evidence for the existence of this structure than for Insularum or Nubium. McCauley[31] noted that this vague, multi-ringed structure appeared to control the irregular shoreline of Oceanus Procellarum and to explain the alternating structural highs and lows in the vicinity of the craters Hansteen and Billy. The outermost recognizable ring is almost 700 km in diameter as opposed to an inner ring diameter of approximately 450 km.[10] If the inner ring represents the transient crater cavity, this basin could have contributed ~40 m of ejecta to the Apollo 14 site. Compared with Insularum ejecta, the material deposited by the Flamsteed-Billy basin was derived from shallower depths within the crust, suffered more extensive shock damage, and mixed more extensively with local material during deposition.[10]

Nubium basin has traditionally been described as a single 750-km-diameter impact structure centered at 19°S, 17°W.[18,32] However, studies by De Hon[33], Hawke and Head[10], and Hartmann and Wood[34] indicated that the Nubium basin is actually composed of a series of overlapping impact structures. Hartmann and Wood[34] described a west Nubium basin defined by two rings that are 195 km and 425 km in diameter and centered at 23.5°S; 22°W. De Hon[33] suggested that a third basin, about 380 km in diameter, is centered at 14°S; 12°W. However, a series of large craters in the same general area better account for the observed topographic relations.[10,11] The east and west Nubium impact events could have delivered ~70 and ~50 m of ejecta, respectively, to the Apollo 14 site.[10]

A number of very large craters have been mapped in the region surrounding the Apollo 14 landing site.[2,10,11,35] Superposition relationships show that these Phase IB craters formed after the basins of Phase IA but before such relatively undergraded craters as Bonpland, Parry, and Fra Mauro. The area west of the landing site contains at least five Phase IB impact structures which appear to have been important in the history of the Fra Mauro region because of their size, proximity, and relative age.[10] Of these, the 135 km "northwest" crater was calculated to have delivered the greatest thickness of ejecta (~210 m) to the Apollo 14 site and is among the oldest features which formed during Phase IB.[10,35] The landing site is only about 25 km (0.37 R where R = crater radius) from the rim crest of "northwest" crater and the bulk of ejecta should consist of relatively unshocked crustal material excavated from depths not greater than 10-15 km. It is likely that impact melt deposits, derived largely from the upper portion of the "northwest" crater target site, were emplaced in the area of the landing site. Later impacts on or near "northwest" crater could have excavated and ejected solidified melt rock to the Apollo 14 site. For example, "big west" crater is superposed on "northwest" crater[35], and this later impact event contributed 80 m of material to the Apollo 14 pre-Imbrian section.[10] Detailed maps presented by Hawke and Head[10,11] showed that many Phase I craters in the Fra Mauro region are superposed on pre-existing impact structures and therefore must have ejected deposits related to the older structures. It is clear that much of the material delivered to the Apollo 14 site has probably been involved in one or more previous impact events.

Phase IC is defined as the time after the formation of the large Phase IB craters but prior to the Imbrium impact event. Most of the craters that formed during Phase IC time are realtively small and contributed only minor amounts of ejecta, largely of near-surface origin, to the Apollo 14 area. While the larger, nearby Phase IC craters such as "central" and "northwest A" did deliver significant thicknesses of ejecta (~60 m), it is clear that Phase IC deposits are dominated by the contributions of Fra Mauro and "site" craters. Fra Mauro crater, about 95 km in diameter, lies only 22 km south of the landing site and could have contributed 130 m of ejecta, the bulk of which was probably subjected to only low shock pressures. However, some shock-melted material may have been emplaced on top of the weakly shocked bulk ejecta deposit. The Cone crater target site was near the inferred rim crest of the 25 km "site" crater.[2,10] Calculations indicate that ~150 m of material excavated from depths up to 2-3 km and deposited on the rim of "site" crater. The relative "youth" and proximity of "site" crater strongly suggest that its deposits dominated the Apollo 14 site just prior to the Imbrium event.

Phase II - Phase II history involves the formation of the Imbrium basin and the emplacement of the Fra Mauro Formation. Pre-mission studies indicated the Fra Mauro Formation was a portion of the Imbrium ejecta blanket and was composed of material derived from the Imbrium target site.[e.g. 4,16,17] The results of early sample studies were thought to be consistent with a primary ejecta origin and the range of thermal effects in the samples was attributed to autometamorphism in an ejecta deposit emplaced in a "hot" mode.[7,8,9] However, some workers disagreed with this interpretation.[36,37] While they considered the Fra Mauro formation to be composed of Imbrium primary ejecta, they indicated that the deposit was emplaced in a "cold" mode and that the thermal effects were caused by pre-Imbrian impact events in the Imbrium target area.

Later, Oberbeck and co-workers[20,21,22,23,24] pointed out the importance of secondary cratering in the formation of impact crater and basin deposits. Their studies demonstrated that the impact of ballistically transported primary ejecta excavates considerable volumes of underlying local material (secondary crater ejecta) and incorporates this material into an ejecta deposit. The resulting mixture of primary ejecta and local material moves radially away from the parent crater or basin as a surface flow or debris surge.

The Apollo 14 site lies at a range of about 1.5 crater radii from the approximate rim of the Imbrium transient crater cavity (R = 485 km).[4, 30] At an analogous distance from the rim of the Orientale transient crater, Head and Hawke[2] identified and mapped well-developed crater chains. At this range, pre-Orientale cratered topography is more easily seen, but shows evidence of having been heavily cratered and eroded by secondary chains. The deposits at the 1.5 crater radii are transitional in nature between the hummocky topography of the textured ejecta unit, and the outer regions where underlying topography is more apparent. Examination of oblique Apollo and low sun earth-based photography of the Fra Mauro region by Head and Hawke[2] revealed the presence of a large number of secondary crater chains and clusters that are radial and subradial to the Imbrium basin. Some of these Imbrium secondary craters had previously been mapped by Eggleton.[16] Crater chains in this region attributed to the impact of Imbrium ejecta range from about 1/2 to 12 km in width and range up to tens of kilometers in length. The results of calculations presented by Morrison and Oberbeck[23] and Hawke and Head[38] indicate that at the radial range from Imbrium typical of the Apollo 14 site area, over 70% of the deposit which resulted from the impact of Imbrium secondary-forming projectiles was composed of locally-derived material. In the area of the landing site, the Imbrium secondary craters are about 1-2 km in diameter, which would imply the presence of 15-20% Imbrium primary ejecta.[38] Head and Hawke[2,10] concluded that the Phase II history of the Apollo 14 region involved the impact of filaments of Imbrium primary ejecta, the excavation and mixing of large volumes of local Phase I crater materials, and the incorporation of these two components into an ejecta deposit, the Fra Mauro Formation, which was sampled by the Apollo 14 mission.

In recent years, the local-mixing (secondary-impact) hypothesis has been under increasing criticism by several workers. Based on the results of clustered impact experiments. Schultz and co-workers[41,42,43,44] have concluded that clustered impacts significantly affect crater morphology and reduce cratering efficiency. If the ejecta curtain around large impacts is viewed as a thick wall of debris and clustered impactors are viewed as a unit section of such a curtain, then the experimental results of Schultz and Gault[41] indicate that the continuous ejecta facies of large lunar impact structures could contain a much larger percentage of primary material.

In addition, Wilhelms and co-workers[5,45] have raised objections to the local-mixing hypothesis. They maintain that the topography of the landing-site region is dominated by ridges formed by the flow of a thick deposit that has obscured the secondary craters and that this flow originated either at the basin rim or at secondary-impact sites much closer to the basin than its present resting place. They also pointed out that local-mixing equations developed by Oberbeck and co-workers[23,24] are model-dependent and they questioned many of the input parameters. Finally, they presented evidence for the presence of abundant melt in basin-ejecta deposits. If Imbrium impact melt was a major component a component of the Fra mauro Formation at the Apollo 14 site, this melt could have been responsible for the thermal effects in many of the Apollo 14 samples as well as the 3.82-3.84 b.y. age cluster in the returned samples.[5,46,47]

Other workers have presented evidence from a variety of sources which supports the local-mixing hypothesis. Detailed investigations of the continuous ejecta deposit of the Reis impact structure by Horz and co-workers[25,58,59,60,61] conclusively demonstrated the importance of local mixing in producing this unit. The result of sample geochemistry studies by Warren and Taylor[48,49] provided evidence that basin-forming impacts were not very effective at transporting large amounts of primary ejecta far across the lunar surface. Numerous sample workers have presented the results of geochemical and petrologic studies which indicate that multiple impact events are required to explain the characteristics of many of the complex Fra Mauro multibreccias.[e.g. 39,40,50,51,52,53,54,55] There appears to be little sample evidence for abundant Imbrium impact melt.[56]

The evidence for multiple impact strongly suggests evolution in the upper portion of the lunar crust. The impact histories of the Apollo 14 samples are inconsistent with an origin as Imbrium ejecta excavated from some deep crustal or subcrustal layer postulated to have been present beneath the Imbrium target site.[12] Since the Apollo 14 breccias and melt rocks appear to have evolved in the uppermost part of the crust, their compositions require the near-surface portions of the target sites of the pre-Imbrian craters to have contained large amounts of material of KREEP composition. The assembly diagrams and intrabreccia stratigraphies of such intensively studied samples as 14321 and 14064 have suggested formation by impact into KREEP-rich terrain overlying ANT-rich crustal material.[12,50,51,57] Hawke and Head[10,11,12] presented a wide variety of remote sensing and photogeologic evidence for pre-Imbrian KREEP volcanism in the Fra Mauro region and proposed that the Apollo 14 samples represent the products of extensive impact reworking of these surface accumulations of KREEP basalt.

Currently, the local-mixing (secondary-impact) model for the Fra Mauro Formation at the Apollo 14 landing site is widely accepted.[5] However, it should be noted that this is still an open question. Reasonable alternatives to the local-origin model have been proposed by Wilhelms and co-workers.[5,45] Additional sample, remote sensing, and geologic studies will be required to resolve this critical issue.[69]

The thickness of the Fra Mauro Formation at the landing site has also been the subject of controversy. Early thickness estimates, based on regional photogeologic studies, were as high as 500 m.[62] The ridge east of the landing site is 50 to 100 m high.[6,63]. Eggleton[16] and Offield[17] interpreted this ridge as one of a group that is characteristic of the Fra Mauro Formation and estimated a Fra Mauro thickness of 100 to 200 m on the basis of ridge relief.[5] The results of the Apollo 14 active-seismic experiment indicated the presence of a 19-to-76-m-thick bedrock unit with a seismic velocity of 299 m/s beneath 8.5 meters of regolith.[64,65] Many lunar scientists have interpreted this bedrock unit to represent the Fra Mauro Formation.[5,64,65,66] However, a few workers[16,17] maintain that the material beneath this bedrock layer is also a part of the Fra Mauro Formation.

Phase III - Subsequent to the formation of the Imbrium basin and the emplacement of the Fra Mauro Formation, the surface deposits at the Apollo 14 site continued to undergo bombardment and additional small primary and secondary craters were formed, although the major pre-existing topographic features were not destroyed. A number of post-Imbrium, Phase III craters in the 10^2-10^3-km diameter range have been mapped at the Apollo 14 landing site.[2,17] Although these Phase III craters did not drastically alter the radial ridge pattern, they did locally modify the surface and often obscure the effects of Imbrium secondary chains and ridges. For example, it has not previously been recognized that the valley in which the Apollo 14 LM landed is actually an Imbrium secondary chain.

Four Phase III craters mapped by Offield[17] and Head and Hawke[2] were of significance in producing the near-surface stratigraphy in the Cone crater target area and range from 230 to 1000 m in diameter., Cone crater lies on a ridge crest near the rims of the three largest craters. A total ejecta contribution of ~15 m could be expected from these craters at the Cone crater target site.[2] Very minor contributions from other small, local Phase III craters and rays from distant craters would also be expected.

Schonfeld and Meyer[67] suggested that the" layered stratigraphy" at the Cone crater targe site (inferred from sample distribution relative to Cone crater[7,67]) was due to the deposits of Phase III craters. More recent work has provided some support for this suggestion. Even though Cone crater is 60-70 m deep, laboratory impact experiments conducted by Stoffler et al.[68] indicated that the Cone crater maximum excavation depth was ~32m. Hence, it appears that the ~15 m of Phase III crater ejecta comprised almost 50% of the section excavated by Cone crater. Based on the estimated depths of excavation of these Phase III craters[2], at least some pre-Imbrian (i.e., pre-Fra Mauro) material could have been present in this 15-m-thick deposit. In addition, this surface material had probably been subjected to considerable impact reworking prior to the formation of Cone crater.

The ridge penetrated by Cone crater is the rim of the pre-Imbrian "site" crater. Since the thickness of the Fra Mauro Formation appears to be extremely variable at the landing site[5,64,65,66] and it might be expected to be particularly thin in the vicinity of the topographic infliction associated with the "site" crater rim crest, it is possible, though not likely[5], that Cone penetrated the Fra Mauro Formation and excavated pre-Fra Mauro material.

CONCLUSIONS

(1) The Apollo 14 site is situated on an isolated uplands area and is surrounded by a number of major Phase I impact structures that contributed ejecta to the landing site. Calculations indicate that a total ejecta thickness of over 1700 m could have accumulated in the area of the ridge on which Cone crater later formed.

(2) The majority (53%) of the ejecta in the pre-Imbrian section at the Apollo 14 site just prior to the Imbrium event was contributed by the numerous Phase IB and IC craters in the vicinity and not by the lunar basins. If only the uppermost 1 km is considered, the deposits are > 90% local crater ejecta.

(3) The landing site lies close enough to the rim crests of four of the Phase I craters to have received significant amounts of impact melt generated by their formation. Much of the material deposited at the landing site had probably been affected be one or more previous impact events.

(4) The deposits of the Phase I cratering events were excavated by the impact of filaments of Imbrium primary ejecta. This primary ejecta mixed with local, pre-Imbrian material to form the Fra Mauro Formation which was excavated by Cone crater and sampled by the Apollo 14 astronauts.

(5) The Phase III craters excavated and mixed the surface of the Fra Mauro Formation without radically changing the characteristic surface topography or the major characteristics of the bulk of the samples.

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HIGHLY EVOLVED LIQUIDS FROM THE FRACTIONATION OF MARE AND NONMARE BASALTS.

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Liquids of relatively low Mg values probably were present in the earliest period of lunar history. For example, mineral compositions of ferroan anorthosites indicate that parent liquids had Mg values less than 0.4 (1), whereas the hypothesized KREEP residuum of the "magma ocean" must have had even lower Mg values. Unfortunately, the composition of residuum can only be guessed, since the KREEP component has probably interacted with more primitive materials to give rise to KREEP basalts and some members of the Mg-suite of plutonic rocks. The only samples of highly evolved magmas are the few samples of lunar granite whose origin is also controversial (2,3,4). The most important unknown is the sequence of liquids that were produced by very advanced stages of crystal fractionation of not only the magma ocean but also of mare and nonmare magmas within high level plutons of the lunar crust.

Low pressure fractional crystallization paths of mare and nonmare lunar basalts are controlled by the crystallization of olivine, pyroxenes, calcic plagioclase and, for some liquids, the iron oxide ilmenite. In contrast to terrestrial equivalents, the range of primitive magma compositions is somewhat limited in the lunar case. Nevertheless, the liquid lines of descent of lunar magmas, particularly those obtained after very advanced stages of crystallization, are not fully understood since they are very sensitive to slight changes in the parent liquid composition and the conditions of crystallization. The origin of multiple differentiation paths for low alkali basaltic liquids is not unique to the moon but is a major poblem that confronts terrestrial petrologists. Bowen (5) long ago proposed that fractionation of Fe, Mg silicates and plagioclase produce liquids characterized by increases in SiO_2,Na_2O and K_2O and decreases in MgO,FeO and CaO. The volcanic rock associations produced by this type of fractionation include basalts, andesites, dacites and rhyolites – a series characterized by a continuum of volcanic liquids from low to high SiO_2 (6,7). Soon after Bowen's ideas were advanced, Fenner (8) found that the crystallization of Fe, Mg silicates and plagioclase sometimes produced a trend of increasing FeO and relatively constant SiO_2 over a large range of fractionation. These paths may suddenly produce rhyolites through the onset of silicate liquid immiscibility (2,9,10,11). In other cases, there exist a continuum of states between the Bowen and Fenner trends. For example, the liquids produced by the crystallization of mid-ocean basalts along the Galapagos rift initially follow the Fenner trend, but then switch to the Bowen trend after about 70% of crystallization (12). The question, then, is to establish which liquid paths exist in the moon and to determine the major element composition of the highly evolved liquids which may be a component of or the precursors to KREEP basalts.

Liquidus equilibria in the $CaAl_2Si_2O_8$-Mg_2SiO_4-SiO_2-$CaSiO_3$ provide the framework to analyze the phase equilibria of lunar basalts. Consider the relatively $CaSiO_3$-poor cotectic liquids (Fig. 1) which produce first troctolites and then norites, as observed in the Mg-plutonic suite. The liquids become enriched in SiO_2 but depleted in MgO, CaO and Al_2O_3 until silica-saturation is obtained . Crystallization of silica, however, halts the increase in SiO_2 content and liquids at the quartenary eutectic containing silica, anorthite, diopside and low CaO-pyroxene have about 62.5% SiO_2 (13).

Adding Fe_2SiO_4 to the $CaAl_2Si_2O_8$-Mg_2SiO_4-SiO_2 system has the effect of shifting the low CaO-pyroxene-silica boundary curve away from SiO_2 with decreasing Mg value (1, 14,15). At Mg values $<$ 0.16, the low CaO-pyroxene liquidus is eliminated and a silica, iron-rich olivine and anorthite eutectic between silica, iron rich olivine, and anorthite (Fig. 2) is formed (1). The lowering of Mg values has the effect of expanding the silica saturation field and of the limiting SiO_2 content of residual liquids. For example, liquids with Mg values of 0.4 and saturated with silica, pigeonite and calcic plagioclase have SiO_2 contents of about 53%, whereas those with lower Mg values have still lower SiO_2 contents (1). Thus, the trend towards SiO_2 enrichment obtained in the FeO-free system is largely reversed as Mg values decrease in the residual liquids; the Bowen trend established at high Mg values is gradually replaced by the Fenner trend at lower Mg-values.

A more complete analysis must consider the role of normative albite, orthoclase and particularly ilmenite in the advanced stages of crystallization. The low Na_2O-content of lunar rocks allows us to largely ignore the role of normative albite (see, however, 1). The K_2O content, however, increases dramatically in residual liquids and has a more significant role during the advanced stages of crystallization. Irvine (14) has shown that the saturation surface for silica contracts with increases in normative Or, giving rise to liquids that are more SiO_2-rich than comparable K_2O-poor liquids. Increasing normative Or opposes the effect that decreasing Mg values have on the SiO_2 contents of silica saturated liquids. Thus, the path towards SiO_2 enriched liquids will depend sensitively on the initial Mg values and K_2O content of the primitive liquids.

The normative $FeTiO_3$ contents has two important but opposing roles. Adding TiO_2 increases the activity of SiO_2 and displaces the silica saturation surface to lower SiO_2 contents (16, 17). However, the crystallization of ilmenite increases the SiO_2 content, moderates the decrease in Mg values and reduces the TiO_2 content of residual liquids (18). In KREEP basalts, the crystallization of ilmenite, pyroxene and plagioclase may produce SiO_2-enriched liquids, which depending on the initial K_2O content, may approach the composition of lunar granites. On the other hand, TiO_2-enriched KREEP liquids undersaturated with respect to ilmenite will not undergo SiO_2 enrichment and will produce granites by silicate liquid immiscibility (18).

Let's consider now the low pressure liquid lines of descent of mare basalt. Hi Ti mare basalts are characterized by the early appearance of ilmenite (and ulvospinel) followed by olivine, calcic clinopyroxene and plagioclase, the exact order being controlled by the composition of the basalt. The residual liquids are enriched in SiO_2 (but only to about 50% SiO_2), K_2O and P_2O_5 but depleted in TiO_2, MgO and to lessor degrees CaO (2, 9). After about 80% crystallization, the liquids are similar to low Ti mare basalt, except for the low Al_2O_3 and CaO and higher contents of incompatible elements (e.g., K, P) (Table 1). In contrast, the low Ti mare basalts have olivine as an early liquidus phase and ilmenite as a near solidus phase (19). The residual liquids (Table 1)generally are poorer in SiO_2, Al_2O_3, CaO and MgO, but enriched in FeO and incompatible elements (2, 19). The TiO_2 content first increases and then decreases after ilmenite joins olivine, CaO-clinopyroxene and plagioclase (see also 10).

Residual liquids to both high and low Ti mare basalts are ferrobasalts which on further cooling become unstable, producing lunar granites by silicate liquid immiscibility (2, 9). The low SiO_2, low Mg values and very low alkali oxide contents of the mare basalts explain why siliceous liquids were not obtained and silicate liquid immiscibility intervened at low temperatures.

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KREEP basalts contain more SiO_2, higher Mg values and several times the K_2O content of normal mare basalt. These parameters create a condition more favorable for the establishment of the Bowen trend. Experimental results (Table 1) for KREEP basalt 15382, however, yield liquids with higher FeO contents and with no SiO_2 enrichment (18). These liquids become immiscible at 1035° C. A similar liquid line of descent terminated by the onset of silicate liquid immiscibility was established for KREEP basalt 14310 (18). Although the liquid path of these KREEP basalts characterize the Fenner trend, only small changes in some of the compositional parameters are needed to cross over to a SiO_2-enrichment trend.

Similar experiments were performed on the 15386 KREEP basalt bulk composition at pressures from 1 bar to 5 kb (20). The bulk composition contains about 20% more TiO_2 than KREEP basalt 15382. This small difference is important because it induces ilmenite to crystallize at higher temperatures and higher Mg values. The liquids produced follow the Fenner trend up to ilmenite crystallization but then become SiO_2 enriched at lower temperatures. The liquids produced at about 1080 (Table 1) bear a remarkable resemblance to some quartz monzodiorite clasts in Apollo 15 and 17 breccias (4, 21). Note that both the natural and experimental liquids have high P_2O_5 values since phosphate fractionation is not expected at these temperatures and compositions (see below). Results parallel to these were obtained for a LKFM composition that contained more than twice the TiO_2 content of KREEP basalts at comparable stages of differentiation (22). However, the resulting SiO_2-enriched liquids were considerably more iron-rich than those obtained from KREEP basalts and do not match the QMD bulk compositions.

It should be emphasized that ilmenite crystallization by itself does not guarantee that the residual liquids will fractionate to high SiO_2 compositions. Clearly, both low and high mare liquids become ilmenite saturated, as do the late stage liquids of 15382 and 14310. Yet in all these cases, siliceous liquids are produced only after the onset of silicate liquid immiscibility. Moreover, even the SiO_2 enriched liquids as found in the 15386 experiments may not progress continually towards granitic compositions. Experiments indicate that the volume of the two liquid field is increased dramatically at pressures up to 5 kb (23). Thus, a greater range of liquid lines of descent may be terminated by silicate liquid immiscibility at high pressures than at low pressures. More experiments, however, are sorely needed to test this hypothesis.

What, then, can be said of the nature of the residual liquids of a lunar wide differentiation? Warren (24) estimates that the final residuum of the magma ocean should be enriched in incompatible elements by a factor of about 200 – 300 over the bulk moon. If this estimate is even nearly correct, it is clear that Mg values of these liquids were extremely low and that ilmenite saturation must have occurred after about 90 – 95% crystallization. In fact, Longhi (25, 26) finds that after about 97% fractional crystallization of various examples of possible whole moon compositions, the liquid remaining is a ferrobasalt with low SiO_2, high TiO_2, low Al_2O_2 contents and still very low K_2O (Table 2). The fractionation path of this liquid would be similar to those obtained for mare basalts, except that the K_2O contents are below those of mare residual liquids at equivalent Mg values. This difference is significant because silicate liquid immiscibility would be delayed until K_2O contents were doubled or tripled. Nevertheless, these results argue that the residuum to the magma ocean was that of a ferrobasalt composition which may have produced small volumes of immiscible granitic liquids. It is not likely, however, that the granite-portion of the immiscible liquid pair was a major factor in the creation of the KREEP component(s). (See below).

A ferrobasaltic residuum has certain features that make it an attractive candidate for the pristine KREEP liquid. The TiO_2 content would be determined by the ilmenite saturation surface at 3-4 kilobars and 1000-1100° C. Such liquids would contain 2-3% TiO_2 (18,20) depending on the temperature and bulk composition. Such high TiO_2 contents are in concert with the relatively high TiO_2 contents of KREEP basalts. The low Ti/Sm ratios of KREEP-contaminated rocks are also consistent with the previous fractionation of ilmenite. Ferrobasalts can dissolve more than 4% P_2O_5 for temperatures above 1000° C without having whitlockite or apatitie on the liquidus (27, 28). This is consistent with the "unfractionated" K/P lunar ratio of KREEP (29) and the characteristic KREEP REE pattern. Phosphate fractionation would lower the K/P ratio and deplete the middle REE to create the typical wing-shaped REE pattern of lunar granites (30, 31, 3). Similarly, zircon saturation in ferrobasalts (32) would require Zr values far in excess of that observed in KREEP basalts.

In contrast, the concentrations of TiO_2, P_2O_5 and ZrO_2 needed to saturate ilmenite, phosphate and zircon respectively, decrease dramatically as the residual liquids increase their SiO_2 contents (20, 27, 28, 29, 30, 31, 32). Granites, for example, need only about 1/5, 1/10 and 1/2 the contents of Ti, P and Zr respectively to cause saturation of the appropriate phases at the same temperature. Even lower values would be realized on the moon because granites would form at lower temperatures than the ferrobasalts.

Table 1
Compositions of residual liquids obtained by fractionation of mare and nonmare basalts (2,18,20,22)

	15382		75055		12038		LKFM			15386	
SiO_2	52.3	50.6	41.3	49.9	47.5	45.1	47.1	48.8	56.1	50.8	54.4
TiO_2	1.8	4.2	10.2	2.9	3.1	3.1	1.2	4.3	2.2	2.2	3.8
Al_2O_3	17.7	11.7	9.8	9.3	12.6	9.3	19.0	12.2	12.1	14.6	11.4
FeO	8.6	13.4	18.2	25.8	17.8	31.1	9.7	15.3	17.3	11.4	12.5
MgO	7.2	3.8	6.8	0.8	6.8	0.6	11.3	6.7	1.2	8.1	2.9
CaO	9.8	8.4	12.3	9.1	11.4	9.6	11.8	11.3	7.3	9.7	9.1
Na_2o	0.9	1.1	0.4	0.4	0.4	0.3	0.4	0.4	0.5	1.1	1.0
K_2O	0.6	2.2	0.1	1.0	0.1	0.7	0.1	0.7	3.7	0.7	1.9
P_2O_5	0.5	2.0	0.1	0.6	0.1	0.8	–	–	–	0.9	1.6
T°C	–	1080	–	1016	–	1007	–	1150	1040	–	1080
%LIQ	100	25	100	10	100	14	100	25	5	100	40

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Table 2
Composition of residual liquids of whole moon compositions (25, 26)

	GA^{III}		GA^{II}	
SiO_2	42.4	43.3	43	44
TiO_2	0.4	8.8	0.9	8.7
Al_2O_3	8.3	9.3	17.8	8.4
FeO	11.2	27.2	14.8	24.3
MgO	32.3	0.4	11.4	0.3
CaO	5.0	9.9	11.6	13.6
Na_2O	0.1	0.8	0.22	0.2
K_2O	0.01	0.27	0.02	0.3
T°C	1562	995		968
%LIQ	100	3	100	3

FIGURE 2

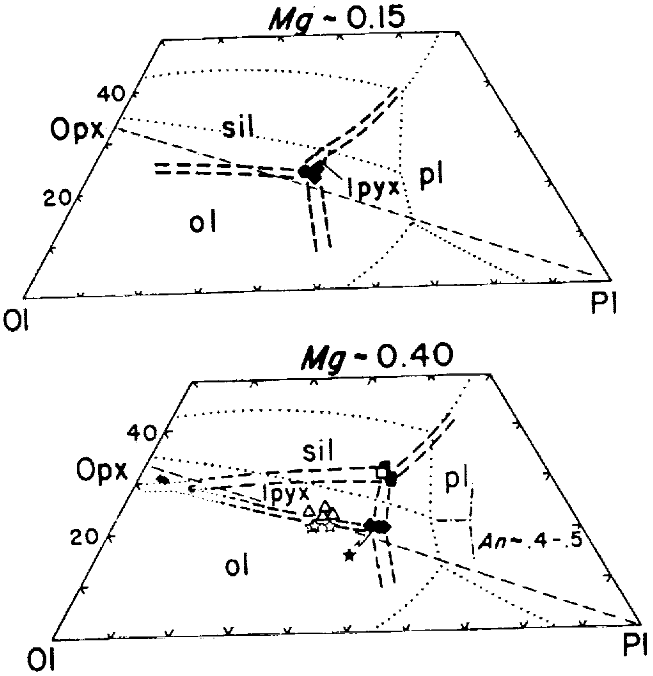
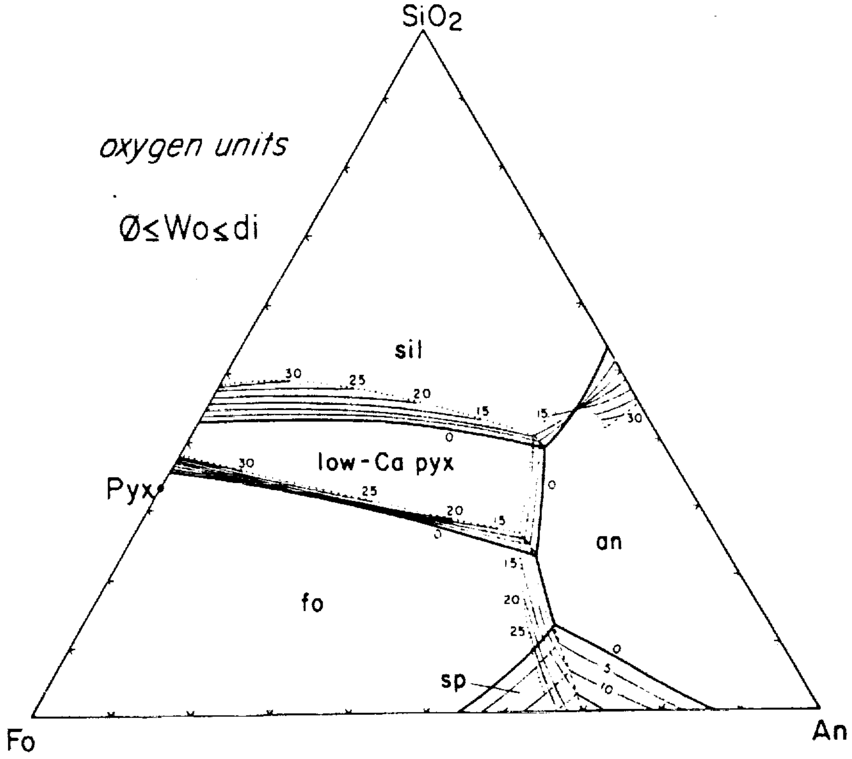


FIGURE 1



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COMPOSITIONAL SURVEY OF 2-4 mm PARTICLES FROM 14161 AND IMPLICATIONS REGARDING KREEP AND IGNEOUS COMPONENTS IN APOLLO 14 SOIL.

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Introduction. We wish to determine from which igneous lithologies the Apollo 14 soils derive, and what polymict and monomict materials are responsible for the compositional trends among Apollo 14 soils and polymict breccias. Several igneous rock types have been identified in the Apollo 14 samples, especially as clasts in breccias [e.g., 1-8]. We are analyzing hundreds of 2-4 mm soil particles from 14161 to determine which rock types found in the breccias are represented among the soil fragments, and in what proportions, and to search for new rock types and compositions.

Experimental. We have developed an INAA procedure that enables us to analyze 100 or more individual soil fragments in a short time. Particles are radioassayed once for 1-2 hours. Three minutes after acquisition of data for a fragment, we obtain concentrations of some 22 elements (Na, Ca, Sc, Cr, Fe, Co, Ni, Zr, Cs, Ba, La, Sm, Eu, Tb, Yb, Lu, Hf, Ta, Au, Ir, Th, and U). Concentrations for these elements are compared by computer to those in a catalog of compositions of Apollo 14 materials to identify the fragment as a highlands monomict rock, a mare basalt, or a soil or regolith breccia. This quickly identifies compositionally unusual particles for later, more extensive assay by our normal procedures. We will section representative and unusual particles and analyze them petrographically and with the electron microprobe.

Results. The most abundant particles, based mainly on binocular microscope classification, are impact melt breccias. They consist of fine-grained crystalline or recrystallized matrix and coarser mineral and lithic clasts. Regolith breccias and fragmental microbreccias comprise most of the remainder of the particles, and there is a small group of particles that appear to be igneous and monomict.

Compositional data for 281 particles are shown for two element pairs (FeO-CaO and La-Na_2O) in Figure 1. Also shown are fields for approximately 300 previous analyses of Apollo 14 samples, broadly categorized as highlands monomict rocks or clasts (HMCT); soils and regolith breccias (SRBX); microbreccias, breccia matrix and melt rocks (BX); basalts (BAS); and mafic-ultramafic glasses (GLS). We chose FeO to represent the proportions of mafic minerals and mare basalt, CaO to indicate high proportions of plagioclase (since we do not have data for Al), La to represent the incompatible trace elements and KREEPy materials, and Na as representative of the trio Na, Eu, and Ba, which are to varying extents feldspar-compatible. Compositions of most of the particles cluster in the soil and regolith breccia area of the diagram, with a strong trend toward troctolites and anorthosites, a trend toward norites, one toward olivine-rich lithologies, and weaker trends that do not clearly lead toward other known rock types. Because the fragments are small, we might expect a wider range of scatter in compositions than obtained from bulk samples of soils and regolith breccias; this is what we observe. Also, if the igneous rock types found as clasts in Apollo 14 breccias have contributed volumetrically important proportions of the material that now makes up the soils, we might expect to see examples of the rock types known from the earlier analyses among the soil fragments. An important result evident from the FeO-CaO plot is that the soil fragments do not cover the compositional range of known Apollo 14 rock types. Only three of the compositions are basaltic, only one is similar to alkali anorthosite, and one, felsite (lunar granite). No fragments of dunite or pyroxenite have been found. In contrast, three particles have the composition of ferroan anorthosite, which is very rare among previously characterized Apollo 14 materials. The fragment with the highest FeO concentration is a vesicular, basaltic glass with 33 $\mu g/g$ La and 0.55% Na_2O.

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Several particles that are compositionally similar to alkali gabbronorites [9] plot at relatively high FeO and low CaO, and at high La and Na_2O. Compositions of 4-10 mm fragments from soils 14160 and 14004 analyzed by Jerde et al. [10] fall well within the range for our samples. McKay et al. [11] reported analyses for several 4-10 mm basaltic fragments high-graded from soils 14150 and 14160; nonetheless, basaltic particles are rare among the soil fragments, as also noted by previous workers [12,13,14,15].

From the La-Na_2O plot, it is evident that our particles include a component rich in incompatible trace elements not yet observed among Apollo 14 basalts and monomict clasts, and richer in trace elements than Apollo 14 "common KREEP," [11,16]. How are these materials related to the phosphate-rich anorthositic fragments from breccias 14305 [17], 14313 [17,18], and 14321 [1]?

The overall REE pattern in the <1 mm soil, 14163, is similar to that of the KREEP composition as given by [19], but REE concentrations in the soil are lower by about one third. Many particles, particularly the impact melt breccias, have the same REE pattern as KREEP [19], but range in REE concentrations from about 0.4 times to 1.2 times those of KREEP, and have lower Eu concentrations (~2-3 $\mu g/g$). Several particles have REE patterns parallel to the KREEP pattern, but REE concentrations up to about twice those of KREEP, except for Eu. Potentially igneous, monomict fragments have REE concentrations lower than average, and have much more variable REE patterns. The mean REE concentrations of all the 2-4 mm particles are somewhat higher than those of 14163, but the mean Eu concentration is about the same as that of 14163. This results from the high proportion of KREEPy or ITE-rich impact melt breccia particles among the 2-4 mm particles.

Particle compositions range well outside of the compositional fields of bulk Apollo 14 soils and regolith breccias. None of the particles has a composition that matches those of Apollo 14 mare basalts 14053 and 14072 or of the several igneous lithologies observed as clasts in breccias 14047, 14303, 14305, 14312, 14316, 14318 or 14321. Some soil fragments produce compositional trends that extend toward the compositions of norites, troctolites, and ferroan anorthosite. Do the absence from the 2-4 mm fragments of certain HMCT rock types and the paucity of fragments with recognizable HMCT and mare basalt compositions mean that the Apollo 14 soils derived from a different bedrock or portion of the lunar crust than the cone crater breccias? Do REE concentrations higher than those in KREEP [19] derive from, or represent, UR-KREEP? Does the range in REE concentrations among samples with KREEPy relative REE abundances reflect dilution of a uniformly KREEPy noritic precursor with material of low REE concentration, or is the KREEPy material a low-proportion contaminant to mixtures of HMCT lithologies? We observe nearly constant REE pattern slopes among all particle types. This implies a common geochemical relationship among Apollo 14 materials, and provides a general constraint on the processes of their formation.

By analyzing a large number of particles without any petrographic pre-selection, we have obtained accurate proportions of compositionally different particle types in 14161. We avoid the inevitable difficulty of making such determinations using only the binocular microscope. Petrographic analysis of this set of particles, coupled with the compositional data, will improve our understanding of what rock types are volumetrically significant in the Apollo 14 regolith and precursor bedrock, and whether our present view of the contributions of different rock types is biased by our observations on clasts in the limited number of large samples.

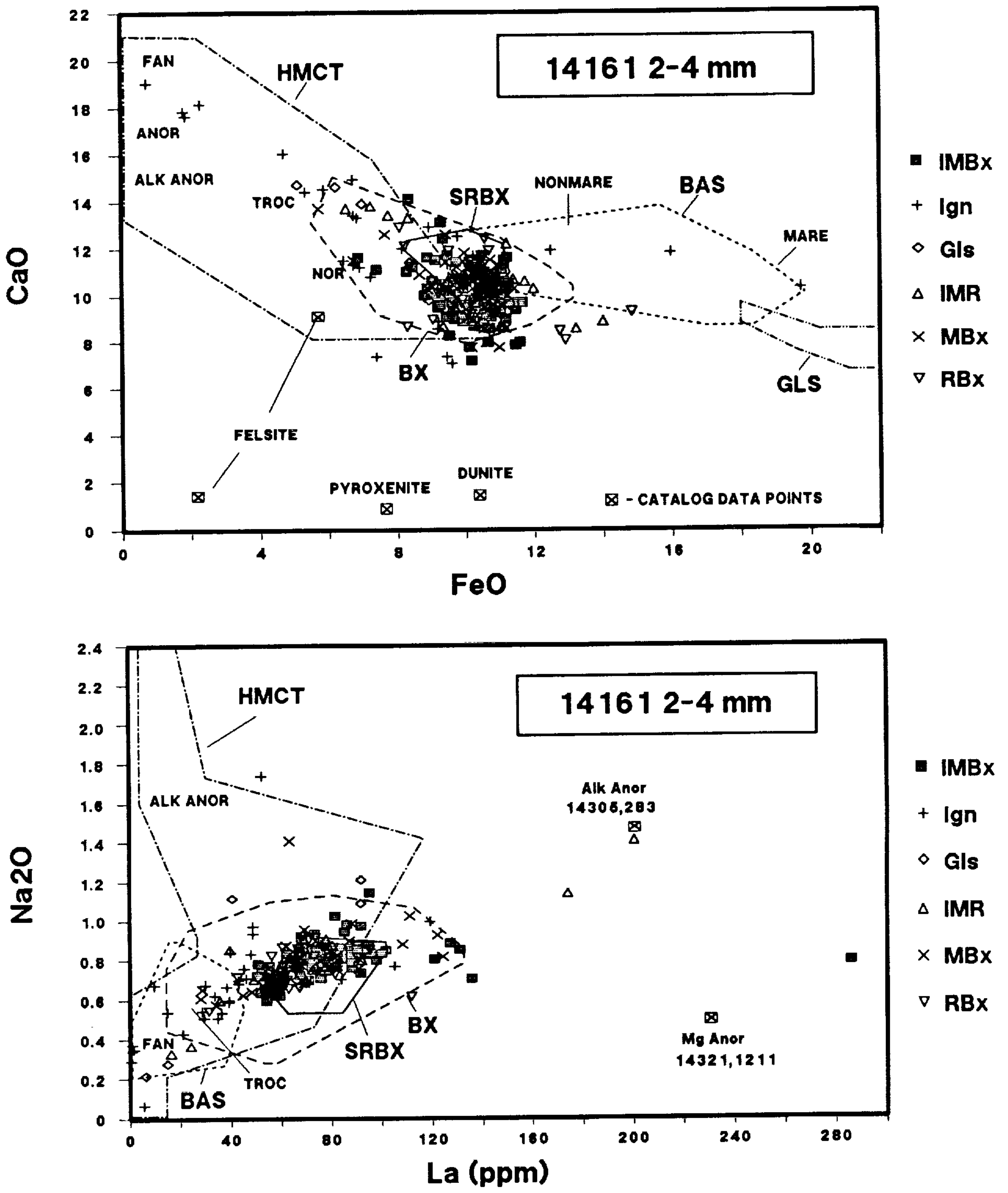

Figure 1. CaO vs FeO and Na$_2$O vs La concentrations for 281 2-4 mm soil particles from 14161 (IMBx - impact melt breccia; Ign - igneous/monomict; Gls - glass; IMR - impact melt rock; MBx - microbreccia; RBx - regolith breccia). Compositional fields are shown for 300 previous analyses of Apollo 14 materials: highlands monomict rocks or clasts (HMCT); soils and regolith breccias (SRBX); microbreccias, breccia matrix, and melt rocks (BX); basalts (BAS); and glasses (GLS) that do not plot in the BX field. Portions of the HMCT field, occupied by anorthosite (ANOR), troctolite (TROC), and norite (NOR), and of the BAS field, occupied by mare and nonmare basalts, are indicated. General locations of alkali anorthosite (ALK ANOR) and ferroan anorthosite (FAN) are also shown. Catalog data points for unusual HMCT compositions are noted where they are well outside the main HMCT field. References for catalog data: [1-8,10-11,16-18,20-33].

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FRA MAURO FORMATION, APOLLO 14: I. COMPOSITION AND FREQUENCY DISTRIBUTION OF IGNEOUS AND IMPACT METAMORPHIC ROCKS.

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Introduction. We report in a series of 4 related abstracts (1, 2, 3) on the work of the Cone crater consortium which has been studying the lithologies of the Fra Mauro formation at the Apollo 14 site by textural, mineralogical, chemical and age dating techniques. This report extends previously published data (4, 5) and gives a more comprehensive view of the genesis of the Fra Mauro formation and the composition of the pre-Imbrian lunar crust in comparison with similar studies on the pre-Nectarian crust of the Descartes region, Apollo 16 (6).

Samples and methods of investigation. Three types of rocks, mainly from the vicinity of Cone crater, were analyzed: (I) Lithic and mineral clasts of fragmental breccias 14063, 14064, and 14082/83; (II) lithic clasts of soils 14140, 14143, 14150, and 14160; and (III) large rock samples 14051, -068, -069, -070, -074, -079, -179, -311, -431, and -434. Petrographic, chemical, and age data of the third group have been reported previously (4, 5) together with petrographic and chemical data of 814 lithic clasts of 14063. Here we present the petrographic classification of 1782 lithic clasts of the first and second group of rocks. Modal compositions, microprobe, and multielement data (INAA) have been obtained on a representative subset of these lithic clasts and on mineral clasts of the clastic matrix of breccia 14063.

Classification of rocks and their modal composition. The analyzed lithic clasts have been classified according to (7) and grouped into 11 classes which include various types of impact melt lithologies, granulitic rocks and igneous rocks (Fig. 1). Fig. 1 represents the total lithic clast population of the so-called "white rocks" (14063, -64, -82, -83) from the rim of Cone crater. Modal compositions of individual rock types are given in Fig. 2.

Mineral chemistry. The chemical composition of coexisting mafic minerals (olivine, pyroxene) and plagioclase in igneous rock clasts of the fragmental breccias (14063, -64, -82/83), of the melt breccia 14068 and of coarse fines (14160,152) is presented in a mg (MgO/MgO+FeO) versus An-content diagram in which well established fields for the various types of anorthosites and/or rocks of the Mg-suite, taken from the literature (9), are given for comparison (Fig. 3).

Bulk chemistry of rocks. The major element and trace element characteristics of our sample suite are summarized in the MgO-Al_2O_3 and Sm-FeO plots of Figs. 4 and 5 which allow a comparison with corresponding lithologies from the Apollo 16 landing site and the lunar meteorites. Typical representatives of the "pristine" igneous rock suites are also shown in order to visualize the potential provenance of the analyzed impact and thermally metamorphosed rock types. The rare earth element patterns of all analyzed Apollo 14 rocks (Fig. 6) are grouped into (a) the two major petrographic types of melt breccia lithologies (feldspathic and mafic) and (b) the two compositional ranges for the large, handspecimen-sized impact melt breccias and melt rocks and for the bulk composition of the polymic fragmental breccias (14063, -64, -82/83) which are believed to be derived from the Cone crater basement (4, 5).

Interpretations and conclusions. The major questions for which the data presented above should provide answers, are the following: (1) What are the main rock types at the Apollo 14 landing site and what is their relative abundance ? (2) Which chemical groups of rocks can be established among the three basic textural classes of rocks: primary igneous rocks, and secondary impact melt lithologies and granulitic lithologies, respectively ? What is their relative abundance ? (3) What are the differences and commonalities of the A-14 rocks to highland rocks from other sites with respect to composition, abundance, and geological setting ? (4) What can be learned from the Apollo 14 samples regarding the structure, composition and stratigraphy of the Fra Mauro formation and, more indirectly, of the primordial lunar crust in the Imbrium region ?

This abstract attempts to give answers to the first three questions. The last, more difficult question, is model-dependent, requires rock ages and other supporting data, and will be discussed, therefore, in the companion abstracts (1, 2, 3).

We classify the analyzed 2719 rock samples (2496 lithic clasts >0.1 mm of 14063, -64, -82/83; 123 large rocks (8); and 100 lithic clasts of the coarse fines 14143.6) into the following main rock types on the basis of texture and mineralogical composition: crystalline impact melt breccias, devitrified impact "glasses", granulitic lithologies, and igneous rocks (Figs. 1, 2). The impact melt breccias are subdivided into a mafic and feldspathic group. Among the igneous rocks, anorthosites, norites, troctolites, basalts (which could be clast-free impact melt rocks), and granophyric (granitic) rocks have been identified. The frequency distribution of these rock types is distinctly different in the fragmental breccias from Cone crater (Fig. 1) and in the individual large rocks collected throughout the landing site. The latter are similar to the lithic clasts of the soil: only 6% plutonic and 3% volcanic rocks in the soil compared to 25% plutonic and 1.2 % volcanic rocks in the Cone crater breccias (assuming that all "basalts" are volcanic). Moreover, it is clear from the mineral modes (Fig. 2) that impact melt lithologies of the large rock samples differ from their counterparts in the clast population of the Cone crater fragmental breccias by occupying different compositional fields. Fig. 2 indicates that the granulitic lithologies and the matrix of the Cone crater breccias might be simply mixtures of primordial plutonic rocks (see below). A comparison with the situation at Apollo 16 (North Ray crater and Cayley plains) shows that the Apollo 14 rock types are probably related to the Apollo 16 samples from the Cayley formation (6) but differ distinctly from the Descartes material as represented by North Ray breccia clasts.

The results of the chemical analyses of the Apollo 14 impact melt breccias (Figs. 4-6) lead to the following conclusions confirming and modifying previous suggestions:

(a) There are two major chemical groups among the Cone crater breccia clasts, a high Mg, low K, medium-high P ("mafic") and a low Mg, medium-high K, medium-low P group ("feldspathic") which only partly overlap the composition of the large rock samples which are lower in Al_2O_3 and exclusively rich in incompatible elements.

(b) The bulk composition of the 14063, -64, -82/83-breccia group of Cone crater is for the incompatible elements within the range of the "mafic" melt breccias which represent 50% of the lithic clast population in these breccias (Figs. 5, 6). A minor discrepancy appears to be compensated by the feldspathic melt breccia clasts which are rich in incompatible elements.

The granulitic lithologies at Apollo 14 are extremely rare (3.7%). One large rock granulite (14179) is rather rich in incompatible elements (KREEP-type (5)) whereas a second small lithic clast from Cone crater breccia 14063 is KREEP-free. This is in contrast to Apollo 16 where KREEP-free granulites are by far predominant and much more abundant (14%).

Based on modal and chemical data the main characteristics of the igneous lithologies are as follows (Fig. 1-3):

(a) 16% anorthosites, 3.2% norites, 5.6% troctolites, and 1.2% basalts have been identified in a population of 2476 lithic clasts of the 14063, -64, -82/83 Cone crater fragmental breccias; the corresponding figures for 100 lithic clasts in the coarse fines of 14143,6 and 95 large rock samples (8) are: 2% and 0% anorthosites, 3% and 0% norites + troctolites, and 12% and 16% basalts, respectively.

(b) All analyzed plutonic rocks belong to the Mg- and alkali suites of the lunar highland rocks (Fig. 3); ferroan anorthosites are obviously lacking.

(c) A comparison with Apollo 16 (6) reveals that plutonic rocks are more abundant (38% within the fragmental breccias of North Ray crater and 28% among the large rock samples) and that the anorthosites are ferroan and occupy nearly 100% of the plutonic suite in the Descartes area.

In summary, our previous findings (4, 5) are confirmed: The Fra Mauro formation consists at least of two major megabreccia units which are chemically and lithologically different. One unit is represented by the large and small rocks in the regolith which is typified by high-K-KREEP lithologies and rare plutonic rocks. The second unit is represented by the Cone crater fragmental breccias which contain distinct impact melt lithologies not present in the first unit. The breccias are rich in plutonic lithologies and contain only minor high-K-KREEP components. Plutonic rocks of both units belong to the Mg- and alkali suites of the igneous highland rocks.

Fig. 1: Number frequency (%) of lithic clast types in 14063 and 14082/83; 2476 clasts; ISG = impact melt glass (devitrified), ISBm and ISBf = mafic and feldspathic impact melt breccias, PK and GR = poikiloblastic and granoblastic (granulitic) lithologies, AN = anorthosite, NO = Norite, T = troctolite, B = basalt, G = "granite", And. = others

Fig. 2: Modal composition of Apollo 14 rocks; AAN, SPAN, TAN, NOAN = alkali-, spinel-, troctolitic, noritic anorthosites, respectively; NO, GANO = norite, gabbronorite, DU = dunite, B = basalt clasts in white rocks

Fig. 3: Composition of coexisting mafics and plagioclase in "pristine" igneous rock clasts; diamonds = clinopyroxene rocks, squares = low-Ca pyroxene rocks, dots = olivine rocks, A = anorthosites, B = basalts, black = own data, open symbols = literature data

Fig. 4: MgO versus Al_2O_3 for Apollo 14 lithologies; solid lines: fields for Apollo 14 melt breccias; abbreviations see Figs. 1-3, HAB = high alumina basalt, MAN = Mg-anorthosite, FAN = Fe-anorthosite, ENT = enstatite troctolite, AB = aluminous basalt

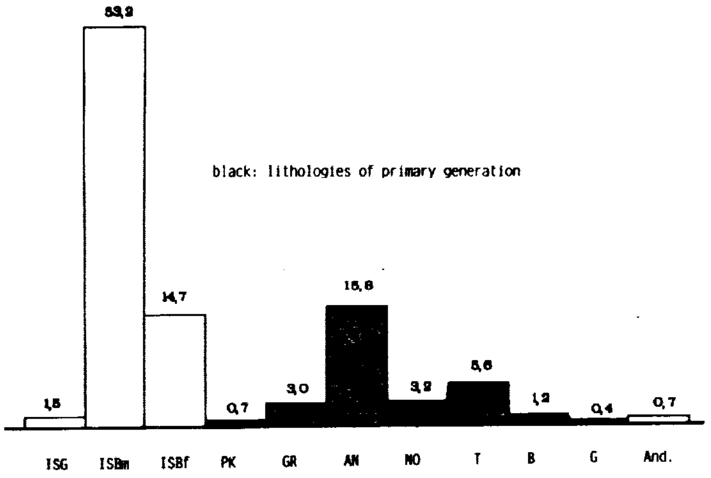

Fig. 1

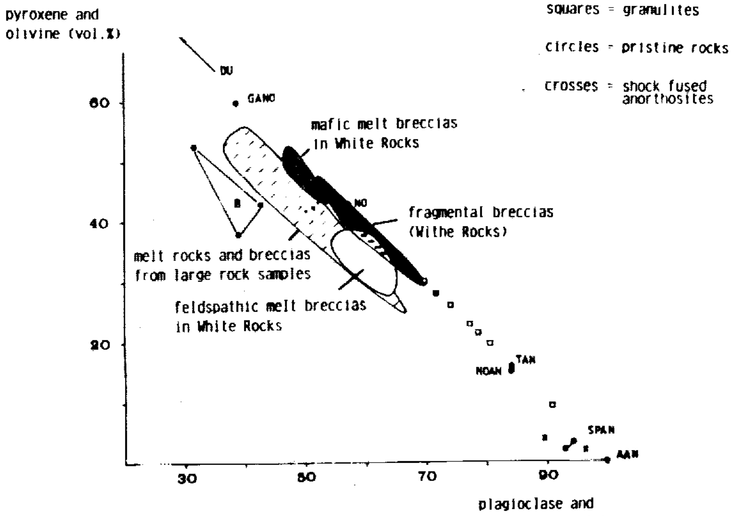

Fig. 2

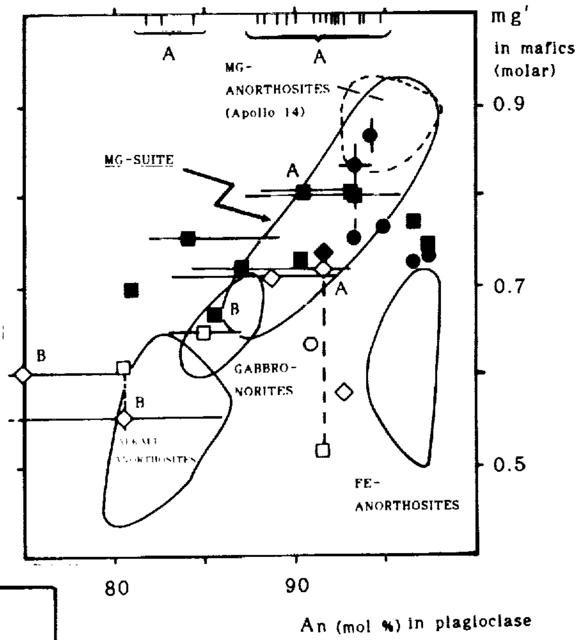

Fig. 3

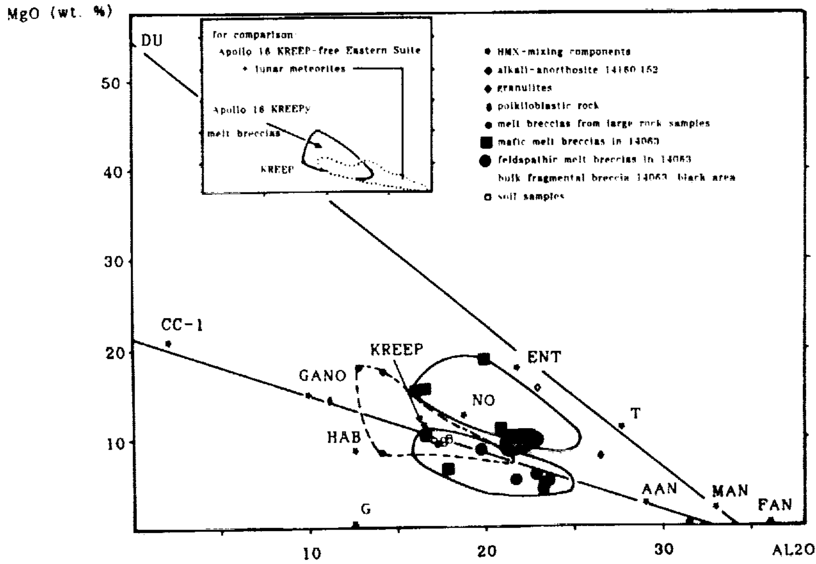

Fig. 4

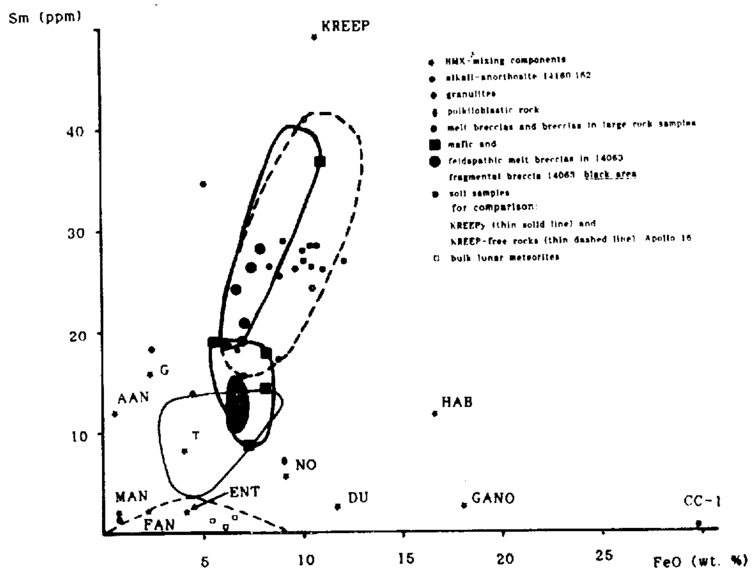

Fig. 5: Sm versus FeO for Apollo 14 lithologies; thick solid and dashed lines: fields for A 14 melt breccias; see Figs. 1-4

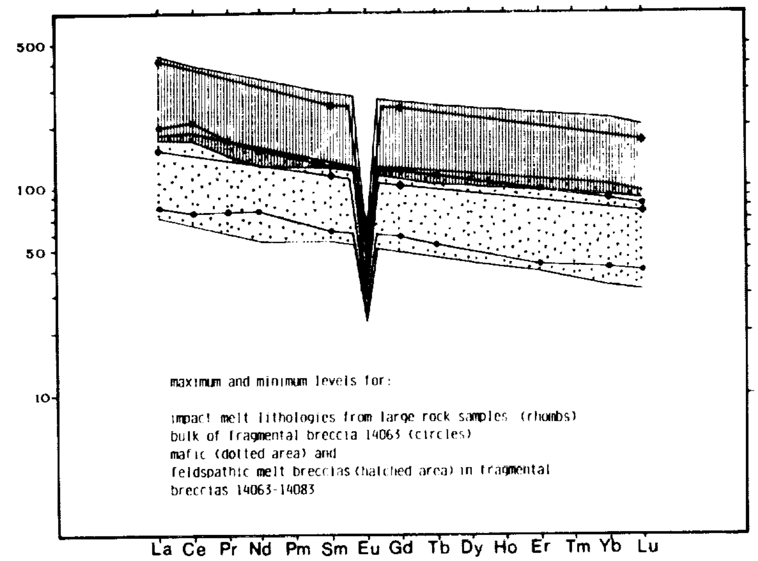

Fig. 6

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FRA MAURO FORMATION, APOLLO 14: III. CALCULATED COMPOSITION OF THE PRIMORDIAL LUNAR CRUST IN THE IMBRIUM REGION.

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Introduction. The lunar highland lithologies contain a large fraction of "secondary" non-igneous rock types which are derived from primary igneous rocks through multiple cycles of impact melting ("impact melt lithologies") or represent igneous rocks or breccias which were completely recrystallized by thermal annealing ("granulitic lithologies"). We have demonstrated for the Apollo 16 highland rocks that the primary igneous rock components of the secondary rocks can be deduced by mixing calculations using as mixing components primordial ("pristine") igneous rocks found at the same site (1). If the chemical composition of the various types of secondary rocks and their frequency distribution is known, the composition of the parental crustal section from which a particular highland formation is derived can be calculated in terms of the proportions of primordial igneous rocks (1, 2). The procedures of mixing calculation are described in (1).

Analytical data base and selection of samples and mixing components. Three types of mixing calculations have been performed, the first one on the basis of major elements only, the second one using major and minor elements, and the third one using major and minor elements and somewhat different mixing components (Table 1). The following rock types considered as "mixtures" have been calculated (Table 2):

(a) lithic clasts of fragmental breccias 14063 and 14083
(b) bulk fragmental breccia 14063
(c) large rock samples across the Apollo 14 landing site (melt lithologies and one granulite)
(d) various types of Apollo 14 regolith (14148, 14149, 14220, 14210, 14211)

The two sets of mixing components (given in Table 1) contain mainly pristine igneous rocks from Apollo 14 except for ferroan anorthosite and the meteoritic component. Other mixing components which have been used but resulted in unacceptable "discrepancy factors" or "square sums of residuals" (see (1)) were discarded. The chemical composition of some secondary rocks analyzed in this study (Table 2) is given in Table 3.

Results. Results of mixing calculations based on Sets 1 and 2 of Table 1 have been reported previously (2, 21) and will be used here only for comparison. The proportions of igneous rocks (mixing components) obtained through the Set-3-calculation have been plotted in Figs. 1-5 for the various groups of lithologies explained in Table 2. For the interpretation of the data presented in Figures 1-5 it is important to emphasize that the resulting igneous precursor rocks for the polymict secondary rock types are model rocks whose abundances depend on the choice of the whole set of model rocks used as mixing components. The main value of the results is twofold: (a) They allow a comparison of different lithological groups of rocks at the Apollo 14 landing site on the basis of primary igneous rock components which might have been present in the parental primordial crust unit of any lithological group (their geological provenance has to be evaluated by other means), and (b) they allow a recalculation of the igneous rock composition of any particular parental crust unit when the frequency distribution of the different lithological groups of rocks for the geological formation in question is taken into account.

We have argued previously (2, 21) that certain lithological groups at the Apollo 14 landing site can be assigned to subunits of the Fra Mauro formation which have a different geological provenance. One such unit is represented by the lithic clast population of the Cone crater fragmental breccias 14063, -64, -82/83 sampled from large boulders and described in this volume (22) and/or by the bulk composition if these breccias (Figs. 1-3). A second unit is represented by rock fragments sampled from the regolith - either large rock samples or bulk soil samples (Figs. 4, 5). The two units differ in the composition and abundance of impact melt and igneous rock components as shown in (22).

If we consider the lithological subgroups of unit 1 (tentatively called Cone crater basement) the following is obvious (Figs. 1-2): (a) only the feldspathic melt breccias contain a minor amount of ferroan anorthosite (FAN) and are intermediate in KREEP, (b) the mafic melt breccias are dominated by troctolite and the third Ti-rich type of melt lithology (a subgroup of the mafic melt breccias) is typically rich in aluminous basalt and KREEP. None of these melt lithologies contain magnesian anorthosite (MAN) in contrast to the bulk of their parent breccia 14063 (Fig. 3). The crystalline melt breccias (Fig. 4) of the second unit (tentatively called the Apollo 14 subregolith basement) are dominated by KREEP, contain all three types of anorthosites, and are free of troctolite. The granulite from this unit is characterized by relatively high contents of KREEP, FAN, MAN and dunite and lacks alkali anorthosite and noritic-gabbroic-troctolitic lithologies. The bulk regolith samples (Fig. 5) are remarkably similar to the average of the large rock crystalline melt breccias (Fig. 4).

As demonstrated by (2 and 21), the two units of the Fra Mauro formation at Apollo 14 may be best represented by igneous precursor rocks if the relative frequency of primary and secondary rock types (2) are combined with the results of mixing calculations made for the secondary rocks (21). This calculation was based on the somewhat restricted data set 1 (Table 1) without minor elements. The results from (21) are compared with the present results in Table 4 where the Cone crater basement (unit 1) is represented by the bulk breccia 14063 and the subregolith basement (unit 2) by the average of the regolith.

It is quite obvious from Table 4 that the breccia unit representing a distinct formation exposed in the Cone crater basement is typified by large amounts of "evolved" anorthosite and of troctolite and by the rare abundance of noritic-gabbroic rocks. In contrast, the subregolith basement throughout the landing site, probably the upper unit of the Fra Mauro formation, is dominated by noritic-gabbros rocks and lacks troctolites. The genetic implications of these results for the origin and emplacement of the Fra Mauro formation will be discussed in a companion abstract (23).

Table 1: Sources for the chemical composition of mixing components and sets of chemical elements used in the mixing calculations (see also Figs. 4 and 5 of (22))

		Set 1		Set 2		Set 3	
Mixing components	References	Comp.	Elem.	Comp.	Elem.	Comp.	Elem.
Ferroan anorthosite,1	(1)	-	Al	-	Al	x	Al
Alkali anorthosite, 3	(3)	x	Ca	x	Ca	x	Ca
Magnesian anorthosite, 2	(4)	x	Mg	x	Mg	x	Mg
Troctolite, 4	(4)	x	Fe	x	Fe	x	Fe
Enstatit-Troctolite, 4	(5)	x	K	x	K	x	K
Dunite, 5	(4)	x	Na	x	Na	x	Na
Norite, 6	(3)	x	Ti	x	Ti	x	Ti
Gabbronorite, 7	(6)	x	Cr	x	Cr	x	Cr
Aluminous basalt, 8	(5)	-		-	Sc	x	Sc
"Granite", 9	(7)	-		-	Sm	x	Sm
KREEP, 10	(8)	x		x	Yb	x	Yb
Meteoritic component, 11 (Cl)	(9)	-		-		x	Ni Co

Number refer to Figs. 1-5

Table 2: Sources for the chemical composition of secondary Apollo 14 rocks impact melt and granulitic lithologies) used in the mixing calculation

Rock type	Number	Reference
(a) Crystalline melt breccias, Ti-rich (clasts), average	14063,212 14063,246	(7)
(b) Crystalline melt breccias, feldspathic (clasts), average	14063,217 14063,221 14063,222 14063,223 14063,230 14063,232	(7)
	14083,2	(10), (11)
(c) Crystalline melt breccias, mafic (clasts), average	14063,215 14063,233 14063,244	(7)
(d) Bulk fragmental breccias, average	14063,37 14063,48	(10), (11)
(e) Crystalline melt lithologies large rock samples, average	14276	(10), (12)
	14305	(13)
	14310	(10), (14)
	14311	(15), (7)
	14321	(16), (17), (18)
(f) Granulite	14179,6	(19)
(g) Regolith, general landing area	14148 14149 14220 14210 14211.	(20)

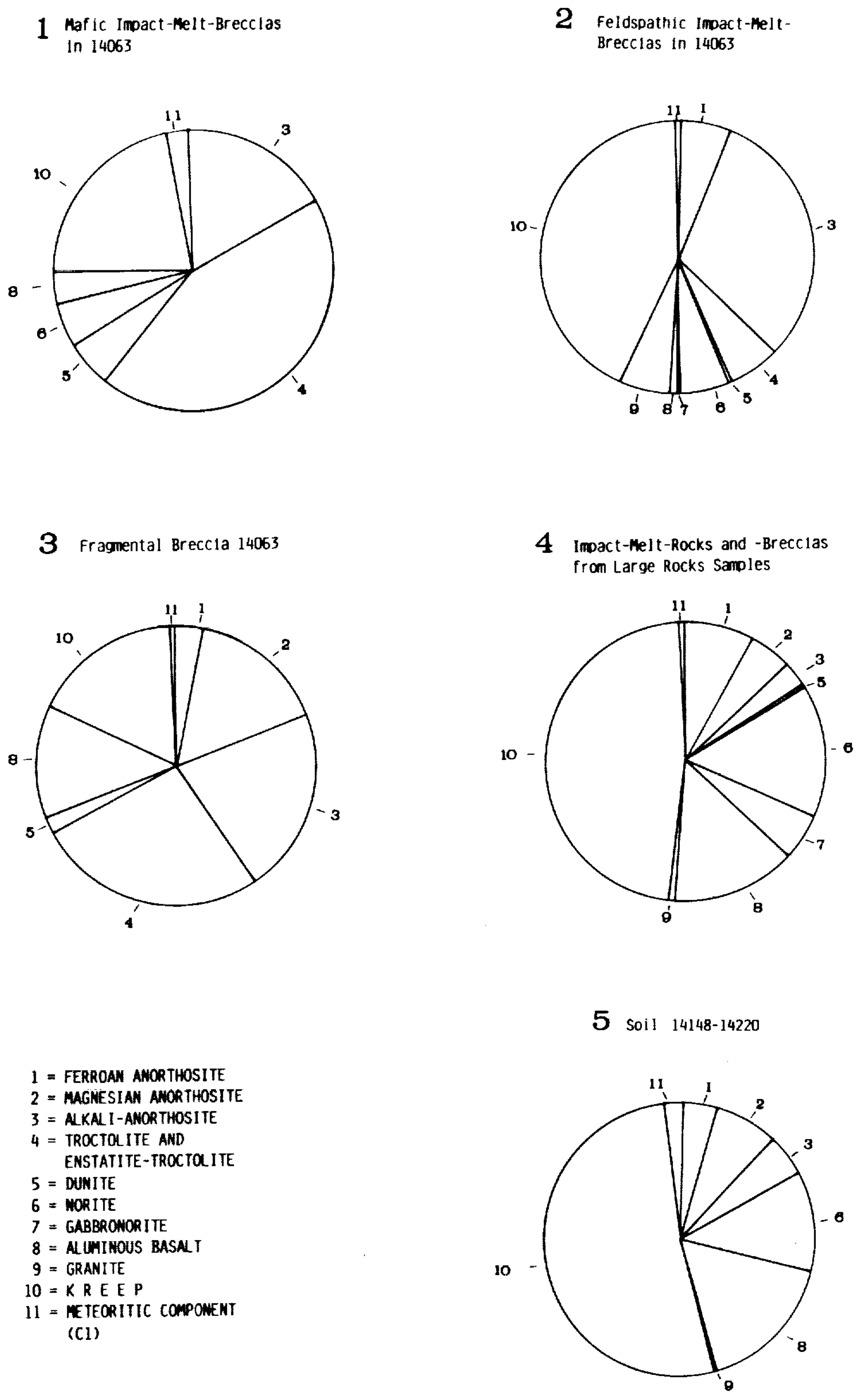
Table 3: Chemical compsition of Apollo 14 rocks analyzed in this study (see Table 2)

		14063		14311
	a	b	c	(7)(15)
SiO_2	47.17	51.21	46.09	47.24
TiO_2	2.13	0.66	0.86	1.81
Al_2O_3	17.25	22.00	19.09	18.05
CaO	10.65	11.63	9.75	10.16
MgO	8.54	6.13	14.37	9.59
MnO	0.15	0.82	0.09	0.14
FeO	9.75	5.64	7.38	11.13
Na_2O	1.07	0.94	0.79	0.85
K_2O	0.27	0.85	0.18	0.81
P_2O_5	0.80	0.42	0.27	0.76
Cr_2O_3	0.19	0.10	0.39	0.15
Sc	17.6	14.5	10.4	18.8
Sm	16.1	22.9	15.2	24.4
Yb	12.0	18.7	12.1	17.1
Ni	454	180	469	250
Co	31.9	18.0	29.2	31.9

a, b, c: averages of Table 2

FRA MAURO FORMATION, APOLLO 14 (III)

S. Lingner et al.



1 Mafic Impact-Melt-Breccias in 14063

2 Feldspathic Impact-Melt-Breccias in 14063

3 Fragmental Breccia 14063

4 Impact-Melt-Rocks and -Breccias from Large Rocks Samples

5 Soil 14148-14220

1 = FERROAN ANORTHOSITE
2 = MAGNESIAN ANORTHOSITE
3 = ALKALI-ANORTHOSITE
4 = TROCTOLITE AND ENSTATITE-TROCTOLITE
5 = DUNITE
6 = NORITE
7 = GABBRONORITE
8 = ALUMINOUS BASALT
9 = GRANITE
10 = KREEP
11 = METEORITIC COMPONENT (C1)

Figs. 1 - 5: Relative abundances of igneous model rocks (in %) in various A14 lithologies obtained by mixing calculations of set 3 (Table 1)

Table 4: Model composition of the primordial igneous crust of the Imbrium region based on mixing calculations (set 3) and on mixing calculations and frequency statistics of rock types (set 1, (22); data of set 3 from Figs. 3 and 5.

	Apollo 14 subregolith basement		Apollo 14 Cone crater basement	
Model component	set 1 (%)	set 3 (%)	set 1 (%)	set 3 (%)
Anorthosite (ferroan; primitive)	-	14.5	-	5
Anorthosite (magnesian + alkali-rich; evolved)	24	43.5	60	54
Troctolite	0	0	30	38
Norite + Gabbronorite	75	42	3	0
Dunite	1	0	7	3

set 3 (subregolith) = data from Fig. 7

set 3 (Cone crater) = data from Fig. 4

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THE PETROGENESIS OF EVOLVED PRISTINE ROCKS; J. Longhi,

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A clear understanding of the details of early lunar differentiation and crustal formation remains elusive. At the time of the LPI workshop on pristine rocks (1) most of the attention was focused the larger samples of the two major suites of pristine rocks, ferroan anorthosite (FA), which seemed at the time to be a fairly homogeneous assembly, and Mg-rich cumulates, which were subdivided into two groups (2): magnesian norites (MN) and gabbro-norites (GN). The relationship of the relatively few samples of evolved pristine rocks (EPR's), such as felsites and alkali-anorthosites, to the major groups of pristine rocks was unclear, although the assemblages of accessory and trace phases suggested that evolved lithloigies had the closest relations to the magnesian norites (2) and might be differentiates of the MN magmas. An alternative hypothesis is that some EPR's might be the plutonic complements to KREEP basaltic magmatism (3). In the past eight years numerous studies of clasts in breccias have produced a wealth of geochemical and petrological information on EPR's with which to evaluate these hypotheses.

Much of the petrological data on EPR's has been tabulated by (4) and some of this data is illustrated in the *Mg* vs *An* plot in Fig. 1. Numbers signify landing sites; capital letters are abbreviated rock names (N = norite, A = anorthosite, I-G = ilmenite gabbro, G-N = gabbro norite, f = felsite, Gr = granite); filled hexagons are Ap 16 alkali gabbronorites. Also shown in Fig. 1 are calculated paths of mineral compositions for low-pressure fractional crystallization of three starting compositions: KREEP basalt 15386 (5), a Mg-Norite parent magma modified from (6), and a ferroan anorthosite parent magma also modified from (6). The abbreviated mineral names mark the onset of crystallization of the indicated phase (plag is always present). The first appearance of opx or pi marks the disappearance of ol; pi marks the disappearance of opx, if present; and fa marks the disappearance of pi. The slopes of the three calculated trends steepen from left right as explained by (6).

The FAN curve passes through the field of ferroan anorthosite mineral compositions (not shown) and mimics the reappearance of Fe-rich olivine (fa) noted by (7). The FAN curve does not pass through the field of EPR mineral compositions -- a fact that illustrates simply what is well known, viz., that EPR's have little in common with ferroan anorthosites or their residual liquids. Regardless of whether ferroan anorthosites formed atop a magma ocean or in serial intrusions, the rocks that crystallized from their residual liquids (olivine-tridymite ferro-gabbros with *An* > .90) have not been described among the returned samples. Remelting of such ferroan compositions would not produce suitable parent liquids for the EPR's either. The onset of ilmenite crystallization, which in and of itself has no special significance, represents 93 mol% crystallization of the FAN parent. If we allow that the FAN parent developed after 60% crystallization of a magma ocean or other primitive magma source, then the ilm point represents 97% crystallization of the original magma. Even such advanced crystallization is nowhere near sufficient to produce KREEP-like enrichments of incompatible elements (8). By the time that fractionation produces KREEP-like enrichments of incompatible elements the residual magma is nearly devoid of MgO and has a temperature well below 1100°C. The density of such hyper–ferroan liquids is above 3.0, so there is no reason to expect that *ur*-KREEP would intrude upward in the crust. Previous thermal calculations (9) suggest that even if this residual liquid were deeply buried, the enrichment in heat-producing radiogenic elements would primarily prolong the cooling and crystallization process and not lead to any significant remelting of the surroundings. Consequently, there seems little reason to expect *ur*-KREEP/crust interactions; rather it seems more likely that ur-

KREEP would have remained molten in isolated pockets at the base of the crust for tens or possibly hundreds of millions of years; some of it may even have been swept back down into the underlying mantle. It has been recognized for some time (10) that most Mg-norites have KREEP affinities (e.g., low Ti/Sm). The present calculations are consistent with previous models that explained these affinities in terms of magma-mixing (11) or assimilation (12) of KREEP into primitive highly magnesian liquids.

The MN composition was devised so that: a) its mineral trend would pass through the compositions of the troctolite 76535 and norite 78235; b) ol would be replaced by opx between the troctolite and norite points; and c) augite and ilmenite would crystallize relatively late. It is not meant to be a unique estimate of the parent magma composition of these rocks, but rather an example of a typical liquid composition. At first glance there is little to distinguish the MN and 15386 trends other than the offset in *An* composition and the absence of ol in the KREEP trend. However, differences in TiO_2 concentration reflected in the appearance of ilmenite at very different *Mg* values are probably real inasmuch as most Mg-norites lack ilmenite (2) whereas KREEP basalts commonly have ilmenite (13). If one accepts the premise of KREEP mixing/assimilation into magnesian liquids, then the differences between the MN (lower Na and Ti) and 15386 (higher Na and Ti) compositions are probably due to differences in the parental magma composition, which in turn may be due to differences in degree of partial melting, differences in source composition, or variable assimilation of anorthosite (14,15). Anorthosite assimilation was originally invoked as means to allow highly magnesian, low-Al_2O_3 liquids to crystallize early ol + plag and then opx + plag, however, it may play an important role in determining alkali and Ti concentrations as well.

In order to compare the EPR mineral compositions with the calculated KREEP basalt and MN mineral trends, it is necesary to make some assumptions about the meaning about the origin of compositional variation within a given sample. Probably, a box pattern develops during *in situ* crystallization when low *Mg-An* rims of accumulated crystals grow from intercumulus liquid and do not equilibrate with the high *Mg-An* cores. Generally, we associate large variations in mineral compositions with relatively rapid cooling and little or no variation with slow cooling. Also, plagioclase is much slower to homogenize than mafic minerals. By analogy with terrestrial intrusions, the box-like patterns are probably indicative of the cooling rates of Skaergaard-sized intrusions (16), whereas the linear (constant *Mg*) and point patterns are generally indicative of the cooling regimes of Stillwater-sized or larger bodies (17), although there are exceptions. Thus we expect that compositions in the upper right hand corner of box patterns are close to the compositions of primary crystals, whereas the rightmost end of linear patterns represent primary plagioclase and a lower limit for *Mg*, and point patterns represent lower limits for both *Mg* and *An*. However, even beyond uncertainties about the size of the intrusions in which the EPR's crystallized, there is no way of knowing whether the most refractory crystals formed in place or, particularly in the case of plagioclase, were transported from another location. If there is differential transport of minerals, then comparing a natural mineral trend with a calculated trend can be misleading. For example, suspension of plagioclase coupled with fractionation of mafics will produce a steeper trend on the *Mg-An* diagram than simple fractional crystallization. Among the Ap14 norites and anorthosites there is only a minor change in the composition of the most calcic plagioclase (.92-.90) despite a change in *Mg* from .73 to .50. The calculated MN trend passes through this range of compositions with a similarly steep slope, thus suggesting that simple cumulus processes may be sufficient to explain the observed pattern for this suite.

Another important feature of the mineral composition trends is the sequence of cumulus phases. In the center of the array of EPR mineral compositions are Ap14 norites and anorthosites, an Ap14 ilmenite-gabbro, and a cluster of Ap16 gabbro-norites. On the basis of *Mg-An* relationships alone, these rocks represent at least three distinct magma types, none of which lays along the MN line of descent. Relative to the MN composition, the Ap14 N and A magmas probably had lower lower SiO_2 relative to *Mg* (this would allow ol to persist to lower *Mg* and delay the appearance of sil); the Ap14 I-G magma had higher TiO_2 and CaO; and the Ap16 gabbro-norite magma had much lower SiO_2 relative to Mg.

With the notable exception of K-feldspar, whose liquidus surface is now incorporated into the quantitative model, a parent of 15386 seems readily capable of fractionating so as to crystallize rocks like the Ap15 granites. However, the Ap12 and 17 felsites require a more sodic parent magma. By invoking the mixing/assimilation hypothesis we can explain the difference between the 4.365 b.y. zircon age (18) and the 3.9 Rb-Sr mineral isochron age (19) of 15405 by interpreting the zircon as an unassimilated relic of *ur*-KREEP (e.g., 15).

In summary, the EPR's appear to have crystallized from numerous Mg-rich parent magmas separable in terms of major element compositions. Variable degrees of KREEP contamination is probably responsible for differences in their incompatible element abundances; whereas different degrees of partial melting and probably assimilation of anorthosite are necessary to explain the differences in the major element compositions. The only link between the EPR's and promordial differentiation appears to be that anorthosite and *ur*-KREEP were produced during that epoch.

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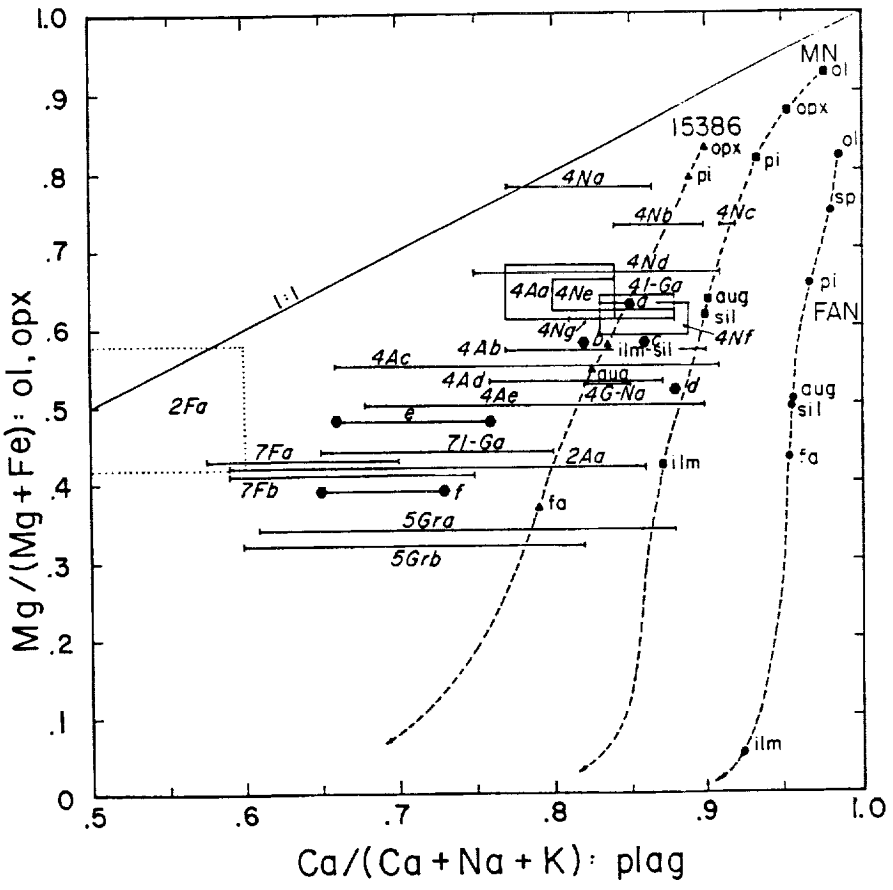

Figure 1. Plot of atomic Mg/(Mg + Fe) [Mg] in olivine or low Ca pyroxene versus Ca/(Ca + Na + K) [An] in plagioclase. Boxes, bars and filled hexagons are mineral compositions in evolved pristine rocks after (4). Apollo 14 norites (4 Na-g): 14318c2; 14318c1; 14305, 396; 14361c; 14304g; 14303, 44; 14311c. Apollo 14 anorthosites (4Aa-c): 14066; 14321c; 14305c91; 14047c; 14305c2. Apollo 14 ilmenite-gabbro (4I-Ga): 14311, 96. Apollo 14 gabbro-norite (4G-Na): 14313c. Apollo 12 anorthosite (2Aa): 12073. Apollo 12 felsite (2 Fa): 12033, 57. Apollo 15 granitic rocks (5 Gra-b): 15405, 12; 15405QMD. Apollo 17 ilmenite-gabbro (7I-Ga): 72275. Apollo 17 felsites (7Fa-b): 72215; 73215. Apollo 16 alkali-gabbro-norites (filled hexagons a-f): 67975, 131N; -86; -44Nm; -42N; -14; -136N; -44Nf. Dotted box (2 Fa) is plotted on the basis of Mg in augite. Dashed lines are calculated mineral compositions produced during plagioclase-saturated fractional crystallization. Starting compositions are KREEP basalt 15386 (5), Mg-norite parent (MN) after (6), and ferroan anorthosite parent (FAN) after (6). Filled symbols and abbreviations mark the onset of crystallization of various phases and the disappearance of others. For example, olivine disappears at the first appearance of opx or pi, opx disappears at the first appearance of pi, and pi disappears at the reappearance of olivine (fa). The calculated spinel is Cr-rich.

Telescopic thermal infrared measurements of the mineralogy of suspected lunar silicic regions: Red spots are not granite.

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Several units on the lunar surface distant from the landing sites have been proposed to be composed of SiO_2-rich rock types[1,2,3]. These proposals have been chiefly based upon either morphologic grounds or upon the presence of geochemical anomalies identified in the Apollo gamma-ray data base. The first group consists of four features of possible volcanic origin in the western portion of the nearside of the Moon. These were identified on the basis of their relatively high albedo, morphological distinctiveness, and bright "red" appearance in ultraviolet-visible color difference photographs [1,2,3,4]. These are the Gruithuisen domes (γ and δ), the Mairan T dome near the shores of northwestern Oceanus Procellarum, and Hansteen α, also known as the Arrowhead, north of the Humorum basin. All four features exhibit morphologic characteristics which suggest that they may have been constructed of lavas much more viscous than the relatively inviscid mare basalt lava [3]. The second group is composed of the areas associated with the major thorium anomalies identified by the Apollo orbital gamma-ray experiment. These include the Aristarchus region, likely Aristarchus crater itself, and the rim of Archimedes crater[5]. These locations also exhibit compositional anomalies identified on the basis of ultraviolet and near-infrared spectroscopy. These characteristics have led some workers to suggest that these areas may be composed of either KREEP[1,2] or possibly more evolved KREEP-related rock types such as the quartz monzodiorite clasts in 15405[5].

If silica-rich evolved compositions do occur they will be characterized by the presence of high SiO_2 minerals such as quartz, and ternary and potassium feldspar[6,7,8,9]. In order to test whether the locations listed above are indeed composed of rocks containing these high silica minerals, the remote sensing technique of thermal emission spectroscopy was employed to search for the presence of such minerals at some of these locations. The measurement of mineralogy with this technique depends upon the detection and characterization of the wavelength of an emission feature known as the Christiansen peak which correlates with the silicate structure of a measured mineral. Figure 1 shows the spectra obtained in the course of this project all of which exhibit the Christiansen emission feature. Figure 2 is a plot of Christiansen emission maximum versus SiO_2 content for important rock forming minerals[10]. In addition to the plotted minerals, ternary feldspars are important minerals in some granites[8] and cristobalite may be expected in extrusive silicic lava. Ternary feldspars are not shown because they have not been measured. However, the systematics of the feldspars which have been measured suggest that the emission maximum is a rough function of An content and is less sensitive to the Ab and Or contents. It seems likely that ternary feldspars will show emission maxima intermediate between anorthite and the alkali feldspars. Cristobalite has been measured and was found to exhibit a slightly shorter emission maximum than quartz in a data set which agrees with that of Figure 2 in a relative, though not absolute sense[11]. The cristobalite point is not plotted due to the absolute calibration problems with the data set. As illustrated in Figure 2, the high SiO_2 minerals found in evolved silicic lunar rocks show emission maxima at much shorter wavelengths than those of the much more common minerals feldspar, pyroxene and olivine. Because the Christiansen emission peak of a rock (a mixture of mineral components) is roughly a linear weighted average of the peak positions of the mineral components, a rock containing significant amounts of the silicic minerals will exhibit a

Christiansen emission feature at a much shorter wavelength than that of more typical lunar basaltic material. A possible exception may be that of a soil composed of a mixture of high silica and very olivine-rich material. Though the measurement has not been made, the Christiansen maximum exhibited by such a mixture may be a double peak due to the wide separation between the component peaks allowing ready distinction between basaltic material and mechanical mixtures of high and low silica minerals. Thus thermal emission spectroscopy is well suited to the task of detection of high-silica evolved lunar rocks.

Our observational strategy was to obtain spectra of as many proposed high-silica areas as possible, and areas either known or assumed to be more typical of lunar basaltic material as comparisons. The relative immaturity of the technique for lunar science applications suggests caution in interpreting absolute mineralogies, however, we are confident that any detected large differences in relative peak positions between typical and test areas would be significant and interpretable.

On July 31 and August 1 of 1988 emission spectra of a variety of locations on the lunar surface were obtained with the NASA Infrared Telescope Facility at Mauna Kea Observatory using a circular variable filter (CVF) spectrophotometer employing a helium-cooled arsenic-doped Si photoconductor detector. The spectra cover 7 to 11μm at 1.25% spectral resolution ($\Delta\lambda/\lambda$). The aperture subtended 2 arcseconds which corresponds with a spot with a footprint of approximately 4 by 8 kilometers (the asymmetry being due to foreshortening near the lunar limb). The following locations were observed: Gruithuisen γ and δ, Hansteen α (the Arrowhead), Aristarchus central peak, the mountain Herodotus X on the Aristarchus Plateau, the craters Mersenius and Hansteen near Humorum, and the mare fill within the crater Billy. The latter three targets were selected as examples of typical lunar material likely completely free of K-feldspar, ternary feldspar, quartz or cristobalite. Apollo landing sites could not be observed due to technical constraints which have been subsequently removed for future observations.

Figure 1 shows the spectra collected. Careful analysis of the position of the wavelength of the emission maximum shows statistically valid variation among the various locations. In order to define the error in measurement of wavelength the central peak of Aristarchus crater was observed three times on the two nights and reduced using two standard stars. The position of the wavelength maximum was determined by fitting the four maximum points with a parabola and solving the first derivative of the parabola for the maximum. The one sigma variation in determination of the wavelength of the Christiansen frequency maximum for the central peak of Aristarchus is approximately 0.026μm. This variation is taken to be the error in wavelength determination. Analysis of the emission maxima of spectra of other locations shows that the emission maxima exhibited by the various locations differ by somewhat more than the error derived from the Aristarchus observations suggesting that real variation in mineralogy was detected. Table 1 lists the emission maximum values and the difference between the emission maximum wavelength of each location and that of the mare fill in Billy. The latter column is shown because the absolute wavelength values derived seem systematically low relative to the lunar samples and previous telescopic measurements[12,13] but differences within the data reported here probably reflect the differences in mineralogy. The expected variation of emission maximum in lunar soils is only somewhat greater than the error in emission maximum described above so that the sampling and sensitivity of this data set is just barely adequate to discern the degree of variation typical in lunar soils. However, these data are entirely adequate to detect larger relative shifts in emission maximum which would be expected if significant amounts of silicic minerals were present in any of the areas measured.

Table 1 shows that, of all locations measured, the mare fill in Billy exhibits the longest Christiansen wavelength and which suggests a lower abundance of plagioclase than the other areas. This is expected of the only mare location measured. The highland craters Hansteen and Mersenius show slightly shorter emission maxima than the mare fill in Billy. The Arrowhead "red spot" has a still shorter maximum followed by the mountain Herodotus X on the Aristarchus Plateau. Shortest emission maxima are exhibited by the Gruithuisen domes and the Aristarchus central peak which show emission peaks differing from that of the Billy mare by more than 2.3 times the estimated error in peak wavelength determination. It is interesting to note that these candidate silicic areas do display the shortest Christiansen peak wavelengths of any of the locations measured, though are not short enough to suggest significantly different mineralogies.

The very minor differences in emission maxima between the high-silica candidates and typical lunar locations indicate that none of the measured areas contain significant amounts of quartz, K-feldspar or other silicic minerals. Hansteen α (the Arrowhead) seems similar to other highland areas nearby thus is composed of typical lunar material. The Gruithuisen domes and the central peak of Aristarchus are also close to typical in mineralogy but may contain slightly more plagioclase than the highland craters and the Arrowhead. Therefore it is presently concluded that the measured red spots and at least a portion of the area exhibiting a Th anomaly at Aristarchus are not composed of high-silica evolved rock types.

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MINERALOGY OF RED SPOTS

Lucey, P.G., and B. R. Hawke

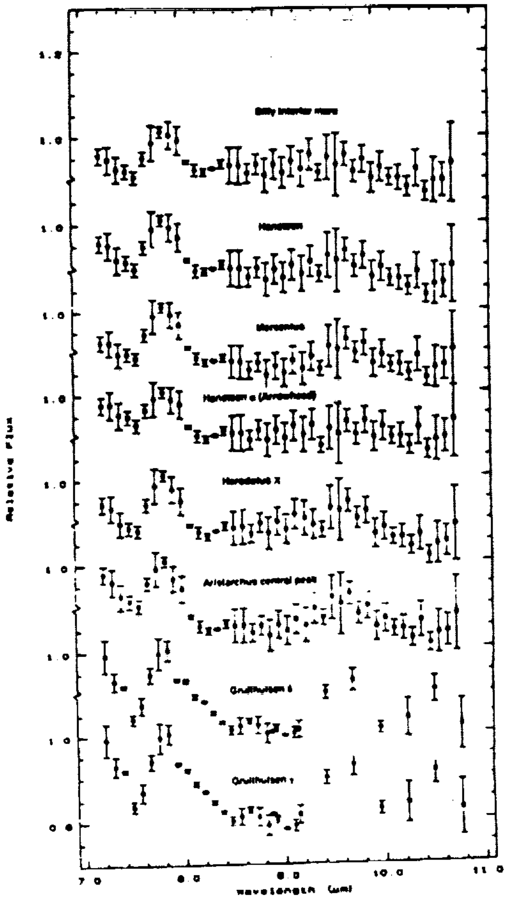

Figure 1. Thermal emission spectra of locations on the lunar surface. The spectra are relative to the star β Andromeda and are multiplied by a ratio of a 2700K blackbody over a 310K blackbody to approximate emission. The Christiansen frequency emission peak is well developed.

Table 1

Location	Emission max, µm	Δ Emission max, µm (Billy = 0)
Billy interior mare	7.880	0
Hansteen crater	7.849	0.031
Mersenius crater	7.846	0.034
Hansteen α (Arrowhead)	7.842	0.038
Herodotus X	7.832	0.048
Gruithuisen δ	7.818	0.062
Gruithuisen γ	7.817	0.063
Aristarchus central peak	7.816	0.064

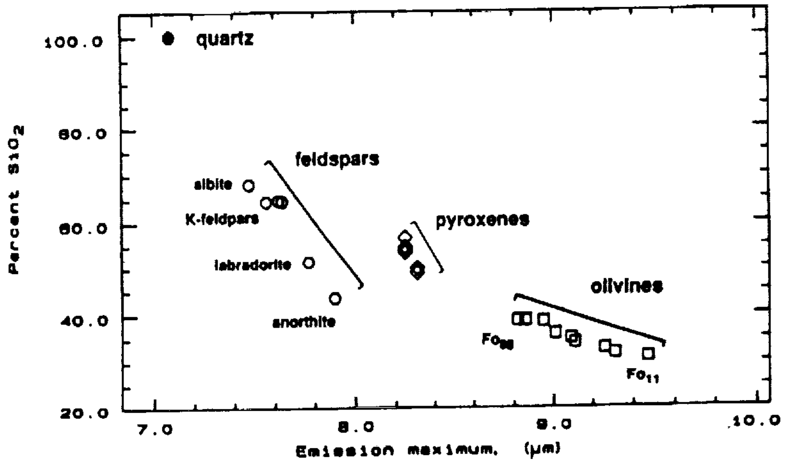

Figure 2. Measurements of Christiansen emission frequency and SiO_2 content for important rock-forming minerals. Note that minerals common in lunar granites and other evolved silicic rocks all exhibit Christiansen emission wavelengths less than than of anorthite. Data from (10).

ZIRCON-CONTAINING ROCK FRAGMENTS WITHIN APOLLO 14 BRECCIA INDICATE SERIAL MAGMATISM FROM 4350 TO 4000 MILLION YEARS;

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On the average, there is about one zircon (> 30 microns) per thin section of Apollo 14 breccia. They range in size from 2 to over 500 microns. Figure 1 gives their range in U content, Zr/Hf ratio and Y content. Lunar zircons with greater than about 300 ppm U are isotropic (metamict), but most are brightly birefringent. Many are homogeneous, but a few range widely in composition. It is difficult to discern the parental rock of the many zircons that are found as individual fragments in the matrix of Apollo 14 breccia.

Only a few zircons have been located within pristine, plutonic rock clasts in thin sections of Apollo 14 breccias. Figure 2 shows the plagioclase and pyroxene compositions of these zircon-containing rock clasts. They range from Ca and Mg-rich gabbronorites to Na and Fe-rich granophyres. Some attached pyroxenes are surprizingly Mg-rich (figure 3). Zircons found in the gabbronorites are homogeneous, while those in the granophyric fragments are chemically zoned.

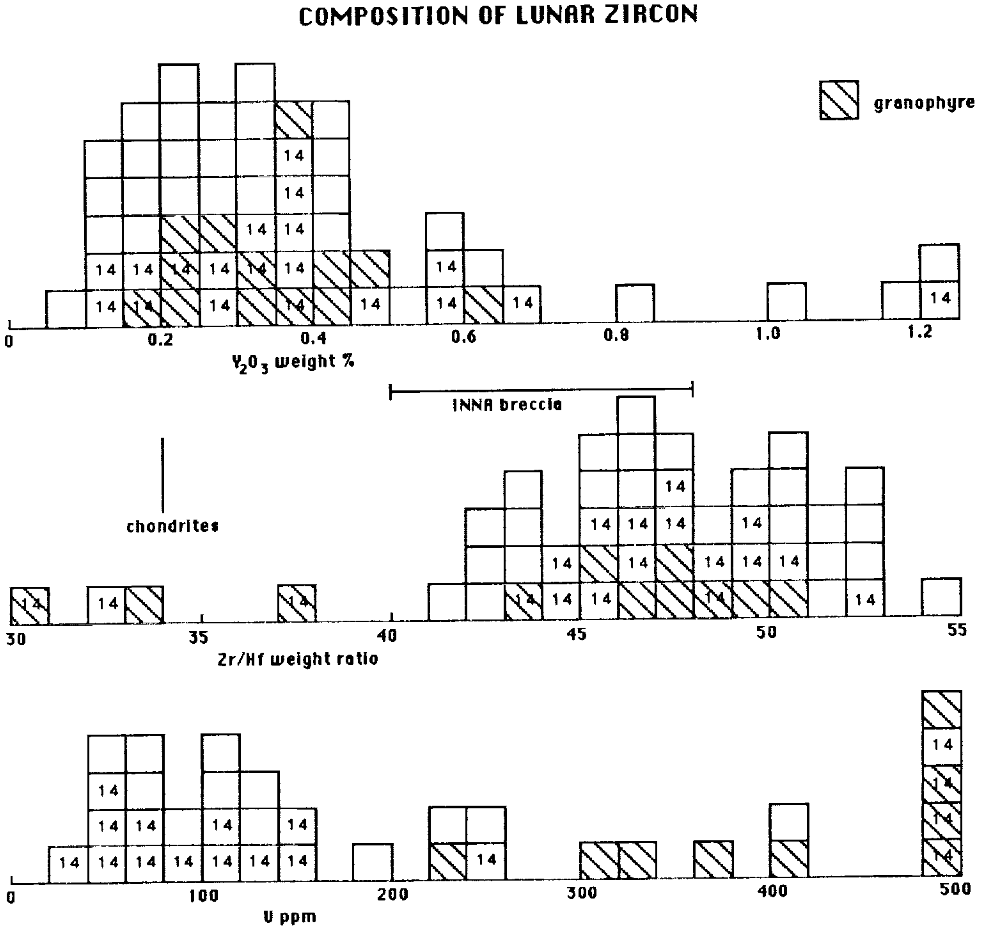

Figure 1

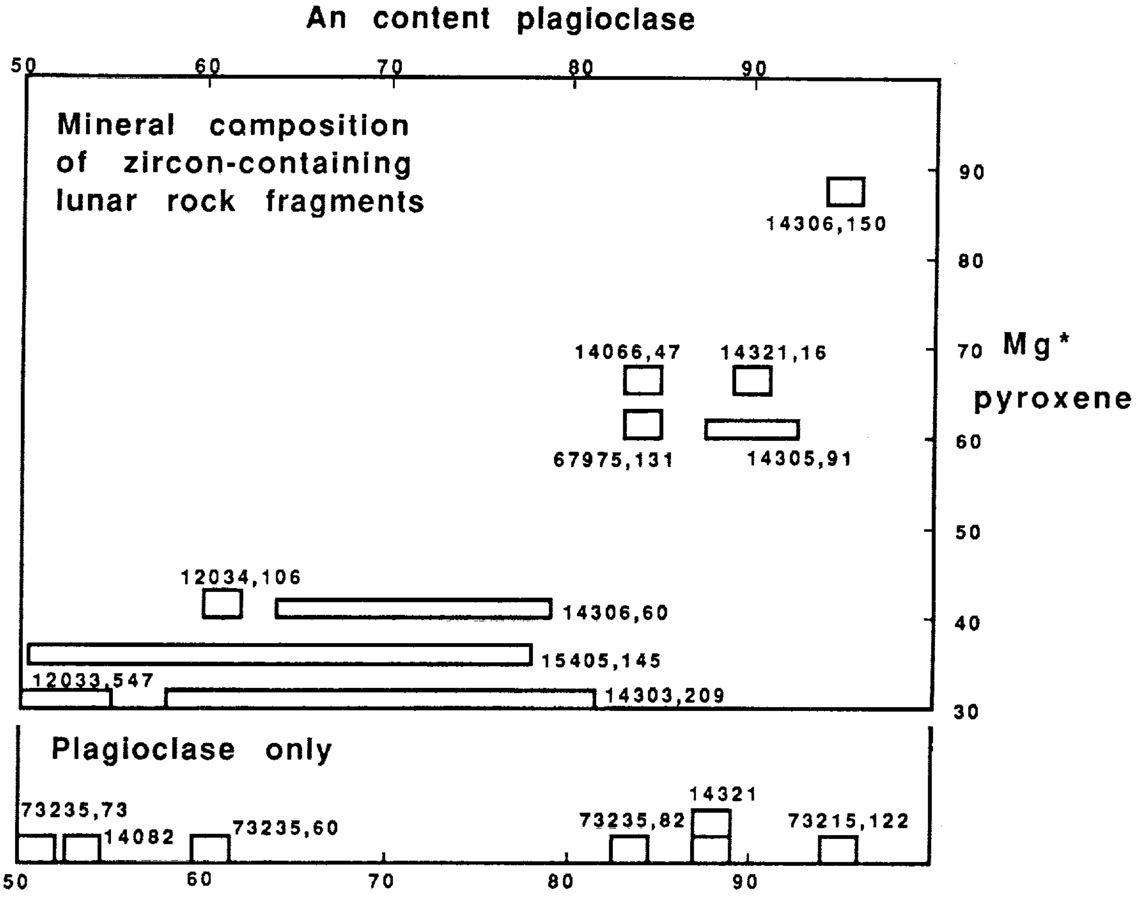

Figure 2

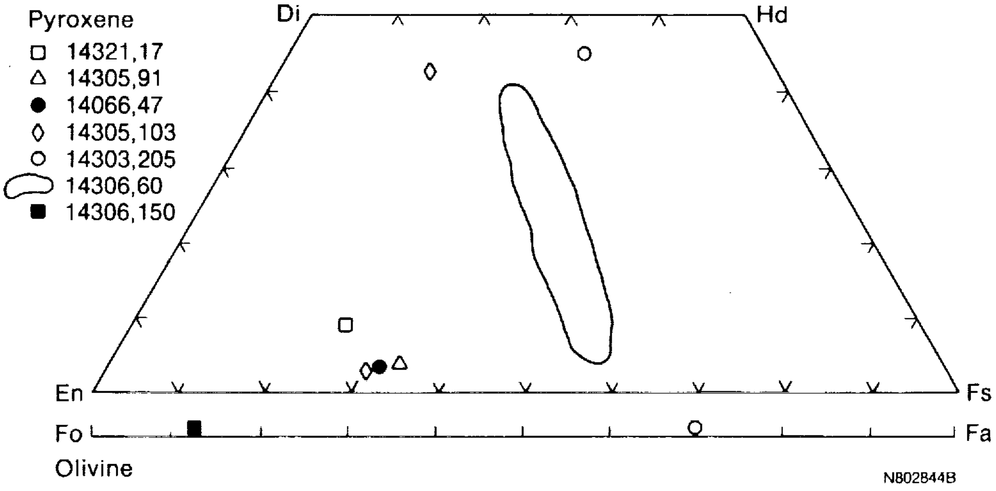

Figure 3

Figure 4

Figure 4 is a backscatter electron image of a large poikiolitic zircon in a small plutonic rock fragment in thin section 14066,47. The zircon is birefringent and surrounds homogeneous Mg-rich pyroxene. A small noritic clast in 14305,103 also includes poikiolitic zircon. A noritic clast in 14305,91 includes zircon, apatite and whitlockite. The pyroxene in this clast is surrounded by plagioclase. These three clasts are prime candidates of urKREEP (8). 14306,60 is an area of monomict breccia that includes several zircons, exsolved pyroxenes (figure 3) and one pyroxene-plagioclase clast with gabbroic texture. All the minerals in this area have similar compostions so that it appears to have once been a single rock. Thin section 14321,17 contains a small clast of polygonal plagioclase with mosaic texture including 20 small zircons and trace pyroxene. This small clast would be termed a lunar anorthosite if it were larger (2). However, the compositions of plagioclase and trace pyroxene indicate that it is related to the gabbronorite population.

Metamict zircons with very high U content and low Zr/Hf ratios have been found in coarse-grained granophyre 14321,1027 (3,7). The relatively young age of this granophyre (6) is confirmed. On the other hand, the zircon in "granophyre" 14303,209 (7) is found to be very old. 14303,209 contains exsolved pyroxene and partially melted plag-kspar-silica intergrowth and has a KREEP-like REE pattern. 14082,49 is an intergrowth of plagioclase and silica with three euhedral zircons. 14311,90 is a clast of unusual ilmenite "ore" with one large zircon (800 microns). 14306,150 contains an annealed cataclastic clast of plagioclase surrounding one large, Mg-rich olivine and several zircons (troctolite?).

We have used the ANU SHRIMP (1) to date zircons within these rock fragments (in situ) as well as several of the individual zircons. The zircon-containing rock fragments from Apollo 14 range in age from 4000 to over 4300 million years (figure 5). No zircons older than 4350 million years have been found so far. Apparently, it took about 200 million years (from about 4550 to 4350 m.y.) for Zr to become concentrated enough in the early lunar magma ocean to form zircon (4). From 4350 to about 4000 million years ago, there was a period of serial magmatism that produced zircon-containing fragments of plutonic rock, probably as parts of multiple, layered, igneous intrusions within the lunar crust. The ages of zircon-containing rock fragments in Apollo 14 breccias are distinctly younger than the supposed age of urKREEP (5,8).

Mineralogical Mode of Zircon-containing Apollo 14 Rock Fragments

*gabbronorites	plag.	pyx.	ilm.	olv.	k-spar	silica	zir.	glass
14066,47	45	45					10	
14305,103	49	49					2	
14305,91	48	48	2				1	
14306,60	48	48			tr.	tr.	2	2
*anorthosite								
14321,16(17)	98	1					1	

ZIRCON-CONTAINING ROCK FRAGMENTS

Meyer, C., Williams, I.S. and Compston, W.

*granophyres	plag.	pyx.	ilm.	olv.	k-spar	silica	zir.	glass
14082,49	55					40	5	
14303,209(205)	25	25	2		18	10	2	18
14321,1027(1613)					60	30	1	9
*ilmenite ore								
14311,90		3	90		1		6	
*troctolite								
14306,150	80			15			5	

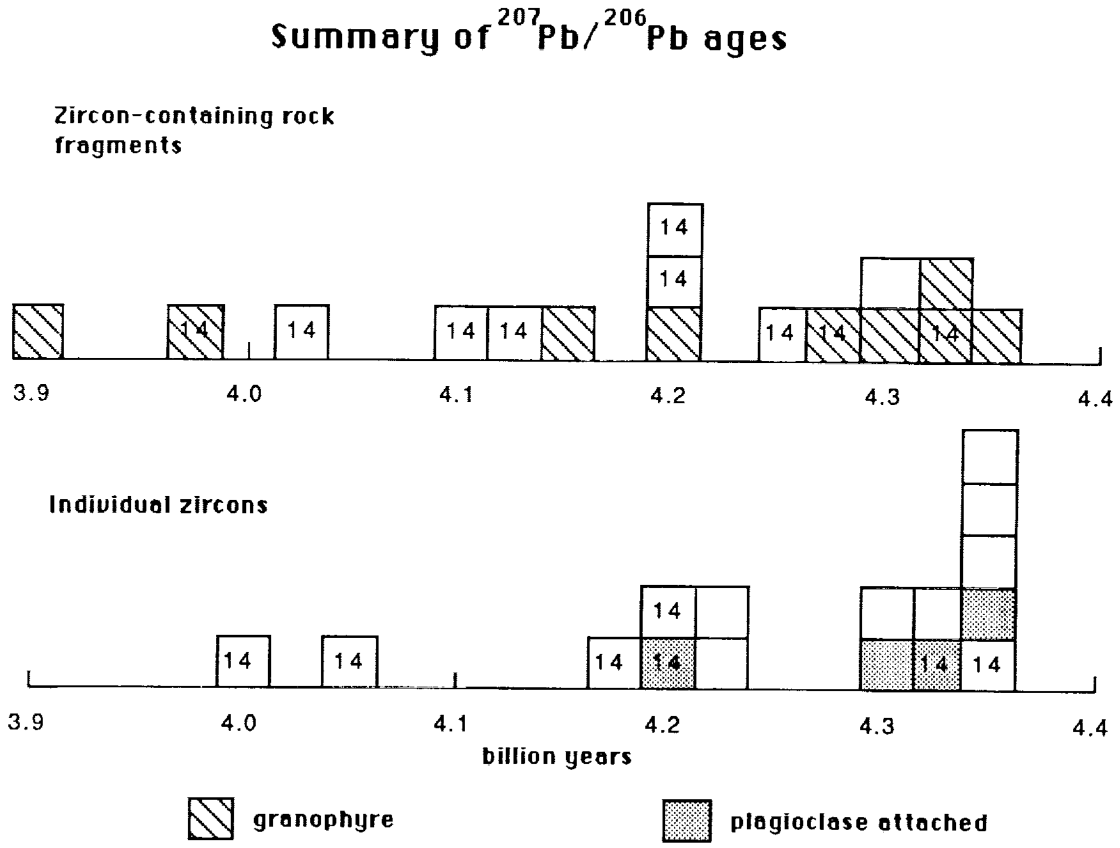
Summary of $^{207}Pb/^{206}Pb$ ages

Figure 5

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SILICATE LIQUID IMMISCIBILITY AND CRYSTAL FRACTIONATION IN A HIGHLY EVOLVED, KREEPY MAGMA:

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Studies of evolved rocks from the Apollo 14 site have greatly expanded our knowledge of the early evolution and differentiation of the Moon. The ongoing search for new lithologies in soils and breccias has uncovered many important rock types, including very high-K mare basalt and granite. We have been studying a suite of 18 rock fragments, 2-4 mm in size, separated from soils 14167, 14161, 14257, and 14001. We will concentrate here on five of these rock fragments; three with a unique REE pattern, and two typical impact melt rocks. The three unique rocks are breccias; consisting of light-colored granitic clasts surrounded by a high-Fe brown glass. Granite is a relatively rare but petrologically important evolved rock type. Although only 6 examples have been found (1), granite has been postulated as the origin of the unusual chemistry of the very high-K mare basalts (2). The three granitic breccias are characterized by extremely high REE abundances whose chondrite-normalized pattern is quite distinct from both KREEP and granite.

PETROGRAPHY - The first of the two melt rocks, sample 14161,203.2 is composed of plagioclase (≈55%), pyroxene (≈40%), and metal (≈5%). Twinned plagioclase laths, up to 1.0 mm in length, form a framework, producing an intergranular texture. Anhedral pyroxene grains, up to 0.3 mm in size, are interstitial to the laths. Ilmenite and chromite grains, up to 0.1 mm, also occur between plagioclase laths. The second melt rock, sample 14257,80.2 is made up of pyroxene (≈20%), plagioclase (≈15%), and metal (≈5%) set in a fine grained matrix. Ragged pyroxene grains, up to 0.8 mm in size, poikilitically enclose small (0.05 mm) plagioclase grains. These pyroxenes and stubby to lath-shaped twinned plagioclase grains (<0.6 mm) are dispersed in the matrix, producing an ophitic texture. Also present are opaque metal grains (<0.15 mm). The matrix is a very fine-grained assemblage of plagioclase and pyroxene, with minor metal and traces of a phosphate mineral.

The three granitic samples are breccias, composed of two lithologies: brown glass and shocked granite. The brown to amber colored glass is high in FeO (≈25 wt.%) and TiO_2 (≈5 wt.%) and makes up about 10 to 40% of each sample. About 2% of the glass appears devitrified to crystals smaller than 1 μm. The glass occurs as large masses and ropy coatings draped over granitic clasts and as veins between clasts. Despite the severe brecciation, hints of the original texture can be seen in the granitic clasts. Highly shocked, granophyric intergrowths of quartz and ternary feldspar (An_{13} Ab_{32} Or_{55}) make up between 10 and 30% of each granite. Intergrowth grains are up to 1.0 mm in size, although most grains are less than 0.4 mm. Individual lamellae range from ≈10 to 40 μm in thickness. The bulk of each granitic clast is made up of rounded grains of shocked quartz (<0.4 mm in diameter), subangular to subrounded grains of shocked feldspar (<0.3 mm), and grains of isotropic feldspar (<0.3 mm) set in a matrix of colorless, feldspathic glass with about 12 wt.% FeO and 6% CaO. Angular grains of zircon, up to 40 by 60 μm, are also found in the colorless glass and make up ≈0.5% of sample 14001,28.3. The zircons are concentrated in a 6 mm by 3 mm area, making up ≈70% of that particular area. Zircon is absent from the other sections.

WHOLE ROCK CHEMISTRY - Samples 14257,80.2 and 14161,203.2, characterized by INAA, have similar major element chemistry with 11.4 and 12.8 wt.% CaO, 7.8 and 7.1 wt.% FeO, and Mg#'s of 48.3 and 61.9 respectively. Na_2O is about 0.65 wt.% in each. These samples have REE patterns that parallel KREEP, with chondrite normalized La/Yb ratios of ≈2.2. Ir is also abundant (≈4 ppb), as expected for impact melts. U and Th are enriched, with the TH/U ratio similar to that of KREEP (3).

Samples 14001,28.3, 14001,28.2, and 14001,28.4, the granitic breccias, contain high abundances of FeO (12.2, 11.0, and 9.1 wt.%) and low CaO (5.4, 5.5, and 3.9 wt.%). The breccias have Mg concentrations that were below the detection limit of ≈0.6%, producing the extremely low Mg#'s (<5.0, <9.0, and <6.8) seen in these highly evolved samples. Cr and Co abundances are very low while the incompatible elements like Th, U, Rb, and REE are extremely enriched. Ir is detectable in 14001,28.2 but not in the others, suggesting that they might be pristine, but the textures are obviously brecciated and non-pristine. The incompatible element abundances showed the unique nature of the three granitic samples. Chondrite normalized (4) REE abundances (Gd value is inferred) of the five samples are shown in figure 1. KREEP (3) and "average granite" (2) are shown for comparison. As can be seen from figure 1, sample 14001,28.3 has extremely high bulk REE abundances, much higher than the KREEP component of (3). The pattern of the three granitic samples is also quite distinct from any previously measured lunar rocks. The chondrite normalized La/Sm ratio is 1.77, much greater than the KREEP ratio of 1.35. The heavy REE pattern is nearly flat, with a TB/Yb ratio of 1.07. KREEP has a much higher Tb/Yb ratio of 1.30 (3).

PETROGENESIS - The petrography of the breccias suggest that they may be simple mechanical mixtures of two components: a KREEPy impact melt and a granite. However, the extreme REE abundances make this unlikely. A least-squares mixing calculation indicates that sample 14001,28.3 would be a mixture of ≈65% "supergranite" (La≈590X chondritic) and≈35% "super"KREEP (La≈1280X chondritic), both of which contain far higher REE abundances than normal.

The origin of lunar granites has generally been explained by two processes: silicate liquid immiscibility (e.g. 5,6) and crystal fractionation (e.g. 7). Despite the severe brecciation of these three rocks, there is evidence for both processes in samples 14001,28.3, 14001,28.4, and 14001,28.2.

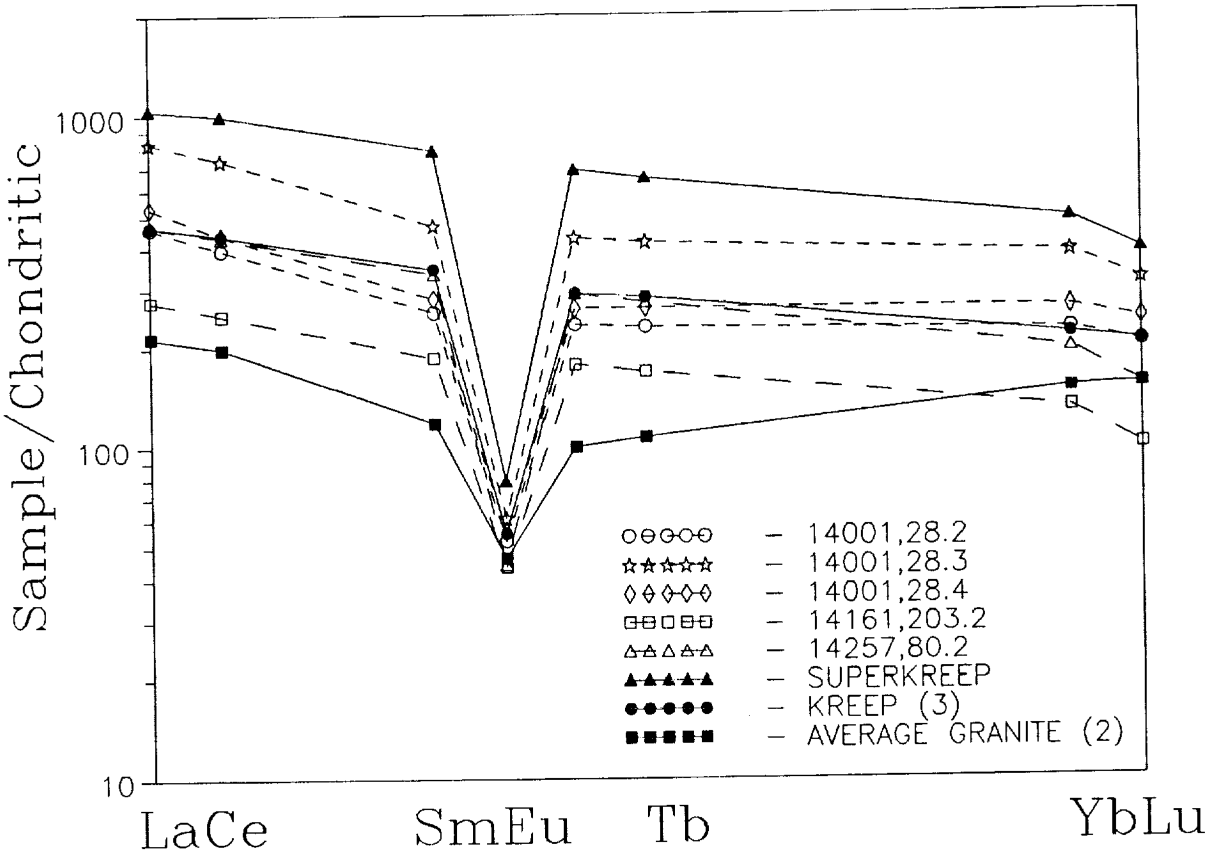
The dichotomy between the granite and the high-Fe glass is suggestive of liquid immiscibility. As was shown by (8) a silicate melt may split into two immiscible liquids; one high in Fe, and the other high in Si. The high-Fe melt will contain the bulk of the FeO, MgO, TiO_2, REE, P_2O_5, and CaO while the high-Si melt will contain most of the SiO_2, K_2O, Na_2O, and Al_2O_3. This is the distribution of elements seen in these breccias. Apparently, these samples represent an immiscible melt pair that were separated and then remixed by impact. However, the abundance of FeO, TiO_2, and P_2O_5 are higher in the bulk granite than would be expected from simple silicate liquid immiscibility (8). The areas of the granite with fairly pristine texture (quartz/feldspar intergrowths) tend to have the very low FeO, TiO_2, and P_2O_5 abundances predicted by liquid immiscibility, but the glassy, highly-shocked areas tend to contain more of these elements. The clear glass might be a mixture of granitic and high-Fe impact melts. A least-squares mixing calculation indicates that the clear glass could be a mixture of about 40% of our high-Fe melt with 60% average granite. The presence of a granite juxtaposed with its high-Fe immiscible partner implies that there was little spatial separation between the two melts in the target source rocks. The relatively uniform K/REE ratios among KREEPy rocks also supports the idea that there could not have been much large scale separation of immiscible melts.

Crystal fractionation of a magma with a KREEPy trace element pattern could produce the unique REE pattern of the granitic breccias. Modelling of this fractionation has shown that this pattern can be produced by 1% fractionation of an assemblage composed of 98.5% apatite and 1.5% zircon, with other phases assumed to have little effect on the pattern. If fractionation of these phases produced the abundances in 14001,28.3, it demands a parent "super"-KREEP with La abundances≈1020 times chondritic (Figure 1). The fractionation of phases could have taken place in the parent liquid prior to immiscibility or in the high-Fe fraction of the melt pair after unmixing. The FeO content of the brown glass is≈25 wt.%, significantly lower than predicted (≈30 wt.%) by silicate liquid immiscibility (8). This implies that the fractionation occured after immiscibility since fayalite would also fractionate from the high-Fe melt.

There is evidence for both crystal fractionation and silicate liquid immiscibility in these granitic breccias but neither process alone is able to produce the observed granites (1,9). Apparently, lunar granite formed by a complex combination of immiscibility and fractionation, probably associated with a KREEPy magma during the last stages of magma ocean differentiation.

ACKNOWLEDGEMENTS - Supported by NASA grant NAG 9-30 to K. Keil, PI.

FIGURE CAPTION - (next page) - Rare Earth patterns normalized to chondrites (4). Gd value is extraploated. Samples measured in this work are shown with open symbols on dashed lines. Inferred compositions are shown with closed symbols on solid lines.



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APOLLO 14 BASALT PETROGENESIS: GENERATION FROM AN OLIVINE-OPX DOMINATED MANTLE, FOLLOWED BY CRUSTAL ASSIMILATION AND FRACTIONAL CRYSTALLIZATION.

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Breccia pull-apart efforts have proven invaluable in the understanding of basaltic volcanism at, and the nature of the mantle beneath the Apollo 14 site. For example, Very High Potassium (VHK) basalts were identified from such pull apart efforts [1]. This discovery led to a re-evaluation of the significance of lunar granite at this site [1-3].

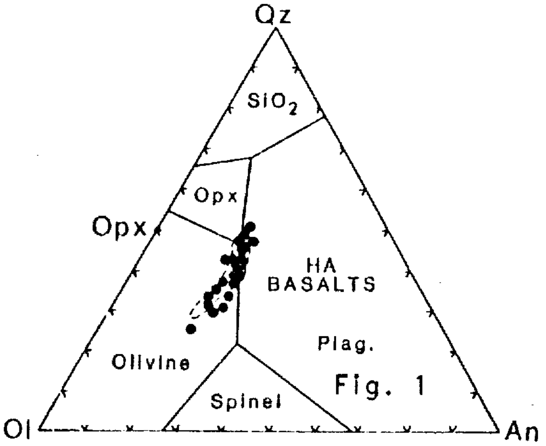

Fig. 1

Two types of basalt exist at the Apollo 14 site: 1) high-alumina (HA) basalts, containing between 11-14 wt% Al_2O_3 and < 0.3 wt% K_2O, with K/La ratios of approximately 100; 2) VHK basalts, containing >0.3 wt% K_2O, a K_2O/Na_2O ratio > 1, and a K/La ratio > 150. Furthermore, unlike the HA basalts, the VHK basalts crystallize orthoclase and have a residual glass containing 7-12 wt% K_2O. Apart from these distinctions, mineral and major element whole rock chemistry, and petrography for both HA and VHK basalts are similar [1,3-7]. It is the trace element contents of these basalts which yield the most information regarding their petrogenesis.

High-Al Basalts When plotted on an Ol-An-SiO_2 pseudoternary, HA basalt major element compositions define a fractionation sequence (Fig. 1). In this diagram, we have plotted our most recent data [7] as points, and our previous data [5] as fields. Olivine and chromite are the first phases to crystallize [8]. By using the lever rule (Fig. 1), only olivine (90%) and chromite (10%) fractionate during the first 14% crystallization. This is consistent with the petrography, where olivine phenocrysts with chromite inclusions are present [6]. After 14% crystallization, the ol-plag cotectic is reached, and plagioclase (50%) fractionates with olivine (40%) and chromite (10%) until 21% of the parental liquid has crystallized. At this point, the ol-opx-plag peritectic is reached, and olivine fractionation ceases with orthopyroxene becoming the dominant liquidus phase. Plagioclase (30%), orthopyroxene (60%) and ilmenite (10%) are the crystallizing phases until 70% of the parental liquid is solidified.

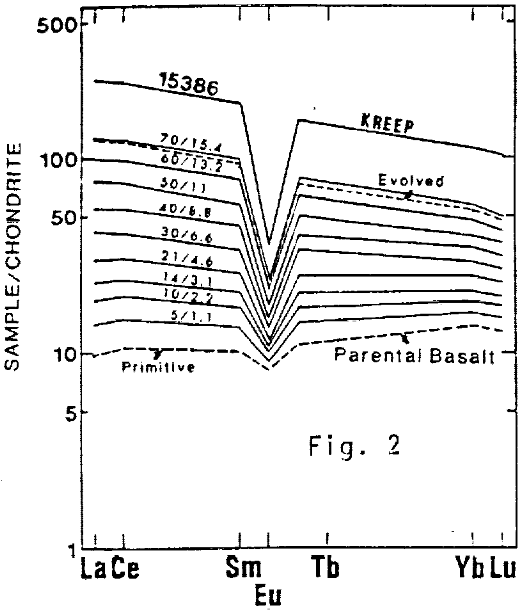

Fig. 2

The HA basalts exhibit a wide range in trace element abundances. There is a continuum of compositions from LREE depleted (primitive) types [$(La/Lu)_N \cong 0.75$; $(Sm/Eu)_N \cong 1.3$], to LREE enriched (evolved) types [$(La/Lu)_N \cong 2.5$; $(Sm/Eu)_N \cong 4.0$] [7]. The compatible elements decrease and LIL and HFS elements increase from primitive to evolved types. The evolved types have REE profiles which mirror those of KREEP (Fig. 2). On element-element plots, the HA basalts exhibit

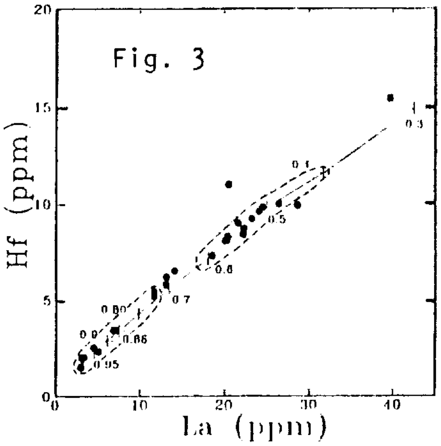
Fig. 3

coherent trends from primitive to evolved, leading towards KREEP. This has led to the formulation of an AFC model between a primitive basalt and KREEP in order to account for HA basalt compositions. The AFC modelling of the new HA basalts is conducted using the same KREEP composition as in Neal et al. [5] (i.e., 15386 "IKFM": Vaniman & Papike, [9]). This is taken as a representative KREEP sample.

In the model calculations, the "r" value [10] was first estimated as 0.2 by studying the compositions of the parental basalt and assimilant. As this is basically a basalt-basalt interaction, the r value will be low. The r value of 0.2 was then adjusted slightly to 0.22 in order that the derived AFC path passed through all HA basalt compositions. Using published Kd values, AFC paths are constructed between a primitive HA (14321,1422: low incompatible trace element abundances and SiO$_2$, and high MG#) and 15386 KREEP (Fig. 2). The HA basalt REE (dashed lines) calculated by our AFC method demonstrates that the LREE-enriched nature of the evolved basalts can be generated from a LREE-depleted parent. In Figure 3, La is plotted against Hf for all Apollo 14 HA basalts. This diagram was used by Dickinson et al. [11] to demonstrate the presence of 5 distinct Apollo 14 basalt groups. Previously reported HA basalt compositions [4,5,11] are presented as fields (as in subsequent diagrams). Two fields exist, but the new basalt data go some way to "closing the gap" on this plot. An AFC path has been calculated between basalt 14321,1422 and IKFM KREEP (Fig. 3). The AFC model must be extended in order to accommodate the new data, and as such, has been calculated to 70% crystallization of the parent and 15.4% KREEP assimilation (r = 0.22). The AFC model is also applicable to other elements (Fig. 4).

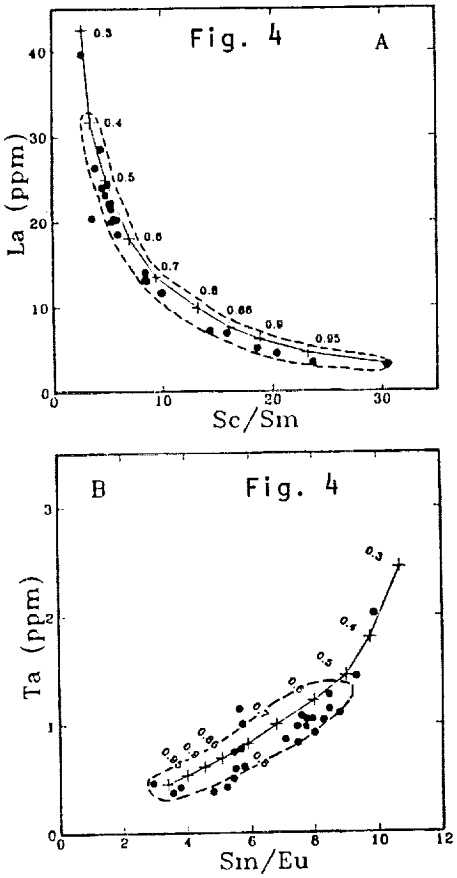
Fig. 4

The relationship between major and trace elements suggests that the assimilant may have an effect upon the major elements. For example, the sample with the highest La abundance does not contain the lowest MgO, even though a general negative correlation exists between La and MgO. Shih [12] noted an inverse correlation between MG# and incompatible elements in KREEP basalts, the opposite of what is expected. Therefore, prolonged assimilation of a KREEP basalt composition could increase the incompatible elements and the MgO content of the residual magma.

VHK Basalts

The similarity in major element compositions between HA and VHK basalts (except for elevated K$_2$O) has resulted in models for VHK basalt petrogenesis by an HA basalt assimilating granite [1,13]. However, the unusually low HFS elements in VHK basalts would appear to negate granite assimilation. It was proposed that preferential assimilation of granitic feldspars would overcome

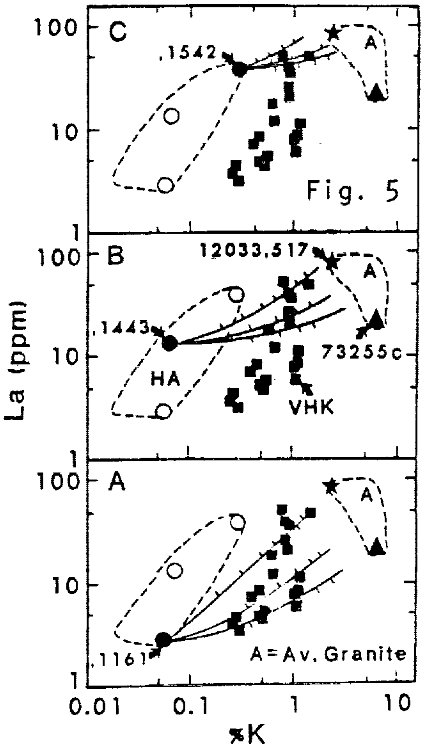

Fig. 5

this problem, and still yield a VHK composition [1,14]. Neal et al. [5] proposed an AFC process (after [10]), involving lunar granite and a HA magma, in order to generate VHK basalts. This model generates the low HFS and high LIL element abundances. Assimilation of granite is supported by the presence of K-feldspar and K-rich residual glass in VHK basalts [6]. One surprising outcome of this model was that no one parental HA basalt can generate all VHK compositions, arguing not only for more than one VHK basalt flow, but also a KREEP component in the VHK compositions. This is necessary because as more evolved HA basalts are required as parental magmas for some VHK compositions.

The VHK basalts fall between HA basalts and lunar granites on trace element plots. In Figures 5 & 6, all VHK data are plotted as points, and Apollo 14 HA mare basalts and lunar granites are plotted as fields. For the purposes of illustration, three parental HA compositions are used in the AFC calculations: 1) Primitive (14321,1161 of [4]); 2) Intermediate (14321,1443 of [5]); and, 3) Evolved (14321,1542 of [7]). These HA compositions span the entire range of Apollo 14 HA basalts. The fractionating phases are the same as for the HA basalts because of the similarity between major element compositions (Fig. 7). The r value of 0.5 is the same as in this previous study. This higher value is required because granite has a lower melting point than basalt. Granite assimilants used are average lunar granite, 73255c [15], and felsite 12033,517 [16]. This approach allows the compositional variability of lunar granite to be accounted for in our model.

Figure 5 is of La (ppm) versus %K, a classic plot for VHK basalts. The diagram has been split into three parts, in order to clearly demonstrate the calculated AFC paths (tick marks represent increments of 5% crystallization or 2.5% assimilation) between each parental basalt and granite assimilant. In Figure 5a, basalt 14321, 1161 is taken as parental. Note that all VHK basalt compositions cannot be generated from this parent magma and one granite composition as the assimilant. In order for magma ,1161 to generate VHK basalts with high La abundances, it must assimilate up to 17.5% of granite 12033,517 (Fig. 5a). Such a large amount of granite assimilation will dramatically affect the major element composition of the resulting VHK basalt. In order for granite to not adversely affect the major element compositions of VHK basalts, a maximum of only 10% can be assimilated. Therefore, basalt ,1161 cannot be parental to VHK basalts with high La abundances. However, it may reasonably be considered parental to VHK basalts with intermediate and low La abundances, as these compositions can be

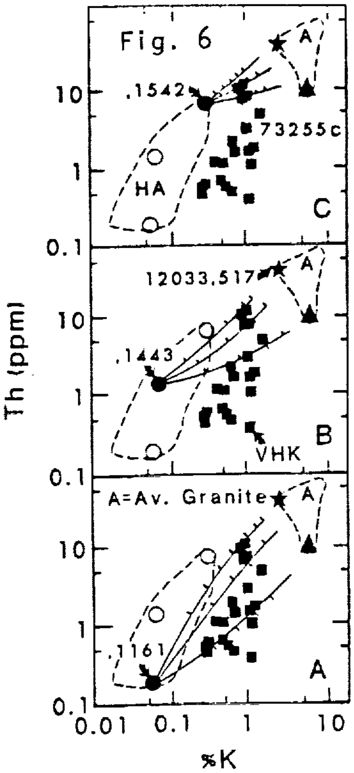

Fig. 6

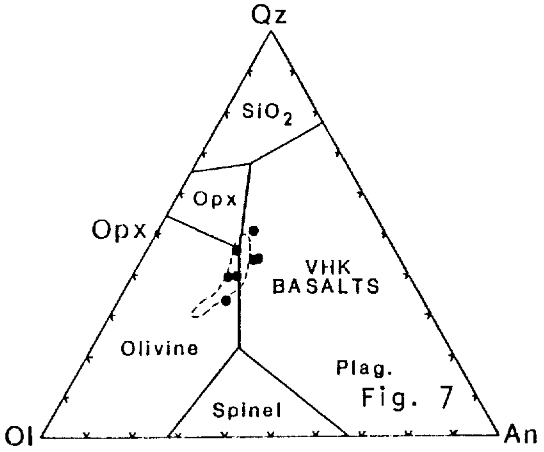

Fig. 7

generated by a maximum of only 8% assimilation of average granite and 73255c, respectively (Fig. 5a).

The VHK basalts with intermediate La abundances are better represented by using basalt 14321,1443 as the parental magma and either the composition of average granite or 73255c (Fig. 5b). A maximum of 7% assimilation of average granite or 73255c is required to generate these VHK basalts. The VHK basalts containing the highest abundances of La are generated by using basalt 14321,1542 as the parental magma assimilating a maximum of 7.5% average granite or 73255c (Fig. 5c).

In Figure 6, Th (ppm) is plotted against %K, an element difficult to model for VHK basalt petrogenesis (e.g., Shervais et al., 1985b), and a similar picture is defined as in Fig. 5. For VHK basalts with low Th abundances, 8% assimilation of 73255c by ,1161 is required (Fig. 6a). For those with intermediate Th abundances, 8% assimilation of average granite by ,1161 is necessary. However, those VHK basalts with intermediate Th abundances are better represented by our AFC model if basalt ,1443 is the parental magma and 73255c is the assimilant (Fig. 6b). A maximum of 7.5% granite assimilation is required to generate these VHK compositions. The highest Th abundances (Fig. 6c) are generated between the parental basalt ,1542 assimilating up to 7.5% of either average granite or 73255c (as for La in Fig. 5c).

The slight variation (± 1%) in amount of required granite assimilation for different elements in VHK basalts of low, intermediate, or high incompatible element concentrations is well within error of the AFC calulation. Another outcome of our modelling is that, generally, VHK basalts with low, intermediate, or high incompatible element abundances are generated by primitive, intermediate, and evolved parental magmas, respectively. This leads us to conclude that the parental magma not only dominates the major elements, but also the trace element composition of VHK basalts. As a maximum of 8% granite assimilation (of either 73255c or average granite) is required, it appears that only potassium is radically affected (see Figs. 5 & 6).

Our modelling suggests that there must be at least **three parental HA magmas** required to generate the observed VHK basalt compositions, and also argues for a KREEP component in the VHK compositions. This is necessary because as more evolved HA basalts are required as parental magmas for the more evolved VHK compositions. As demonstrated above, HA basalts form a continuum of compositions as a result of KREEP assimilation. We regard VHK basalts as offshoots from this HA basalt evolution trend by granite replacing KREEP as the assimilant. This adds support to a KREEP-granite relationship as suggested by Ryder [17] and Neal and Taylor [18]. Once again, the importance of lunar granite cannot be over emphasized in light of the new VHK basalt clasts recovered from Apollo 14 breccias.

The recent work of Dickinson et al. [19] has highlighted the importance of the siderophile element concentrations in Apollo 14 HA and VHK basalts. These authors noted that the Ge abundances in both HA and VHK basalts could not be generated using the proposed end members of our AFC model. Rather, Ge must have been enriched by several orders of magnitude over observed concentrations in 15386 KREEP and twice that in lunar granite. However, we do not feel that this negates the proposed AFC models for HA and VHK basalt petrogenesis. As stated earlier, a pure KREEP composition has not, as yet, been defined and may contain greater abundances of the siderophiles than in our proposed end member. A siderophile-rich KREEP component incorporated into HA basalts will also account for the Ge composition of VHK basalts.

Source Modelling

The modelling of Apollo 14 basalts by AFC defines a parental magma composition, which is LREE depleted with a small, negative Eu anomaly, enriched in incompatibles, and has low SiO_2 and a high MG#. This composition is assumed to be an unmodified mantle melt, and can be used to estimate the composition of the lunar mantle. A source composition is assumed from the magma ocean theory (i.e., mafic cumulates containing a negative Eu anomaly: [20]). By iterative calculations, several possible source trace element patterns are generated by varying the degree of partial melting (i.e., assuming our parental basalt is a product of 2%, 5%, 10% partial melting etc.). The trace element composition of the magma ocean from which these hypothetical sources have crystallized, can now be calculated. The HA source crystallized from a magma ocean with a $(La/La)_N$ ratio of 2 and a $(Sm/Nd)_N$ of 0.89 [21-23]. Although the source mineralogy has been varied (Ol 40-50, Opx 30, Cpx 10-20, Plag 5, Ilm 5), the degree of partial melting required to generate the parental HA magma from the calculated trace element abundances is 4-5% (Figures 8 and 9).

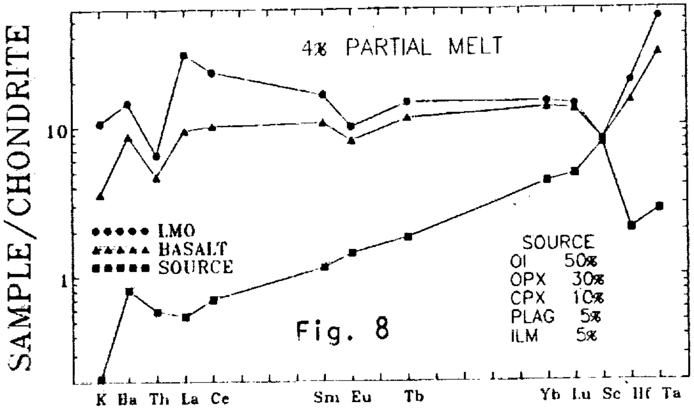

Fig. 8

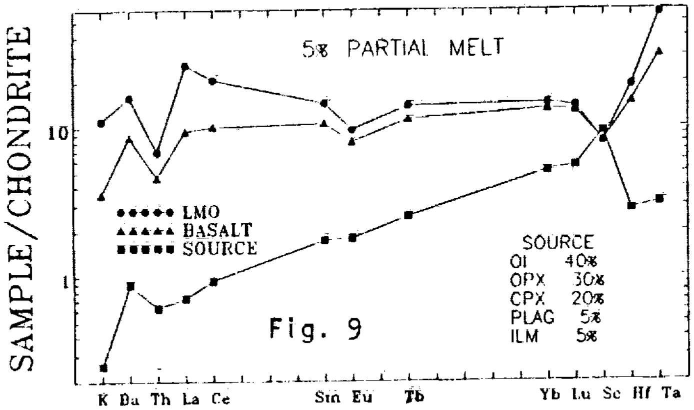

Fig. 9

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LUNAR GRANITE PETROGENESIS AND THE PROCESS OF SILICATE LIQUID IMMISCIBILITY: THE BARIUM PROBLEM.

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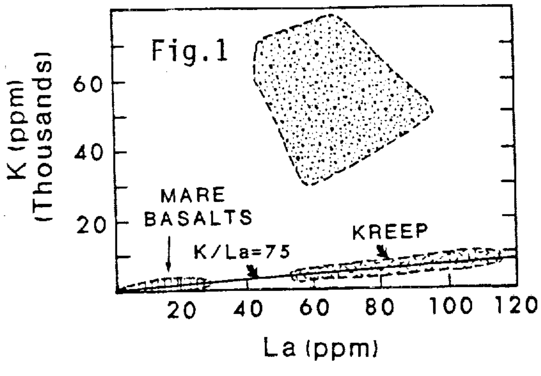
The Apollo 14 sample return has been particularly fruitful in that several lunar granite samples have been identified. Granites contain the highest Ba, K, Si, Al, and Cs abundances of any lunar rock type. The presence of granite in generally mafic settings [1-3] is perplexing because of the lack of any intermediate rock-types between basalt and granite, which would be expected if normal magma fractionation generated such SiO_2-rich rocks. This lack of intermediate rock types between basalt and granite, coupled with the excellent experimental work on lunar basalts [4,5], demonstrate that silicate liquid immiscibility (SLI) may be an important process in the formation of lunar granite.

The Process of Silicate Liquid Immiscibility. When a fractionated magma encounters the immiscibility field, high- (acidic) and low-silica (basic) melts are produced. The experiments of Rutherford et al. [4], Hess et al. [5], and Rutherford and Hess [6], and the observations of Roedder and Weiblen [7-9] and Weiblen and Roedder [10], suggest that SLI can only occur after extreme (90-98%) crystallization of a basic magma. Hess et al. [5] concluded that the fractionation path required for ultimate immiscibility of the residual is very similar to the "Fenner Trend" (i.e., FeO rather than SiO_2 enrichment, with a dramatic decrease in MgO). These authors also suggested that under conditions of low oxygen fugacity (such as in a lunar environment), there is a "thermal valley" which leads residual magmas towards a ferrobasalt composition. This type of fractionation does not produce intermediate rock types between basalt and granite, because silica enrichment is suppressed. Experimental results, which demonstrate SLI in actual lunar basalts [4-6], coupled with immiscible glass analyses from lunar lunar basalts [7-10], indicate that SLI is a feasible process in the lunar environment.



SLI in Lunar Granite Petrogenesis. Inter-element ratios of such elements as K, U, Th, Rb, Ba, P, REE, and Zr are relatively unaffected by normal fractional crystallization of basaltic magmas (e.g., [11]). However, SLI can dramatically alter such ratios as K/P, K/La, and K/Zr. Therefore, in order to ascertain the role of SLI in the production of lunar granite, comparison of the K/La ratio between granite, Apollo 14 basalts, and KREEP has been made (Fig. 1). Lunar granite is compared with Apollo 14 HA mare basalts [12-14] and KREEP compositions [15]. The K/La ratio is similar for both the basalts and KREEP (≅ 75). The granites exhibit K/La ratio of up to 1000. Therefore, if the parent to granite was either a KREEP or mare basalt, it is unlikely that granite was produced by fractional crystallization alone.

Immiscible granitic glasses in basalt mesostasis have similar compositions to actual lunar granites, suggesting a similar petrogenesis. Experimental results from high- and low-Ti mare basalts [4-6], demonstrate the relative ease with which lunar basalts, under low fO_2 conditions and slow cooling, can eventually undergo silicate liquid immiscibility. Finally, the lack of any intermediate rock types between basalt and granite on the Moon negates any fractional crystallization scheme that does not follow the "Fenner Trend". This type of fractionation scheme produces a ferrobasaltic residual, ideal for the production of immiscible melts [5].

Partitioning Between Immiscible Melts. Partitioning of elements between these melts is a function of melt structure [16-19]. We have presented liquid-liquid Kd's determined by experimentation and calculated from immiscible glasses in basaltic mesostasis (Table 1). These Kd's are presented as:

$$D_{b/a}^{*} = \frac{\text{conc. of element in basic melt}}{\text{conc. of element in acid melt}}$$

(* $D_{b/a}$ = liquid-liquid Kd)

and are produced for both major and trace elements. A $D_{b/a}$ value of >1 indicates that the element is preferentially partitioned into the basic melt. The magnitude of the liquid-liquid Kd's has been shown to increase with decreasing temperature and the addition of phosphorus to the system [17, 18]. Variable P_2O_5 contents coupled with temperature variations cause a widening of the immiscibility gap and probably account for the range in Kd values presented in Table 1. The elements Si, Al, Na, K, Rb, and Cs are concentrated in the acid or granitic melt (i.e., Kd < 1), whereas Ti, Cr, Fe, Mn, Mg, Ca, P, Zr, U, Th, the REE, F, Cl, Sr, and Ta are concentrated in the basic or ferrobasaltic melt (i.e., Kd > 1: [4-6,19]).

TABLE 1: Liquid-liquid partition coefficients calculated from immiscible glasses in basaltic mesostases and experimental results.

	1	2	3	4	5	6	6	6	6	7	7	7	7	8
SiO_2	0.498		0.553	0.588	0.715	0.518	0.662	0.650	0.513	0.710	0.730	0.580	0.590	0.754
TiO_2	6.856	8.100	6.180	5.420	2.330	4.430	2.750	2.590	9.000	2.790	2.280	4.130	3.110	3.077
Al_2O_3	0.375		0.469	0.417	0.788	0.609	0.700	0.812	0.381	0.580	0.620	0.640	0.770	0.639
Cr_2O_3	8.000		---	---	---	---	1.500	4.000	2.670	---	---	---	---	3.755
FeO	16.517		10.97	10.21	2.420	4.820	3.190	3.200	45.50	2.570	2.770	5.920	4.430	2.179
MnO	21.86		---	---	---	6.800	2.710	2.750	---	2.320	2.300	6.800	8.290	2.933
MgO	59.36		11.29	---	1.500	10.20	2.330	2.360	80.00	2.130	3.040	9.000	4.250	2.148
CaO	11.06		6.690	7.840	2.070	5.440	2.500	2.360	20.90	2.130	1.980	6.710	4.390	2.352
BaO	0.493	0.610	---	---	---	---	---	---	---	---	---	---	1.340	1.498
Na_2O	0.299		---	---	0.667	0.405	0.510	0.540	0.225	0.470	0.460	0.460	0.440	---
K_2O	0.117	0.369	0.061	0.026	0.463	0.137	0.198	0.362	0.004	0.310	0.320	0.180	0.210	0.450
P_2O_5	35.61	6.380	3.800	---	---	21.60	12.42	4.600	42.90	---	---	33.20	13.26	10.84
Sr	3.770	1.170	---	---	---	---	---	---	---	---	---	---	---	2.365
La	9.600	---	---	---	---	---	---	---	---	4.580	3.920	13.80	---	3.907
Sm												---	---	4.474
Yb												16.57	---	---
Lu												---	---	5.655
Ta												---	---	4.313
Cs												---	---	0.303

References: 1 = 15434,188 this work; 2 = Ryder, unpub.; 3 = Roedder and Weiblen, 1971; 4 = Weiblen and Roedder, 1973; 5 = Rutherford et al., 1974; 6 = Hess et al., 1975; 7 = Ryerson and Hess, 1980; 8 = Watson, 1976.

The Barium Problem

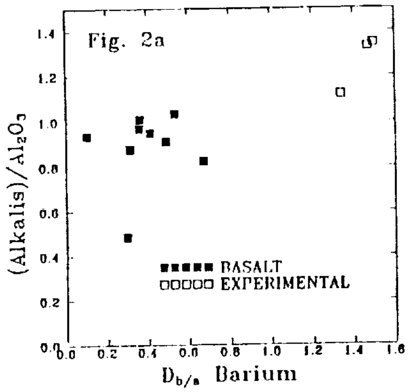
Analyses of immiscible glasses in lunar basalts [7-10], and interpretation of preliminary experimental results [4,5], led to the conclusion that Ba was concentrated in the granitic melt ($D_{b/a}$ < 1). However, the experimental results of Watson [19] and Ryerson and Hess [18] demonstrated that Ba was concentrated in the ferrobasaltic or basic immiscible melt ($D_{b/a}$ = 1.5 and 1.4, resp.).

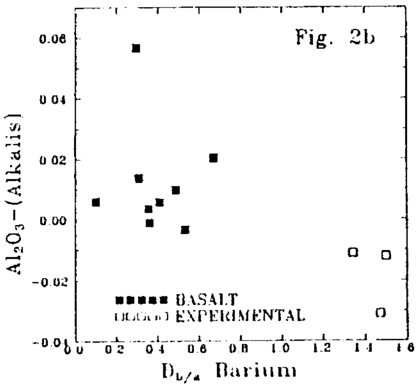
We have recently analyzed immiscible glasses from basalt 15434,188 to evaluate $D_{b/a}$ values for use in SLI modelling ($D_{b/a}$'s calculated from adjacent immiscible glasses). In order to increase the precision of the minor element analyses, extended count times of 60 seconds were used. Our results agree with experimental $D_{b/a}$ values, except for Ba ($D_{b/a}$ = 0.49). Other immiscible glass analyses from Apollo 15 KREEP basalts (Table 1), give a $D_{b/a}$ for barium of 0.61 (G. Ryder pers. comm., 1988).

The variability of the Ba two-liquid Kd is addressed by consideration of the immiscible melt structure. Al can assume the role of either a network-forming or network-modifying cation in silicate melts [20-22]. However, in order to assume the capability of a network-forming cation and substitute for Si, Al must be charged balanced by a mono- or divalent species.

Hess and Wood [22] and Roy and Navrotsky [23] proposed a list of cations which would complex with tetrahedral Al. These are, in order of preference:

$$K > Na > Li > Ba > Sr > Ca > Fe^{2+} > Mg.$$

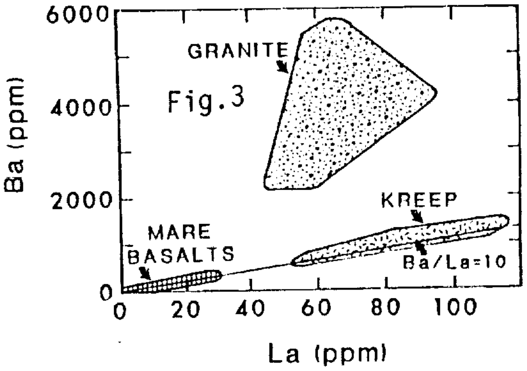




Hess and Wood [22] concluded that AlO_4 species formed with cations at the beginning of this series preferentially enter the most polymerized silicate units (i.e., the high-SiO_2 melt); those formed with cations at the end, favor the least polmerized melt structures (i.e., the basic melt). Ryerson and Hess [17] suggested that the liquid-liquid Kd for Ba and Sr is ≅ 1, and Wood and Hess [21] indicate that the transition between the the two states occurs at Ba.

It has been demonstrated that in a K- and Na-free system which undergoes SLI, Al is preferentially partitioned into the low-SiO_2 melt as a $CaAl_2O_4$ complex (Ca is strongly partitioned into the basic melt; see above) [21-22]. However, with increasing alkali content, Al is preferentially partitioned into the high-SiO_2 melt. Potassium (or Na) displaces Ca as the charge balancing cation for the network-forming AlO_4 tetrahedra. The $(Na,K)AlO_2$ species favor the more polymerized silicate melt structure. Ryerson and Hess [18] concluded that the behavior of K^+, Na^+, and Ba^{2+} is explained by their strong affinity for sites associated with tetrahedral Al. Calcium and the REE's display the opposite effect as a result of their greater affinity for the phosphate complexes in the basic melt.

We have combined our acid immiscible glass data with the experimental results of Watson [19] and Ryerson and Hess [18], and plotted the $D_{b/a}$ for barium against the alumina - "alkali" and alkali/alumina ratio ("alkali" = K_2O+Na_2O+CaO+ BaO) in the granitic melt (Fig. 2 a,b), using oxide moles. Our data, coupled with experimental results, suggest an Al_2O_3-("alkalis") value ≅ 0 corresponds to a $D_{b/a}$ for Ba of 1. This indicates that an excess of Al in the high-SiO_2 melt is required for the $D_{b/a}$ for Ba to be < 1. The alkali/Al_2O_3 ratio of ≅ 1 corresponds to a $D_{b/a}$ of 1. A similar correlation between Ba and La (Fig. 3) as for K and La (Fig. 1), demonstrates that Ba is partitioned into the high-SiO_2 immiscible melt during lunar granite petrogenesis involving SLI.



Conclusions. It is probable that SLI was involved in lunar granite petrogenesis, at the conclusion of extreme "Fenner Trend" fractional crystallization of a basaltic magma. Such a scenario accounts for the lack of intermediate rocks between basalt and granite on the Moon. The high Ba abundances in lunar granite can be explained by SLI, even though experimentation suggests Ba preferentially partitions into the basic immiscible melt. Barium partitions into the high-SiO_2 melt if "alkalis"-Al_2O_3 is > 0, and the Al_2O_3/"alkalis" ratio is > 1.

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THE SPLITTING OF KREEP INTO IDENTIFIABLE COMPONENTS: THE "K-FRAC" AND "REEP-FRAC" HYPOTHESIS.

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KREEP contains high abundances of K, REE, and P and is considered to have a noritic composition [1]. A generalized KREEP composition, as taken from the literature, contains ≅1wt% K_2O, ≅1wt% P_2O_5, Rb = 20-25ppm, Rb/Sr ≅ 0.11, La = 300-350 times chondrite, Hf ≅ 35-40ppm, Th = 15-20ppm, and Ba = 1000-1500ppm. Generally, KREEP has a LREE-enriched profile (e.g., [1,2]), which contains a large negative Eu anomaly (Fig. 1) with La/Lu ≅ 22-25.

There have been basically two models proposed for the generation of KREEP, based upon the Lunar Magma Ocean hypothesis (LMO): 1) partial melting of an "ANT-suite" (Anorthosite, Norite, Troctolite) cumulate (e.g., [3-5]); or 2) as a residual magma after extreme fractional crystallization (e.g., [1,6-8]). Warren and Wasson [1] argued for a uniform, almost Moon-wide KREEP reservoir, and concluded that KREEP could not be produced by partial melting. Warren and Wasson [1] also suggested KREEP to be the residual from the LMO. They used the German prefix "ur" (meaning primeval) to describe KREEP produced in this way.

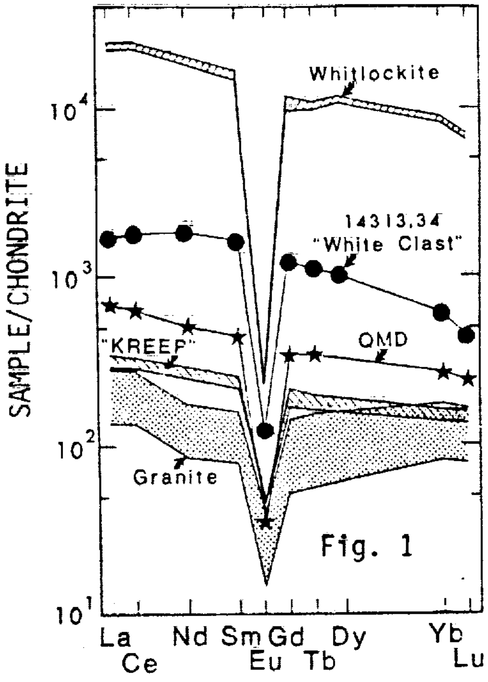

Fig. 1

The urKREEP hypothesis does not adequately explain several KREEP-related phenomena. For example, the large KREEP quantities (50-90%) that are essential in the trace element modelling of soils, breccias, and olivine vitrophyres, facilitates the need for hypothetical "high-Mg" components, (e.g., "primary matter" [9,10]; "SCCRV" [11]; "MAF": [12,13]; "MAF-14" [14]), in order to generate the observed MG#'s. Yet these "high-Mg" compositions have not been observed in the lunar sample returns.

The existence of "super-KREEPy" rocks (Fig. 1) is also difficult to explain with the KREEP composition defined above. REE abundances of "KREEP" (Fig. 1) are below that of the Apollo 15 quartz monzodiorite [15,16] and the "white clast" 14313,34 [17,18]. It has been demonstrated that these two rock types cannot be generated from the idealized KREEP composition by fractional crystallization or silicate liquid immiscibility [16,19].

It must be emphasized that in reality, KREEP is a chemical signature, not a specific rock-type. This KREEP signature is seen in KREEP basalts, where an inverse correlation between MG# and incompatible element concentration exists [18], the opposite of what is expected. Warren and Wasson [1], Ryder [20], and Warren [21] concluded that this dichotomy in KREEP basalts is due to the incorporation of a possible urKREEP component into the basaltic melt during magma petrogenesis. This highlights the problem of identifying a pure, pristine KREEP composition. In order to reduce the effects of contamination, we have attempted to identify possible KREEP components. These must contain high abundances of K, REE, and P, as well as other incompatible elements.

Identification of KREEP Components

Lunar granite contains the highest K concentrations of any rock returned from the Moon, and is considered to be a product of silicate liquid immiscibility or SLI (e.g., [22-25]). SLI tends to fractionate K (which is preferentially partitioned into the acidic melt) from the REE and P (which are preferentially partitioned into the basic melt [23,26,27]). Therefore, if granite represents the K in KREEP, the KREEP signature can be split by SLI into a **K-Fraction** (acid immiscible melt) and a **REEP-Fraction** (basic immiscible melt). However, another KREEPy component, enriched in the REE and P, is required. A likely candidate for this component is not a rock type, but a mineral. As reported by Shervais et al. [28] and Lindstrom et al. [29], highly evolved phosphates (whitlockite and apatite) are present in primitive Mg-rich highland lithologies. These phosphates (Fig. 1) are highly enriched in the REE - >10,000 times chondrite [30].

A Model for urKREEP Evolution

One of the significant implications of our model is that there is no distinction between "KREEP" and "urKREEP". In the following discussion, the terms are synonymous. The model proposed for KREEP petrogenesis involves the residual magma from the LMO undergoing SLI. We consider that urKREEP represents the composition of the residual LMO fractionate just prior to the onset of SLI. Although urKREEP formation was extensive [1], SLI was more localized in extent. Extensive separation of immiscible liquids will only take place at depth [25], which may be at the base of the ferroan anorthositic lunar crust (Fig. 2). We envisage that urKREEP was present as residual pockets in the LMO crystallate and locally underwent SLI. The granitic K-Fraction, although less dense than the ferrobasaltic REEP-Fraction, will not migrate far from the scene of SLI, because of its high viscosity (≅ 30000 poise; Table 1). However, it must be emphasized that most urKREEP does not undergo SLI. Evidence for this is that a "pre-SLI" KREEP composition is an important component required in HA basalt petrogenesis at the Apollo 14 site [31], and of Apollo 15 KREEP basalts [20].

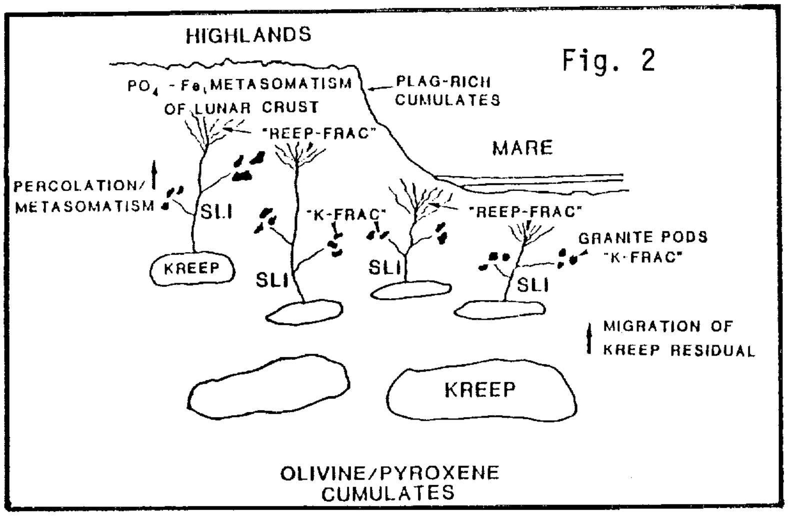
Fig. 2

As the viscous granitic melt cannot readily disseminate, the formation of significant granite pods can occur, as required for VHK basalt generation [32-34]. However, the ferrobasaltic "REEP" melt is less viscous (10-15 poise; Table 1) by over 3 orders of magnitude such that it is likely to separate from the granitic portion. The density of this Fe-rich melt is relatively high (≅ 3.3 g/cm^3) so it should readily separate from the granitic melt (≅ 2.7 g/cm^3) by gravity. However, after separation, it is the low viscosity of this water-like melt that will permit it to move independently of gravity, largely because of surface tension effects along grain boundaries. We suggest that portions of this melt migrated upward, promoting the metasomatism of the lunar crust by crystallizing the highly evolved phosphates noted by Lindstrom et al. (1984) and Shervais et al. (1984) in highlands lithologies.

From the calculated norms of ferrobasaltic immiscible liquids (Table 1), we should expect to find a "REEP" assemblage of apatite/whitlockite, ilmenite, feldspar, pyroxene, quartz, but dominated by fayalite. In the lunar highlands, we find predominantly apatite/whitlockite with minor plagioclase, which would appear to negate our SLI model. However, just because a magma undergoes SLI does not mean that crystallization ceases. It is perfectly feasible for this ferrobasaltic immiscible melt to undergo further crystallization. For example, comparison of mineral densities demonstrates that if fayalite (density = 4.14) crystallizes immediately after SLI, it will settle out from the residual liquid, promoted also by the melts' low viscosity. This will significantly reduce the density of the residual liquid, further promoting upward migration through, and metasomatism of the lunar crust by grain boundary percolation. Therefore, post-SLI fractionation can account for the phosphate-dominated lithologies observed in the lunar highlands.

Table 1: Compositions with calculated norms and viscosities of analyzed immiscible melt glasses from experiments (Hess et al., 1975) and lunar basalts (Weiblen and Roedder, 1973).

	EXPERIMENTAL		BASALTIC	
SiO_2	74.3	38.4	75.6	44.6
TiO_2	0.70	3.10	0.60	3.25
Al_2O_3	11.1	6.73	11.6	4.82
FeO	6.86	33.1	3.17	32.4
MgO	0.05	0.51	0.04	1.67
CaO	2.07	11.3	1.46	11.4
Na_2O	0.42	0.17	0.29	<0.03
K_2O	4.17	0.57	7.26	0.19
P_2O_5	0.22	4.76	0.10	1.50
TOTAL	99.89	98.64	100.12	99.83
Or	24.6	3.4	42.9	1.1
Ab	3.6	1.4	2.5	0.3
An	8.8	15.9	6.6	12.5
Ilm	1.3	5.9	1.1	6.2
Di	---	8.0	---	30.2
Fa	11.6	52.7	4.9	42.4
Phos	0.5	11.0	0.2	3.5
Qz	46.8	0.3	41.0	3.8
Cor	2.7	---	0.9	---
Viscosity (n)*	30,031	11	28,582	15

* calculations based upon the method of Bottinga and Weill (1972).

The above model does not conflict with isotopic evidence. The crystallization age determined for granite is 4.1 Ga [18], whereas measured KREEP ages are generally 3.9-4.1 Ga [e.g., 36]. However, KREEP model ages cluster around 4.3-4.4 Ga [37], and granite model ages range from 4.25-4.56. The discrepancy in measured and model ages is facilitated by the ability of the residuum from the magma ocean to remain liquid for at least 200 Ma after the bulk of the crystallization [38,39]. The similarity of model ages for KREEPy materials and granite may indicate a common source.

Another outcome of our hypothesis is that the REEP-Fraction may be synonymous to the "LKFM (Low Potassium Fra Mauro) basalt" which has been considered to be important in "KREEP" petrogenesis [40,41]. However, no evidence has been found to suggest that this is an igneous rock type [18-42]. The name LKFM basalt was originally given to one of the dominant glass compositions in highland soils [43-45]. Also, Apollo 16 and 17 breccias are close to this composition. An experimental study by [42], showed that LKFM "basalts" probably represent a cotectic melt, saturated with olivine and plagioclase. These authors considered that LKFM basalt is a fractionation product of the LMO, and it occurs as an intercumulus phase in the anorthositic crust. This conclusion is supported by our hypothesis. The REEP-Fraction by definition is "Low-K" and is ferrobasaltic in composition. This could well be the LKFM component found in the lunar highlands, but rather than being an intercumulus phase, we conclude that it is a metasomatic product.

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ELEMENTAL ABUNDANCES AROUND APOLLO 14 AND OTHER SELECTED LUNAR REGIONS FROM THE APOLLO GAMMA-RAY SPECTROMETER EXPERIMENT*;

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The orbital geochemical experiments that flew on Apollos 15 and 16 provide our best descriptions of the regional and global distributions of various elements on the Moon's surface. The Apollo Gamma-Ray Spectrometer (AGRS) and the X-Ray Fluorescence (XRF) experiments obtained data from which maps of thorium, potassium, iron, titanium, magnesium, and aluminum have been derived for the parts of the Moon overflown by these two Apollo missions (1,2). The elemental results from these orbital experiments have been reported in many publications. This paper briefly reviews these experiments and gives and discusses some of the results from the AGRS, mainly for regions around Apollo 14. The gamma-ray results for the naturally radioactive elements (Th, U, and K) have been our best indicators of the evolved lunar materials that concentrated these relatively rare elements, such as the KREEP found in high concentrations at Apollo 14 and granite.

The Ground Tracks and the Data Integration Regions. The Apollo 16 mission was in a nearly equatorial orbit that flew over the crater Fra Mauro and near the Apollo 14 landing site, so provided data on the distribution of elements in a narrow band on either side of Fra Mauro. The Apollo 15 mission had a ground track that went ≈30° north of Fra Mauro near the crater Archimedes, over parts of Mare Imbrium, and over the crater Aristarchus. Unfortunately, these two missions only provided gamma-ray data for ≈20% of the Moon, and there are large gaps in the data base for the regions where KREEP could be present, especially north and south of Fra Mauro. The XRF experiment required solar X rays as the fluorescence source and only measured Mg/Si and Al/Si ratios for about half of the two ground tracks. The Apollo 16 XRF experiment obtained only poor-quality data west of Fra Mauro (2) due to low sun angle.

The XRF experiment with its collimators and high count rates produced results with fairly high spatial resolution (~100 km), but the AGRS results have much poorer spatial resolution because the spectrometer wasn't collimated and because considerable amounts of data (counting times of ~1000 seconds or more) were needed to obtain reasonably good results. Initial elemental results for the AGRS were reported for various longitudinal bins along the two ground tracks (3,4), but such an approach often combined different kinds of regions, such as highlands just south or north of a mare. Therefore, more detailed outlines were used to define regions that combined many adjacent 1° × 1° units into a fairly homogeneous region such that the amount of γ-ray data was adequate for elemental analysis. These regions are defined in (5), with some minor revisions in (6), and have been used in many of the papers reporting orbital geochemical results.

The Orbital Geochemical Experiments. The Apollo geochemical experiments are described in detail elsewhere (1, 2, and references therein). The AGRS was a 7×7-cm NaI(Tl) scintillator crystal connected to associated electronics and a 512-channel analyzer. The energy of a gamma ray indicates the element from which it was produced (7,8). As a NaI(Tl) spectrometer has poor energy resolution (unlike the germanium detectors planned for future planetary missions), considerable efforts were involved in getting elemental results from the Apollo gamma-ray data. Initial processing of the AGRS data concentrated on unfolding most of the 512 channels per spectrum using response functions for the γ rays from various elements. Initial results for Th, K, Fe, Mg, and Ti are given in (3), and the last set of spectral-unfolding results, for Th, K, Fe, and Mg, are published in (4).

To get better spatial resolution, another approach was used where count rates were integrated over various groups of energy channels. This approach was used for the initial maps of natural radioactivity (e.g., 9) as these elements emit most of their γ rays with energies of 0.55 to 2.75 MeV. Such maps showed that regions of high radioactivity were fairly localized on the Moon and firmly established that KREEP was not a major component of the highlands (9). An improved version of the radioactivity map was published in color (10). This same energy band was used by (5) to get thorium abundances for the lunar regions mentioned above. Other energy bands have been used to map iron from its high-energy neutron-capture (6,10,11) and low-energy neutron-inelastic-scatter (12) γ rays, titanium (11,13), and potassium (14). The Fe and Th results from (10) are in a color map, the rest of these papers give elemental abundances determined for a few (6,14) or most (11–13) of the lunar regions defined by (5). The count rates used to map thorium (and uranium) were high enough that the data could be "deconvoluted" to get better spatial resolution for the distribution of these radioactive elements on the lunar surface (15). Maps with such improved spatial resolution for thorium have been published for Mare Smythii (15), the Apenninus region (16), Mare Imbrium, Aristarchus, and adjacent regions (17), and the central highlands (18).

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Selected Results from the Apollo Gamma-Ray Experiment. Table 1 gives the elemental abundances of Th, K, Fe, Ti, and Mg determined for regions along the Apollo 16 ground track on either side of Fra Mauro and for selected Apollo 15 regions. Data sources are indicated. Agreements with abundances determined by others for these regions are generally good for Th (4,5), Ti (11,13), and Fe (4,6,11,12). The Mg results (4) are in good agreement with the XRF values of (19). The largest difference between two sets of analyses of the AGRS data is for potassium, where the results of (14) are consistently lower that those of (4). The biggest differences are for regions of low K, such as highlands (e.g., regions 12A and 12D in Table 1). Comparisons with lunar-soil analyses (e.g., 20) are in better agreement with the K abundances of (14) than those in (4). Other studies using the orbital geochemical data give results that are consistent with lunar sample results (e.g., 21–24), and there are no indications that the orbital elemental abundances, such as those summarized in Table 1, are seriously in error. The uncertainties of these elemental abundances determined from the orbital data are typically ~20% (higher for the lowest concentrations), but this range of uncertainties is adequate for most lunar investigations.

Discussion. Only a few of the regions overflown by the orbital geochemical experiments on Apollos 15 and 16 have elemental abundances characteristic of KREEP or other lunar materials that have evolved with high contents of Th, U, or K. The regions of highest radioactivity are, besides Fra Mauro, around the Imbrium basin, such as near the craters Archimedes and Aristarchus. There are no signs of such materials elsewhere on the Moon, although a region of enhanced radioactivity was observed on the lunar far side near the crater Van de Graaff (3,4,9,25). Van de Graaff and nearby highland regions also have unique results from the Apollo 15 laser altimeter and magnetometers (25). The nature of the material near Van de Graaff is unknown, but the elemental concentrations (cf., Table 1) are similar to those in a mixture of mare basalts and far-side highland material. There is a topographic low mainly south of Van de Graaff (the "big backside basin"), which could have a unique chemical composition (3,4). However, until more of this region is covered by orbital geochemical experiments, the presence of unusual, evolved materials there is just speculation.

The thorium concentrations for the large regions given in Table 1 are not very high, being $\lesssim$8 ppm. However, Metzger and co-workers have shown with their deconvolution techniques that there are "hot spots" of thorium in each of these regions, centered at large craters. A 4° × 4° (≈120-km×120-km) unit centered on Aristarchus has 18–22 ppm thorium (17), a region about 5° × 5° in dimension south of and including Archimedes has 15–20 ppm Th (16,17), and the crater Davy east of Fra Mauro has 16–22 ppm Th (18). These thorium concentrations approach those (22 ppm) determined by Warren (26) for average high-K KREEP, showing that several lunar regions with dimensions of ~100 km are highly enriched in KREEP (or some other highly radioactive component). The next "warmest" spots for thorium have ~10-ppm Th and are located at smaller craters, in the mare west of Davy (and southeast of Fra Mauro), and on the Apennine Bench south of Archimedes. The regions south and west of Fra Mauro have not been deconvoluted for thorium. Concentrations for other elements have not been deconvoluted. For the three hottest regions in Table 1 (Fra Mauro, Aristarchus, and Archimedes), potassium is also very high (≈2200–3000 ppm), iron is fairly high (≈7–11 %), but titanium and magnesium are quite variable (≈0–3 %) and (≈3–7 %). The large variability for titanium could reflect the presence of other materials around or mixed into these regions, such as high-titanium mare basalts near Aristarchus.

Another region with unusual results from the AGRS is Ptolemaeus, which has an iron abundance as determined from the inelastic-scatter γ ray that is considerably higher than that from neutron-capture γ rays (12). The presence of elements with high neutron-absorption cross sections (such as iron, titanium, gadolinium, or samarium) in the lunar surface could cause such a "flux-depression" effect for thermal neutrons (8,27). As Th, Fe, and Ti are not unusually high, one is tempted to ascribe the flux depression to the presence of large amounts of REE, but other possible explanations (such as undetermined interferences) have not and need to be eliminated. Similar flux depressions were also seen for Ptolemaeus and several other regions by (3). However, the quality of the NaI(Tl) data from the AGRS is not good enough to allow us to use such indirect methods of geochemical mapping. With future instrumentation for planetary γ-ray and neutron spectrometers, it should be possible to use such indirect techniques (28).

The results of the AGRS show that the regions of high radioactivity around Fra Mauro are fairly limited in extent, with the highest radioactivities being near and somewhat east (the Lalande-Davy region) of Fra Mauro. Further east, highland-like material dominates, although some radioactive material is mixed into the western parts of the central highlands. To the west, mare basalts with relatively high titanium dominate in Oceanus Procellarum, with typical lunar highland materials present west of Oceanus Procellarum. The standard interpretation of the orbital results is that the highly radioactive material (most likely KREEP, because of its presence in returned samples from other Apollo landing sites) is somehow related to the formation of the Imbrium basin (and possibly other basins near Imbrium now covered by Oceanus Procellarum) and that the later emplacement of mare basalts left large amounts of KREEP present only on higher lunar features not flooded by mare basalts, such as Fra Mauro, Aristarchus, and Archimedes.

Table 1. Elemental abundances determined from the Apollo Gamma-Ray Spectrometer data for regions along the Apollo 16 ground track on either side of Fra Mauro and for some selected lunar regions along the Apollo 15 ground track. (Order of regions is usually from west to east.)

Region[a]	Latitude[a]	Th (ppm)[a]	K (ppm)[b]	Fe (%)[c]	Ti (%)[d]	Mg (%)[b]
Apollo 16 ground track around Fra Mauro						
High. Far West No. (12D)	120–180°W	0.37±0.09	630	3.9±1.0	1.0±0.4	2.7
"			(340±110)			
High. West Limb (11B)	78–120°W	0.38±0.09	660	4.3±1.0	0.2±0.4	2.9
"			(510±120)			
Oceanus Proc. South (9B)	30–64°W	4.1±0.4	1900	10.4±0.9	1.8±0.4	6.8
"			(1710±150)			
Oceanus Proc. South (9J)	50–62°W	3.3±0.3	–	11.2±1.5	1.1±0.6	–
Oceanus Proc. South (9K)	40–50°W	4.0±0.4	–	11.0±1.5	2.2±0.5	–
Oceanus Proc. South (9G)	30–40°W	4.8±0.4	–	10.8±1.3	1.8±0.5	–
Mare Cognitum (1)	20–28°W	6.1±0.5	2600	11.6±1.4	0.5±0.6	5.3
Fra Mauro, Total (24A)	5–20°W	8.0±0.6	3100	7.7±1.0	1.5±0.4	7.0
"			(2680±200)			
Fra Mauro, Limited (24C)	14–20°W	8.2±0.6	–	8.1±1.5	1.6±0.7	–
Lalande–Davy (24B)	8–14°W	8.4±0.6	3100	7.2±1.5	1.8±0.6	6.9
Ptolemaeus (32)	4°W–1°E	4.8±0.4	2600	4.5±1.5	0.5±0.6	6.8
"			(2210±250)			
Albategnius ejecta (41)	0–8°E	3.5±0.3	–	6.1±1.6	0.4±0.7	–
Andel (19)	6–12°E	2.7±0.2	1400	5.7±1.5	0.1±0.6	5.5
Descartes (23)	12–22°E	1.89±0.19	1200	4.4±1.3	0.7±0.5	5.3
"			(910±160)			
Theoplilus ejecta (33A)	22–30°E	2.1±0.2	880	6.5±1.3	1.7±0.6	3.5
Selected regions along Apollo 15 ground track						
Van de Graaff (35A)	162°E–166°W	2.4±0.2	1500	7.7±1.1	0.2±0.5	4.8
"			(880±160)			
High. Far West So. (12A)	120–166°W	0.48±0.09	620	5.6±0.9	0.6±0.4	4.6
"			(200±150)			
Oceanus Proc. North (9A)	50–78°W	3.6±0.3	1800	13.4±1.1	2.4±0.5	2.7
"			(1470±200)			
Aristarchus (22A)	42–54°W	6.9±0.6	2600	10.6±1.2	2.6±0.5	6.4
M. Imbrium (4A)	9–33°W	5.4±0.4	1900	13.6±1.0	2.0±0.4	4.9
"			(1700±190)			
Archimedes (21)	8°W–2°E	6.7±0.5	3400	10.6±1.7	0.5±0.6	3.6
Apennines (20)	≈4°W–6°E	4.6±0.4	–	9.0±1.7	0.8±0.7	–
M. Serenitatis (5A)	≈9–29°E	2.1±0.2	1300	13.4±1.2	2.3±0.5	4.8
"			(1100±190)			
M. Tranquillitatis (7A)	≈18–45°E	1.99±0.17	1100	10.6±1.1	2.9±0.5	4.9
"			(1030±200)			

[a] Name, region number, latitude, and thorium abundance from (5).

[b] Mg and K by (4). The K abundances on the following line in ( ) by (14) are lower, especially in low-K regions, and are probably better values (20). Mg abundances are generally in fairly good agreement with XRF values of (19)

[c] Iron from neutron-capture γ rays by (11). Generally these values are in good agreement with iron abundances by (4), (6), and (12).

[d] Titanium by (13), which are similar to Ti abundances by (11).

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Understanding Lunar Mantle Metasomatism: The Terrestrial Mantle Analogy.

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Mantle differentiation and partial melting were important processes during the initial 1.5 Ga of lunar evolution. Similar processes are recognized on Earth, and it appears probable that the lunar lithosphere experienced some of the more subtle chemical variations eg. metasomatism, inferred for the terrestrial mantle. We describe present understanding of terrestrial mantle metasomatism, discuss those aspects that may be applicable to the lunar mantle and the consequences of metasomatism for the evolution of lunar partial melts.

The paradigm of a terrestrial mantle simply composed of olivine (dominant), clinopyroxene, orthopyroxene and either plagioclase, spinel or garnet (depending upon pressure) fails to satisfactorily explain the lack of correlation between the isotopic and lithophile trace element characteristics of primitive basaltic magmas. This behaviour requires decoupling of trace elements as a consequence of mantle metasomatism, although more fundamental mantle differentiation processes may also have contributed (1).

The characteristics of metasomatism can vary widely, but two main types have been recognized (2,3,4):

1. A subtle geochemical signature sometimes called "cryptic" metasomatism in which apparently barren (from a major element viewpoint) peridotites are enriched in incompatible elements without any visible alteration to the rock.

2. A microscopic signature called "patent" or "modal" metasomatism in which incompatible element enrichments are reflected in the presence of occasional to common grains of unusual minerals such as amphibole, mica, calcite, sulfide.

Reconciling these types has proven difficult (5) and although the ad hoc concept of mantle metasomatism has been established the relations between various metasomatic signatures, their relative importance and mantle extent have not been determined. Insights provided by detailed petrochemical studies of composite metasomites (6,7) suggest that many observations that have been used as evidence for various metasomatic "styles" (enrichment in LREE of cpx with compositions that are high in Cr relative to Al and correlation of high LREE/HREE with lower CaO in bulk samples) occur in one sample and can be accomodated in a single model for mantle metasomatism. An important observation is that the operation of metasomatism rapidly enriches the host and depletes the fluid in incompatible trace elements (LREE, K, Ti, Rb) together with Fe. Thus, excepting very large "fluid"/rock ratios, a single mantle metasomatic event must be a relatively local phenomenon and not mantle-wide, and enrichment of large mantle segments must involve multiple stages of igneous activity

Proposed terrestrial metasomatizing mechanisms that require large scale mantle convection (recycling of continental crust; injections of slab-derived melts) are untenable on the Moon given the early thermal history (8). Mechanisms involving permeation of an aqueous fluid are not viable in a dehydrated Moon although a carbonated fluid would be permitted. However, based upon detailed studies of composite xenoliths we conclude that the Earth's upper mantle is a complex of peridotite and basic igneous intrusions (in toto, the term pyrolite would be appropriate !) and that **magmatism** is the principal cause of enrichment of the lithospheric mantle. Given that the lunar mantle was thermally capable of delivering magma to the surface for at least 1.5 Ga we conclude that magmatic enrichment of the lunar lithosphere to be an inevitable consequence.

The concept of a lunar magma ocean and its subsequent cooling implies the development of a mineralogically layered mantle and a complimentary salic crust. Recent studies (9) have questions the evidence for a planet-wide magma ocean and the evidence for a layered lunar mantle has never been particularly compelling. The possibility exists that the lunar mantle is a relatively uniform olivine pyroxenite, parts of which have been enriched in Fe and Ti through metasomatism associated with repeated pulses of magmatism. This plum pudding structure could then provide the spectrum of major element compositions observed in most mare basalts whilst meeting the constraints provided by high pressure experiments which require an olivine-pyroxene source for both high and low titanium mare basalts (10). Such mantle complications might also add a measure of ambiguity to the role of ACF processes (numerically precise but mechanistically obscure) in the evolution of KREEP, VHA and HA basalts (11,12).

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THE ABSENCE OF A HEAVY EARLY LUNAR BOMBARDMENT, THE PRESENCE OF A 3.85 GA CATACLYSM, AND THE GEOLOGICAL CONTEXT OF APOLLO 14 ROCK SAMPLES.

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Jack. Yes, but you said yourself that a severe chill was not hereditary.
Algernon. It usen't to be, I know- but I daresay it is now. Science is always making wonderful improvements in things.
Jack [picking up a muffin dish]. Oh, that is nonsense; you are always talking nonsense.
(Oscar Wilde: The Importance of Being Earnest. 1895)

The vogue that the ~3.85 Ga lunar highland rock ages represent the sharp termination of a continuous bombardment, and not an intense spike, actually rests on no hard evidence derived from the Moon. Rather, the postulation of a declining heavy bombardment, a lingering accretion, is the scion of models of planetary accretion and of philosophies favoring uniform change. However, the heavy bombardment is undoubted by workers in many disciplines [1-7], is a cornerstone for understanding of the inner solar system, and is supposed to have had dramatic effects even on the earliest endogenous evolution of the Moon [e.g 6,8]. The entirely separate concept of a superposed late intense "terminal lunar cataclysm", cogently advocated by Tera et al. [9] and once popular, has been disparaged and fallen into almost universal disfavor [1-7].

The purpose of the present abstract is to argue that

1) there was no heavy bombardment of the Moon after about 4.4 Ga ago; accretion was rapid and did not linger, and then much endogenous activity went on with little external disturbance.
2) there was a late (~3.85 Ga) cataclysmic bombardment of the Moon that had severe effects for both exogenous and endogenous processes.
3) the majority of the impacting in the entire 4.4-3.85 Ga period for the Moon was confined to the Earth-Moon system and cannot be extrapolated to any other body in the solar system.
4) the Apollo 14 samples both assist in constructing this revised evolution of the Moon, and must be considered in the light of a revised geological history.

My approach is to show the weakness of the case for an old heavy bombardment, and the strength of the case for a Moonwide set of large and small impact events at ~3.85 Ga. The theme uses new and old sample data, and several ideas at least mentioned by other workers. The predictions of a heavy bombardment are not fulfilled by the realities of lunar sample characteristics. I concentrate on the accretion of the Moon, the absence of old impact melts, the presence of old mare basalts, and the absence of a well-mixed crust at 3.85 Ga. I consider the evidence for a cataclysm, its possible cause, and its significance for the Apollo 14 samples.

1. Lunar accretion:

Models for the bombardment history were created ten years ago [e.g. 4] and have not yet changed in response to the "new" (giant impact splash to produce orbiting disk) model for the origin of the Moon; hence they have become strangely independent of the accretion of the Moon. One cannot assume that accretion from a disk splashed into earth orbit would follow a course similar to accretion from the heliocentric swarm that created the Earth. The Moon also accreted then somewhat later than the Earth when much of the swarm had disappeared; the FINAL stages of growth are dominated by large planetesimals [4,5]. Two probable consequences of the "new" lunar origin concept are: 1) that the Moon accreted much faster than in previous heliocentric swarm models (consistent with its early differentiation) since material was closer together at the start, and 2) that the Moon accreted with others in different orbits (referred to again below).

Even Wetherill [4], advocating a continuous bombardment, noted that the lunar basin-forming population had a remarkable size distribution (dominated by large bodies); to keep such material available for impact at ~3.85 Ga required storing in Mars-crossing orbits. He found the best explanation for Orientale, Imbrium, and possibly Serenitatis to be Roche limit break up of a single large heliocentric planetesimal; i.e. some ad hoc events in the natural heliocentric accretion models are required. (Whether what [4] was talking about constitutes a cataclysm is partly semantic; if other basins were to be included it certainly would be a cataclysm). Taking into account the "new" origin of the Moon, other possibilities develop (below).

An inspection of estimated cratering rates e.g.[1] indicates that an extrapolation of the rates at ~3.85 back to 4.5 Ga would build a Moon many times larger than the Moon actually is.

2. Absence of impact melts older than 3.85 Ga:

Only the radiometric age of an impact melt can safely be said to date an impact event. I can find no conclusive evidence for a single sample of impact melt older than 3.85 Ga among the analyzed Apollo or Luna samples or the lunar meteorites. There is only one group of impact melts for which an older age has been claimed: [10] obtained Ar-Ar data for some very feldspathic Apollo 16 particles which they claimed gave plateau ages consistently of ~4.15 Ga. However, nearly all the samples give rather poor plateaus, with considerably lower, non-plateau characteristics for much of the release suggesting events somewhat younger, ~3.8-3.9 Ga. Given the fine grain-size of the melt and clasts, the abundance of the clasts, and the very low K/Ca of the material giving the apparent old ages, these ages (as admitted by [10]) are almost certainly dating plagioclases, not the melt. Some other samples of the same group give good ~3.85 Ga plateaus, and a coarse-grained equivalent gave an excellent Rb-Sr isochron of 3.81 Ga [7].

Lange and Ahrens [11], concluded that the amount of impact melt present among lunar samples could be explained by a continuous bombardment, but that the number of samples with old ages was too small to be so consistent. They advocated a much higher flux at 4.0 Ga than had been postulated by "continuous bombarders" e.g. [12]. The problem is even worse, for two reasons: none of the samples with old ages (>4.0 Ga) that [11] used are impact melts, and the amount of melt they claim to exist in the lunar highlands (30%) is too high by a factor of 2 or 3, because of biases in the collected populations (see e.g. [13]. If there had been a heavy bombardment, there would be both more melt and older melt among the samples. The absence of older melt could be explained by a "stonewall" effect (Hartmann [14]), but then there would be even more (young) impact melt among the samples. The existence of mare basalts (below) demonstrates that there is not a 4.0 Ga "stonewall" effect, and that if old impact melts had been produced, they would be among the sample collection. None have yet been identified. For instance, the Apollo 14 landing site was affected by several pre-Nectarian events that should have left an imprint, but among the Apollo 14 impact melts, none is older than 3.85 Ga; I conclude that none of these pre-Nectarian events is older than 3.85 Ga either.

The highlands rocks do show evidence of ages older than 3.85 Ga, but in only a few cases do these demonstrate that impacts took place; most of the ages are for pristine (if brecciated) old rocks, for which the age of brecciation is not known and could easily be 4.0 Ga. Most granulites for instance also give ages of ~3.85 Ga; a real exception appears to be sample 78155, which has a good Ar-Ar plateau age of ~4.2 Ga. The older ages for impact produced rocks indicate some impacting prior to 3.9 Ga, but do not provide any evidence for a heavy bombardment.

3. The presence of mare basalts older than 3.85 Ga:

Mare basalts with ages older than 3.85 Ga and up to 4.33 Ga have been discovered in Apollo 14 breccias [15-18]. Their preservation is an important factor: [19] used the absence of such basalts to support the concept of a "stonewall" effect at ~3.9 Ga (following [14]), especially as mare basalts would be most susceptible to destruction. This stonewall is clearly not real. Indeed, the characteristics suggest that from 4.3 to 3.9 Ga somewhere near the Apollo 14 site a huge tract of fairly undisturbed surface existed: sample 14321 contains a range of basalts fragments with fairly regularly varied ages (up to 4.3 Ga) and chemistry i.e. they are not an entirely random collection. The effect of a heavy bombardment would have been to disperse mare basalts, not concentrate them in a breccia. This might be coincidence if it were not for the presence of many more old mare basalts among other Apollo 14 breccias and soil particles. I conclude that a terrain which had existed with little modification from 4.3 Ga was modified by the pre-Nectarian (but still 3.85 Ga) events; yet while the flows were seriously broken up at 3.85 Ga, the mare fragments were neither widely dispersed nor totally buried.

4. Absence of a well-mixed crust at 3.8 Ga:

A heavy bombardment would have tended to homogenize the crust, but at least over large areas the crust was not well-mixed, laterally or vertically, at 3.8 Ga. Orbital geochemical data shows quite small-scale variations. Pure anorthosite terrains existed in the uppermost crust, as shown by the Apollo 16 dimict breccias and other "genomict" anorthosites. Basins at ~3.85 Ga excavated ungardened material, such as norites and troctolites, and not material which had been mixed by impact [20]. One argument of [9] for a cataclysm was the great range of Pb compositions that were present at 3.85 Ga, rather than a fairly uniform, well-mixed crust. The Imbrium basin probably induced KREEP volcanism [21], yet KREEP volcanism had not happened in the region ever before, as far as we can tell. In fact the arrival of KREEP at the surface, by both volcanic (impact-induced) and impact processes is confined to very close to 3.85 Ga wherever we have information. The siderophile abundances in both rocks and soils show considerable variations showing a lack of mixing and that late (~3.85 Ga) additions could have a strong influence; the lunar meteorites have demonstrated this point, by showing how abnormal some of the Apollo 16 material is [22]. The sum of the data demonstrate that just after the completion of the bombardment the crust retained both regional and small-scale heterogeneities, inconsistent with the mixing expected of a heavy bombardment; if it was well-mixed at 4.0 Ga, then the 3.85 Ga events (both exogenic and endogenic) added the variations.

5. A cataclysm:

The highlands show abundant evidence of severe impacting and isotopic resetting at ~3.85 Ga. There have been attempts to explain these ages as dominated by a few basin-forming events, in particular Imbrium, partly because all sampling sites have some Imbrium morphological influence. However, the bulk of ejecta from an impact is cold, and only a small portion has its radiogenic isotopes reset. These attempts also ignore the wide range of variation of isotopic and chemical compositions of the reset samples (or contend that a basin event produces a wide variety of impact melt products), and the geological context of the samples. For example, the dimict breccias at A16, if Imbrium material, require that the anorthosites into which they are intruded were also ejected by Imbrium. However, a more local origin for these anorthosites is suggested by the regional chemistry and by the fact that the sampled Apennine Front, surely partly Imbrium ejecta, has little anorthositic component. The 6 lunar meteorites, which apparently represent at least three distinct ejection events, show the same ages of ~3.85 Ga, showing that this age is not an Imbrium artifact but is moonwide; it is improbable that all of these meteorites sample areas near Imbrium-affected areas.

The basins with reasonably defined ages i.e. Orientale, Imbrium, Serenitatis, and Nectaris, all formed within a short period between 3.8 and 3.9 Ga. I know of no evidence which demonstrates that they could not have formed within a few days of each other. But the absence of older ages at the Apollo 14 site, which should show the effects of some of the oldest pre-Nectarian craters (e.g. Insularum, Nubium) suggests that these older craters were also formed within this short time span. It appears that a moonwide range of both small and large (including basin) impacts occurred at 3.8-3.9 Ga. This intense activity induced endogenic activity from the crust (A15 and A17 KREEP basalts) and excavated KREEP in the form of Low-K Fra Mauro to the surface, which had also not happened before. The production of mare basalts, from much deeper sources, was not noticeably affected by this impacting.

6. A possible cause of a cataclysm:

Meteorites do not show evidence of any terminal decline or peak of collisional intensity at the 3.9 Ga "horizon" shown by lunar highland samples. Thus an explanation for their protection is required for models which extrapolate the lunar history to the rest of the inner solar system. Wetherill [4] noted the unusual size distribution of the lunar basin-forming population, requiring some adjustments to a uniform heliocentric wipe-up. Both these factors suggest to me that the cataclysm may be instead confined to the Earth-Moon system. With the "new" model for lunar origin, it is at least possible to suggest that the accretion of a geocentric disk produced several moons (of which the present may have been the largest). The orbits of two others may have gradually closed until a collision at 3.85 Ga created a cataclysm in the Earth-Moon system, with profound effects on the Moon and the Earth. The impacting would not have affected Venus, Mercury, or Mars, and their intense cratering (accretionary) history may have terminated much earlier, or have their own local histories.

7. Apollo 14 samples:

The Apollo 14 samples provide important information on the evolution of the Moon, particularly in its mare basalts and its impact melts. What little we know about the Apollo 12 highlands suggests its similarity with the Apollo 14 site. Photogeology indicates a complex set of events including pre-Nectarian affecting the site, and whose products should be included in the samples collected. These include impact melts from pre-Nectarian events; no impact melt older than 3.85 Ga has been dated, although a range of (mainly KREEP-rich) compositions exists. More work needs to be done to better establish the range of compositions (from coarse-fines and rocks), including trace siderophile elements, and to establish their ages. The mare basalts are critical by their presence, since a heavy bombardment history should have dispersed them, and by their character they are important for understanding internal processes. It is most unlikely that much of the A14 material is Imbrium ejecta, as it differs so much from A15 highlands material, and it more likely represents material from local plains which had existed perhaps a short way to the north, prior to the cataclysmic events. Mare volcanism may have continued after the Imbrium event in the Apollo 14 general area, but into the nearby basins formed during the cataclysm (Nubium, Riphaeus, Insularum, etc) and been buried.

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LUNAR CRUSTAL STRENGTH AND THE LARGE BASIN-KREEP CONNECTION

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The interpretive evolution of the Moon as a planet can be divided into seven major stages beginning sometime near the end of the formation of the solar system (1). These stages and their approximate durations in time are as follows:

1. The Beginning - 4.6 billion years ago.
2. The Melted Shell - 4.5-4.4 billion years ago.
3. The Cratered Highlands - 4.4-4.2 billion years ago.
4. The Large Basins - 4.2-3.9 billion years ago.
5. The Light-colored Plains - 3.9-3.8 billion years ago.
6. The Basaltic Maria - 3.8-3.0(?) billion years ago to the present.

Qualitative comparison of the relatively old and relatively young large circular basins on the moon suggests that the strengthening of the lunar crust occurred during the formation of these basins. The younger basins (Nectarian and Imbrium Systems) are sharply circular and are underlain by mass concentrations (mascons) surrounded by mass deficiencies under raised mountain rims several thousand meters high. The older basins (Pre-Nectarian System) are only irregularly circular with relatively low rims and are fully compensated isostatically (2).

These differences strongly suggest that in the midst of large basin formation about 4.2 billion years ago, a major change occurred in the strength of the lunar crust. A working hypothesis to explain this change includes the following elements:

1. Prior to the beginning of the Large Basin stage of lunar evolution, uncrystallized KREEP-like liquid existed below the 60-70 km thick anorthositic crust. This residual liquid from the Melted Shell stage would probably remained uncrystallized due to the concentration of radiogenic heat within it and the unusually insulating properties of the battered upper crust underlying the cratered highlands.

2. As the Pre-Nectarian large basins formed, the underlying KREEP-like liquid and the pervasively fractured crust permitted the rapid isostatic adjustment of the lunar crust to mass concentrations and deficiencies.

3. Also after the first large basins formed over much of the moon's surface, the relatively low density KREEP-like liquid moved upward into the now deeply and closely fractured crust beneath and around the Pre-Nectarian large basins.

4. After moving upward into the cooler upper crust and becoming significantly contaminated with crustal debris in the process, the KREEP-like liquid crystallized and formed interlocking networks of dikes. Once solidified, these interlocking dikes, combined with the removal of underlying KREEP-like liquid, strengthened the crust so that the mass concentrations and deficiencies produced by Nectarian and Imbrium age large basin events could not be fully compensated.

5. After the deeper of the older large basins formed about 4.2 billion years ago, KREEP-like magmas, contaminated with anorthositic crustal materials, may have reached the floor of these basins. Later redistribution may account for the observed distribution and ages of the spectrum of KREEP basalts and related materials (3).

6. After the KREEP-like material had entered the lower regions of the upper crust, the initial crustal excavation of the Imbrium Basin was apparently deep enough to excavate dike material and distribute it to where sampling and geochemical remote sensing (4) find it today.

This KREEP dike network hypothesis appears to explain the change in crustal strength during the Large Basin stage of lunar evolution as well as several puzzling aspects of the distribution and ages of KREEP related materials.

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AN ION MICROPROBE STUDY OF TRACE ELEMENTS IN APOLLO 14 "VOLCANIC" GLASS BEADS AND COMPARISONS TO MARE BASALTS; C.K. Shearer[1], J.J. Papike[1], S.B. Simon[1], N. Shimizu[2], H. Yurimoto[3], and S. Sueno[3]: 1) Inst. for the Study of Mineral Deposits, S.D. School of Mines & Tech., Rapid City, SD 57701; 2) Dept. of Earth, Atm. & Planetary Sciences, M.I.T., Cambridge, MA 02139; 3) Inst. of Geoscience, Univ. of Tsukuba, Ibaraki 305, Japan

Homogeneous, mafic lunar glasses are believed to be volcanic in origin [e.g. 1, 2, 3, 4]. The major element geochemistry of these glass beads indicates that unlike mare basalts which have undergone significant near-surface fractionation and possible crystal accumulation, the volcanic glasses are closer to liquid compositions and in many cases represent less fractionated magmas [4]. The petrogenetic relations between mare basalts and picritic volcanic glasses is enigmatic. Longhi [5] demonstrated that most mare basalts are not derived by simple low pressure fractionation from parental melts with compositions of picritic glasses as tabulated by Delano [4]. However, Hughes et al. [6], using trace element data, presented several petrologic scenarios illustrating the connection between mare basalts and picritic glasses. Trace element evaluation of the petrogenetic connection between mare basalts and the picritic volcanic glasses is difficult due to the rarity and small size of individual glass beads (less than 100 μm). Only in rare occurrences (A-15 green glass; A-17 orange glass) have trace element analyses of picritic glass beads been performed [e.g. 6, 7, 8, 9, 10, 11, 12]. With the introduction and advance of trace element microbeam technologies (e.g. secondary ion mass spectrometry, SIMS), the analysis of minute lunar glass beads (10 μm-100 μm) is possible [13], and is not restricted to glass types present in high concentrations. The purpose of this study is to focus upon the following aspects of a larger ongoing trace element study of lunar glass beads: the trace element characteristics of the picritic glass beads at the Apollo 14 landing site, their relation to mare basalts, and the nature of their source regions within the lunar mantle.

In this study, glass beads were identified and documented in selected polished thin sections of A-14 regolith breccias using an electron microprobe. This allowed us to differentiate volcanic from impact glasses [4] and to place the volcanic glasses within the chemical classification scheme as defined by Delano [4]. These chemically documented glass beads were then analyzed with Cameca IMS-3f ion microprobes operated by the MIT-Brown-Harvard Consortium (MBHC) and the University of Tsukuba (UT). The REE were analyzed at MBHC using moderate energy filtering to remove molecular ion interferences [14, 15] and with a 25 to 30 μm spatial resolution. Using well-defined INAA-analyzed REE abundances [16, 17, 18] in Apollo 15 green glass as a standard, and calculated α factors for each REE from the green glass, we were able to define calibration working curves for the lunar glasses. The trace elements analyzed at UT were obtained with a beam diameter of 10 to 30 μm and with more stringent energy filtering. Calibration working curves for Li, Sc, V, Co, Sr, Zr and Ba were defined using glass standards prepared at UT. Apollo 15 green glass was used to define calibration working curves for Zn, Rb, and Y. At both MBHC and UT, all concentrations were calculated from empirical relationships between intensity ratios against Si (as Ce/Si) and abundances in the standards. Using these calibration techniques Apollo 17 orange glass [74220] and Apollo 15 green glass [15426] were analyzed as secondary standards (Table 1).

REE patterns for the Apollo 14 picritic glasses analyzed in this study are illustrated on a plot of TiO_2 vs. MgO in Figure 1. Green B, Green A and VLT glasses are typically LREE enriched with Sm/Eu = 6-14. The total REE abundances of Green A and VLT overlap (Ce = 30 to 70 X chondrite) whereas the

REE abundances of the more MgO-rich Green B is substantially lower (Ce = 12 to 14 X chondrite). Zirconium (66-508 ppm) and Ba/Sr (>1.4) in these glasses are distinguishably different from low-Ti mare basalts at other sites. Their trace element signatures (REE, Zr, Ba/Sr) are similar to other basalts sampled at the Apollo 14 site [20, 21]. The high-Ti picritic glasses exhibit a flat to slightly positive LREE slope and a negative HREE slope. The orange glass has a higher total REE abundance (Ce = 85 to 120 X chondrite) and a slightly larger negative Eu anomaly (Sm/Eu = 4-7) than the black glass (Ce = 55 to 90 X chondrite; Sm/Eu = 3-5). Relative to Apollo 17 orange glass (74220), the Apollo 14 high Ti picritic glasses are enriched in REE, LREE/HREE, Y, V, Zr, Sr, Ba and Ba/Sr and are similar in the alkali elements (Li, Rb), Co and Sc.

Genetic linkages among the picritic glasses, between the picritic glasses and the aluminous basalts at the Apollo 14 site and between the picritic glasses and other mare basalts can be evaluated using the liquid line of descent and crystallization sequence constructed from Longhi [5], distribution coefficients in the literature and trace element characteristics of the Apollo 14 picritic glasses documented in this study. Liquid lines of descent suggest the black, orange, Green A and VLT-Green B are not related by low pressure crystallization processes. Modeling of the trace element abundances of basaltic liquids along the liquid lines of descent using the different picritic glasses indicates (1) calculated basaltic liquids derived from orange or black glasses have Sr, Ba, and REE concentrations considerably different from most high Ti basalts; (2) it is possible that either the GREEN A or VLT glass compositions may be derived by crystallization of olivine from a liquid of GREEN B glass composition; (3) Apollo 17 VLT basalts are not derived from liquids represented by Apollo 14 VLT glasses; (4) picritic volcanic glasses sampled at the Apollo 14 site are not related by low pressure crystallization processes to produce the Apollo 14 aluminous mare basalts; and (5) if the glasses sampled at the Apollo 14 site represent unmodified primary basaltic liquids, the basalts derived from these picritic parents have not been recognized.

Although the above modeling indicates low pressure crystallization processes do not petrogenetically link the different basaltic liquid compositions represented by the picritic glasses and basalts at the Apollo 14 site, many of the basaltic compositions share similar trace element signatures (e.g. Ba/Sr, Sm/Eu, REE enrichment, LREE enrichment). This suggests an intrinsic character of the crust-mantle at the Apollo 14 site that imparts this signature to many of the basalts produced. This signature has been attributed to the assimilation of a KREEP component [20, 21, 22] or partial melting of a hybrid mantle source with varying proportions of trapped or mixed evolved liquid [6, 20, 21]. These data indicate that these trace element signatures occur in some of the more "primitive" basalt compositions. In addition, substantial assimilation of KREEP (20-30%) necessary to modify the trace element chemistry of the picritic liquids to those observed in A-14 picritic basalts, would affect the major element characteristics of these basalts in a manner not observed.

As a possible alternative to a magmatic origin for these picritic glass beads, impact fusion-mixing of a picritic basalt component and a KREEP-rich regolith component may produce similar chemical characteristics. Delano [12] illustrated that KREEP-like element abundances in glass of a basaltic composition (A-15 yellow glass) could be produced by impact.

Table 1. Ion microprobe analyses of Apollo 15 green glass (15426) and Apollo 17 orange glass (74220). REE, Y, Rb and Zn were calculated using green glass as a standard.

	Green Glass	(s.d.)	Lit.	Ref.	Orange Glass	(s.d.)	Lit.	Ref.
Rb					.8	(.1)	1.1	18
Li	5.2	(.1)			11.1	(.8)	15	7
Sc	38.2	(.7)	43.0	16,17	57.9	(2.0)	47.4	6
V	145.7	(.8)	150	16,17	108.7	(4.9)	120	6
Co	80.8	(3.0)	72	16,17	79.5	(5.2)	61.7	6
Zn					270.1	(17.3)	253	7
Zr	14.4	(2.3)	22.0	16,17	194.6	(5.3)	185	18
Sr	27.3	(1.0)	28	18	193.2	(6.0)	200	9
Ba	14.7	(1.3)	17.0	16,17	70.6	(3.4)	76.4	18
Ce					22.8	*	19.0	18
Nd					18.9	*	17.8	18
Sm					6.8	*	6.53	18
Eu					1.89	*	1.80	18
Dy					8.6	*	9.40	18
Er					4.5	*	5.10	18
Yb					4.0	*	4.43	18
Y					42.5	(2.6)	43.8	19

*Additional data for statistical analysis in preparation.
s.d.: standard deviation
Lit.: Literature value

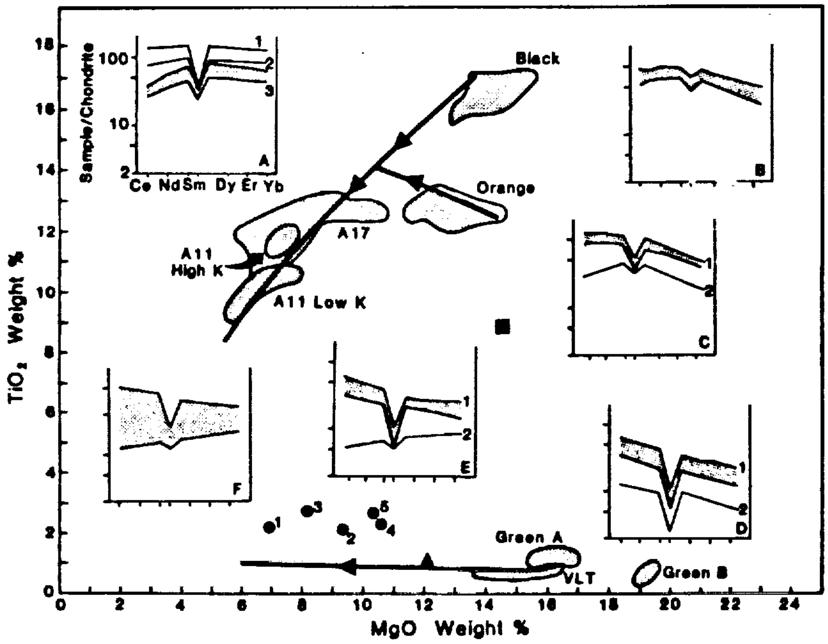

Figure 1. TiO_2 vs. MgO for Apollo 14 volcanic glasses, selected glass compositions from other landing sites, and selected mare basalt compositions. Superimposed on diagram are REE patterns for selected mare basalts and picritic glasses and liquid lines of descent (constructed from Longhi [5]) for low-Ti and high-Ti basaltic liquids. Black square: Apollo 17 orange glass (74220); Black triangle: Apollo 17 VLT [18]; Numbered black dots: Groups 1-5 of Apollo 14 aluminous mare basalts [20, 21]. Index to REE diagrams: A: High-Ti basalts; (1) Apollo 11 High-K, (2) Apollo 11 Low-K, (3) Apollo 17; B: Apollo 14 Black Glass; C: (1) Apollo 14 Orange Glass, (2) A-17 Orange Glass 74220; D: (1) A-14 Green A, (2) A-14 Green B; E: (1) Apollo 14 VLT glass, (2) Apollo 17 VLT mare basalt; F: Range in Apollo 14 aluminous mare basalts [21].

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HIGHLAND CRUST AT THE APOLLO 14 SITE: A REVIEW

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Recent petrologic studies of pristine nonmare samples from the Apollo 14 site have demonstrated the unique character of the western highlands crust. Many of the lithologies which occur here are not found at other highland sites or represent unique variations of more common lithologies. Rare highland samples found at the Apollo 12 site have petrologic and geochemical affinities with the Apollo 14 highland suite and the two sites taken together constitute what can be called the Western Highland Province. Rocks of the Western Highland Province are geochemically distinct from similar lithologies found at eastern highland sites (Apollo 15, Apollo 16, Apollo 17, and the Luna sites) -- a fact which adds further complications to current petrogenetic models for the lunar crust (e.g., [1]; [2]; [3]). Nonetheless, an understanding of how the Western Highlands Province formed and why it differs from highland crust in the east is crucial to our overall understanding of primordial lunar differentiation and petrogenesis.

OCCURRENCE: Highland plutonic rocks at the Apollo 14 site occur only as clasts in the crystalline-matrix Fra Mauro breccia (e.g., 14304, 14305, 14321) or in younger regolith breccias (e.g., 14312, 14318). Many of these clasts have rims of an older, dark breccia matrix attached, which shows that these rocks have been effected by at least two or three episodes of brecciation. Texturally the clasts vary from cataclasites with no surviving primary textures, to texturally pristine clasts with well preserved igneous textures. The texturally pristine clasts are generally chemically pristine as well, unless they have been invaded by thin glass veins of melt rock. Many texturally pristine clasts are known only from thin section and electron microprobe study, and no chemical data are available. Pristinity of the cataclasites must be evaluated chemically using siderophile element concentrations and the cut-off values for siderophile contamination suggested by Warren and Wasson [4].

LITHOLOGIES: Three distinct suites of plutonic rock are important at the Apollo 14 site: the Magnesian suite, the Alkali suite, and a variety of evolved lithologies. The Magnesian suite can be further subdivided into the olivine-bearing magnesian troctolite association (which includes troctolite, anorthosite, dunite, and pyroxene-bearing troctolites) and the less abundant magnesian norite association (which includes norites, olivine norites, gabbronorites, and ilmenite gabrros/norites). Ferroan anorthosites ("FAN"), which dominate highland suites in some eastern provinces (Apollo 15, Apollo 16) are rare in the Western Highland Province. Each of these suites, including FAN, will be considered here in order of their relative abundance.

MAGNESIAN SUITE

Magnesian Troctolite Association: The magnesian troctolite association includes a variety of olivine-bearing rocks characterized by relatively calcic plagioclase compositions (An93-96) and a range in olivine compositions (Fo75-90). *Troctolite* is the most common lithology in this association, with modes around 30-40% olivine and 60-70% plagioclase ([1]; [5]; [2]; [6]; [7]). More mafic compositions with 50-60% olivine are less common (e.g., [7]; [11]), but troctolitic anorthosites with 10-15% olivine and 85-90% plagioclase are widespread ([5]; [8]; [9]). A few troctolites also contain minor enstatite and diopside. Other important members of the Apollo 14 magnesian troctolite association include magnesian anorthosite, dunite, and pyroxene-rich troctolite.

Magnesian anorthosites are relatively new additions to the Mg-rich suite ([9]; [7]). These rocks are characterized by plagioclase-rich modes (90-99% plagioclase) with mineral compositions similar to the Mg-troctolites: An94-97 plagioclase with minor Fo84-90 olivine. An REE-rich Ca-phosphate phase (probably whitlockite) forms a large, 500 x 120 micron, anhedral grain in one of these anorthosites ([7] [19]) and may contain almost all of the REE found in this samples.

Dunite is another rare but important member of the magnesian troctolite association. Two small dunite clasts have been found to date: one in breccia 14321 ([7]), the other in breccia 14304 ([11]). Both consist of nearly pure Fo88-89 olivine with almost no compositional variation either within or between the two clasts.

Two *pyroxene-rich troctolite* clasts have also been found. One is an anorthositic troctolite with 80% plagioclase, 15% olivine, and 5% diopside, the other is a mafic troctolite with 46% plagioclase, 47% olivine, 7% enstatite, and minor Cr-pleonaste [8,9,10]. Mineral compositions are similar in both, with An94-95 plagioclase, Fo88-89 olivine, and pyroxene Mg#s (= 100*Mg/[Mg+Fe]) of 90. The Mg-rich compositions of the olivines and coexisting pyroxenes indicates that the parent magmas reached pyroxene saturation early in their fractionation history, prior to extensive olivine fractionation. In addition, the stable coexistence of olivine-enstatite and enstatite-spinel (both in discrete grains and in enstatite-spinel symplectites) indicates that crystallization occurred relatively deep in the crust, where the four-phase assemblage ol-plg-opx-sp was stable [8,9,10].

Hunter and Taylor [5] were first to notice a compositional gap between two troctolite subgroups (figure 1). Group I troctolites tend to have more mafic-rich modes and more magnesian phase compositions (olivine Fo85-90); Group II troctolites are more felsic modally and have more Fe-rich mineral compositions (olivine Fo74-81). All of the minor lithologies discussed above plot with the Group I troctolites. Only one sample of Group II troctolite has been analyzed chemically (14321 c2 -- [2]). Its incompatible element abundances are in the same range as the more numerous Group I troctolites.

Magnesian Norite Association: The magnesian norite association contains a diverse assemblage of rocks referred to as ilmenite gabbros, ilmenite norites, and gabbronorites [3,5,8,11]. Only four clasts have been described so far that can be considered unequivocably part of the Mg-suite: norite 14063 ,61 [5], gabbronorite 14304 ,125 [11], olivine norite 14318 ,149 [6], and olivine norite 14305 ,489 [12]. These rocks have modes with subequal portions of plagioclase and pyroxene -- generally pigeonite with minor augite. Ilmenite is a common accessory phase in some of these clasts, along with Ti-spinel, Fe-metal, and troilite. Plagioclase compositions are around An87-90 and mafic silicates have Mg#s between 70-75. One a plot of An content of plagioclase versus Mg# of mafic silicate (figure 1), these rocks plot between rocks of the magnesian troctolite association and the alkali suite.

Several clasts in breccias 14303, 14304, and 14305 are gabbronorites with An90-95 plagioclase and relatively Fe-rich mafic silicates with Mg#s 65-70 [8,11,12]. These rocks generally have orthocumulate or mesocumulate textures, with primocrysts of plagioclase and pigeonite surrounded by post-cumulus feldspar, pigeonite, augite, ilmenite, and Ti-spinel. Their modes are similar to the magnesian norites described above, but they plot *below* the Mg-suite field on an An-Mg# diagram, between the magnesian norites and the ferroan anorthosite field (figure 1). This is the same region where Apollo 14 mare basalts plot, suggesting that some of these gabbronorites may be cumulates derived from aluminous pigeonite basalts (e.g., [8]). Potential mare cumulates are characterized by high modal ilmenite and Ti-rich (TiO_2 > 0.5 wt%) cumulus pigeonites. These rocks also fall on calculated fractionation trends for Mg-suite parent magmas [13] and may be related to the Group II troctolites by fractional crystallization. Gabbronorites with Ti-poor pigeonite and low modal ilmenite may thus be related to more magnesian members of the Mg-suite.

ALKALI SUITE

Alkali Anorthosite/Norite Association: The Alkali suite was first recognized by Warren and Wasson [4] and subsequent studies established it as the second most common highland rock association at the Apollo 14 site [2,5,6,8,9,10]. This suite was once thought to be unique to the Western Highlands Province, but similar alkali gabbronorites are now known from the Apollo 16 site [7,14]. The most common lithologies are anorthosite and norite or gabbronorite; olivine norites are rare.

Alkali anorthosites were the first alkalic highland lithology recognized [1]. Seven true alkali anorthosites are known from Apollo 14 [1,5,9,10,11]. These rocks are characterized by modes of 95-100% plagioclase (An76-86) with minor pigeonite, augite, K-feldspar, ilmenite, silica, whitlockite, and Fe-metal. Mafic silicates have Mg#s 50-70, with the higher Mg#s being augite. Plagioclase primiocrysts are up to 1.5 mm across; accessory phases are generally much smaller. Whitlockite (an REE-rich Ca-phosphate) occurs either as interstitial grains or as small inclusions in plagioclase primocrysts (indicating co-saturation) and may comprise up to 2% modally.

Alkali norites are another common alkalic lithology -- at least six clasts are currently recognized [5,6,8,10,11]. These rocks typically contain 75-85% modal plagioclase (An80-85), but more mafic clasts with 14-40% plagioclase are known. Pigeonite or hypersthene are the most common mafic phases, and may occur either as cumulus primocrysts or as post-cumulus crystals interstitial to plagioclase. Augite, K-feldspar, ilmenite, and whitlockite are common post-cumulus accessory phases; Mg#s in the mafic silicates are typically the same as in the alkali anorthosites (53-63 in pigeonite, 64-68 in augite). Whitlockite is found in most alkali norites and may comprise up to 35% of the mode [10]. As a result, REE in these clasts exhibit a wide range in concentrations.

Two *alkali olivine norites* have been described [12,14]. These rocks contain about 65% modal plagioclase, 25% orthopyroxene or pigeonite, and 5-10% olivine modally, with minor ilmenite, whitlockite, and troilite. Plagioclase compositions are typical of the alkali suite (An78-83), but the mafic silicate compositions are Mg-rich compared to typical alkali norites and anorthosites, with olivine Fo70-80 and pyroxene Mg#s 75-85 (figure 1).

EVOLVED LITHOLOGIES

The most common evolved lithology at Apollo 14, commonly referred to as "lunar granite", is a granophyric intergrowth of quartz and alkali feldspar, either alone, with sodic plagioclase (An60-80). The alkali feldspar vary from nearly pure orthoclase (Or95 Ab5) to a ternary feldspar (Or45 Ab25) which plots in the forbidden zone in a feldspar ternary [15,16,27]. In one small granite clast orthoclase and ternary feldspar both occur as granophyric intergrowths with quartz [27]. Accessory minerals include pigeonite, augite, ferroaugite, fayalite, ilmenite, zircon, and Ca-phosphates (apatite, whitlockite). Variations in mineral assemblages and in mineral compositions (e.g., BaO in alkali feldspars, Mg# in mafics) indicate that at least four distinct parent magmas are involved.

The only age data available at the Apollo 14 site on highland lithologies are from lunar granite 14321 , 1027 [16,28]. This granite has been dated at 4.1 Ga using Rb/Sr isochron techniques [28]. Its ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr ratios are the highest yet measured on any lunar material [28].

Granite clasts are relatively common at the Apollo 14 site, which suggests that granite differentiates of mafic plutons are a common and important crustal component in the Western Highlands Province. Based on the abundance of K,Si-rich glasses in Apollo 14 soils and regolith breccias, granites are estimated to comprise 0.5% to 2% of the crust here [17,27].

FERROAN ANORTHOSITES

Ferroan anorthosites are rare at the Apollo 14 site. Only one clast of ferroan anorthosite has been characterized chemically and petrographically [6]. This clast is a monomict cataclasite which consists of nearly 100% plagioclase (An95.5) with relict grains up to 1.3 mm across. Olivine (Fo69) is the only mafic phase.

GEOCHEMISTRY OF THE WESTERN HIGHLANDS PROVINCE

Plutonic rocks of the Western Highlands Province are characterized by high concentrations of incompatible trace elements compared to their eastern counterparts. This characteristic applies to the only FAN clast analyzed to date, as well as to rocks of the magnesian and alkali suites [6]. Despite the fact that whole rock analyses of Apollo 14 plutonic rocks are very sensitive to accessory mineral contents due to the small size of most analyzed samples (< 100 mg), the observed enrichment of incompatible elements in these rocks appears to reflect a fundamental geochemical characteristic of the Western Highlands Province, and is not a spurious effect of sampling problems.

Troctolites, anorthosites, and dunites of the magnesian suite are characterized by a wide range in REE concentrations, with La ranging from 15x to 700x chondrite (figure 2). The highest REE concentrations are found in magnesian anorthosites that contain abundant whitlockite [7,19]. More realistic estimates of crustal composition may be obtained from rocks with the lowest REE contents, but even these are much more enriched than comparable Mg-suite rocks from the east. In addition, parent magma REE concentrations of 3000x (for La) to 1500x (for Lu) chondrite are implied by whitlockite/liquid partition coefficients and the high REE concentrations found in the accessory whitlockite [7,19]. The calculated parent magma REE concentrations are about 10x KREEP --- far to high to have precipitated the observed primitive mineral compositions [7,9,19]. Lindstrom and others [7,19] suggest that the whitlockites may not be in equilibrium with the Mg-suite parent magma. They envisage formation of the phosphates after crystallization from metasomatic fluids which penetrate the rock from below. The source of this fluid and its physical nature (aqueous ? magmatic ?) is not yet resolved.

Rocks of the alkali anorthosite suite are characterized by a similar wide range in REE concentrations, with La from 35x to 600x chondrite (figure 3). As noted in the Mg-suite plutonic rocks, the highest incompatible element concentrations seem to occur in samples with high modal whitlockite and apatite (e.g., [10]). REE concentrations in accessory Ca-phosphate phases are similar to those observed in the Mg-suite rocks -- about 10,000x chondrite. Again, the parent magma composition implied by these concentrations is unrealistically high. In addition, major element compositions of the minerals in the alkali suite are much more evolved than minerals in the Mg-suite rocks, but their accessory phases have nearly identical trace element contents. Clearly, there is no simple explanation to this apparent paradox.

Chemical differences between rocks of the Western Highlands Province and nonmare plutonic rocks from the east are clearly illustrated by a plot of Sm (an incompatible MREE) and Eu (an MREE which is compatible with plagioclase under the reducing conditions found on the moon). Figure 4 shows data for ferroan anorthosites, eastern Mg-suite rocks, western Mg-suite rocks, and western alkalic rocks. Ferroan anorthosites and eastern Mg-suite rocks are characterized by low concentrations of Eu (.5 to 1.0 ppm) and a wide range of Sm concentrations, with Sm in FAN < 0.3 ppm and Sm in the eastern Mg-suite rocks > 0.5 ppm (figure 4). Western Mg-suite rocks have a range in Sm similar to the eastern troctolites (from 2 to 100 ppm Sm) but are enriched in Eu relative to the eastern rocks. Alkali anorthosites are even richer in Eu, with 2 to 10 ppm Eu in rocks with the same Sm content as the Magnesian suite.

ORIGIN OF THE WESTERN HIGHLAND PROVINCE

The high Sm concentrations which characterize plutonic rocks of the Western Highland Province also result in low Ti/Sm and Sc/Sm ratios [1]. These ratios are sub-chondritic, as in KREEP, and suggest derivation of western plutonic suites from an evolved crustal or upper mantle source. Alternatively, these low ratios may reflect the assimilation of residual urKREEP by magmas parental to Mg-suite rocks (e.g., [20]). However, if the incompatible element-rich magnesian suite troctolites, anorthosites, and dunites of Apollo 14 crystallized from Mg-rich magmas that were severely contaminated with urKREEP [20], where did the alkali suite magmas come from ??

Several scenarios can be envisioned for the origin of the western magnesian and alkali suite highland rocks. All of these models have certain attractive features, but none are entirely consistent with what we currently know about the western highland suite. Some possibilities include:

(1) The Mg-suite and alkali suites represent distinct parent magmas, derived from different parts of the lunar mantle, each of which assimilated variable amounts of urKREEP prior to crystallization. This model begs the question of ultimate source, and does not address why there are two distinct parent magmas. It does seem consistent with the gap between the alkali suite and troctolites of the Mg-suite, and with the steep apparent fractionation trends seen in the magnesian troctolite association and in the alkali suite (figure 1). This steep trend in the alkali suite is accentuated by the recent discoveries of primitive olivine norites with typical alkalic plagioclase compositions.

(2) The alkali suite represents Mg-suite magma which has evolved by AFC processes; its high alkali and trace element contents are attributed to relatively large fractions of assimilation. This model has the advantage of one parent magma, and seems in general consistent with the overall trend of the Mg-suite in figure 1. It does not explain, however, why both suites have the same range in trace element concentrations, or why the alkali suite has higher Eu concentrations than either the Mg-suite or KREEP -- fractional crystallization of plagioclase and KREEP assimilation should both act to lower Eu in a residual magma derived from the Mg-suite. It is also puzzling why there are so few Mg-suite norites intermediate to the alkalic rocks and the Mg-troctolites (figure 1). If variable contamination of a single magma was operative, a continuous trend in compositions would be expected.

(3) The alkali suite represents cumulate rocks which crystallized from a KREEP parent magma. This magma was assimilated by Mg-suite parent magmas before they crystallized, or penetrated already crystallized Mg-suite plutons to enrich them metasomatically. It is not clear if the alkali suite cumulate rocks are consistent with this origin, but it does offer an attractive explanation to the contrasts in major and trace element compositions observed between the two suites.

The origin of the evolved lithologies cannot be established with any certainty [15,16,17,27]. Lunar granites are characterized by V-shaped REE patterns with LREE and HREE concentrations 100-200 times chondrite, MREE 100 times chondrite, and significant negative Eu anomalies [15,16,17]. Dickinson and Hess [29] have shown that lunar granites cannot form from KREEP parent magmas because overall REE concentrations are too low in the granites, and because KREEP has a steep negative HREE slope, while granites have a shallow positive slope. Other potential parent magmas include mare basalt, the alkali suite parent magma, and the Mg-suite parent magma [15,16,17,30,31]. The V-shaped REE patterns have been attributed to apatite fractionation [17], but fractional crystallization alone cannot create the observed major and trace element characteristics. In particular, the high K/La ratios of lunar granites seem to require silicate liquid immiscibility at some point in the fractionation history [15,16,17,27,30,31].

WHERE DO WE GO FROM HERE ?

Despite the tremendous increase since 1980 in geochemical and petrologic data on the Western Highlands Province, there are still large gaps in our understanding of how the western crust formed, and why it is different from the eastern crust. Since much of this uncertainty revolves around KREEP, a major priority should be detailed studies which focus on the origin of KREEP, its geochemistry, and its phase relations. In addition, age data is virtually nonexistent on highland lithologies at Apollo 14. Age data are critical to understanding how the alkali suite and Mg-suite rocks are related to one another, and to the aluminous mare basalts which are common at this site (e.g., [21,22,23]. The Apollo 14 aluminous mare basalts range in age from 3.75 to 4.3 Ga -- the same age inferred for many highland crustal rocks [24,25,26]. The relationship between this early mare volcanism and crust forming-processes needs to be thoroughly explored. In addition to these efforts, more data are needed on the variety of highland rock types present at the Apollo 14 site, with special emphasis on integrating whole rock chemistry with phase chemistry (e.g., [19]). The question of possible metasomatism must be addressed, including the specific transport mechanism and the source of the metasomatic fluid.

The unique nature of the highland suite at Apollo 14 provides an exciting opportunity to investigate variations in the lunar crust which formed during the earliest stages of lunar differentiation and perhaps earlier, during accretion. Understanding the origin of these primordial variations in the lunar crust will increase our understanding of how planetary crusts form and evolve, and should give us important insights into the early evolution of the Earth as well.

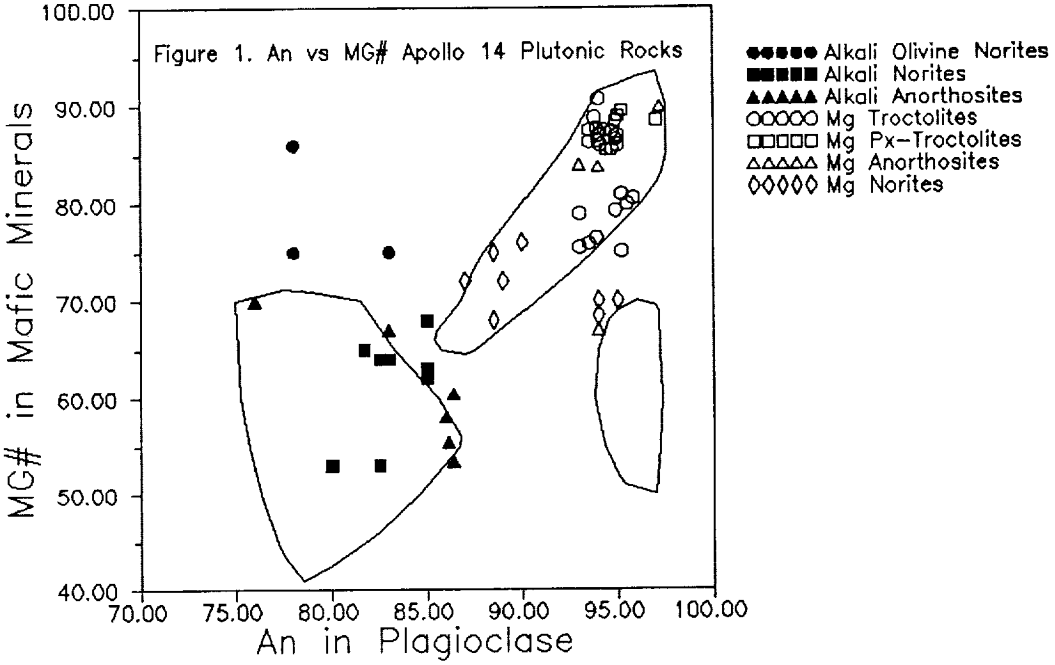

Figure 1. An in plagioclase versus MG# in mafic mineral for plutonic rocks from the Apollo 14 site. Mg-suite rocks are shown in open symbols, as are norites which plot between the Mg-suite data field and the FAN data field. Alkali suite rocks are shown in filled symbols.

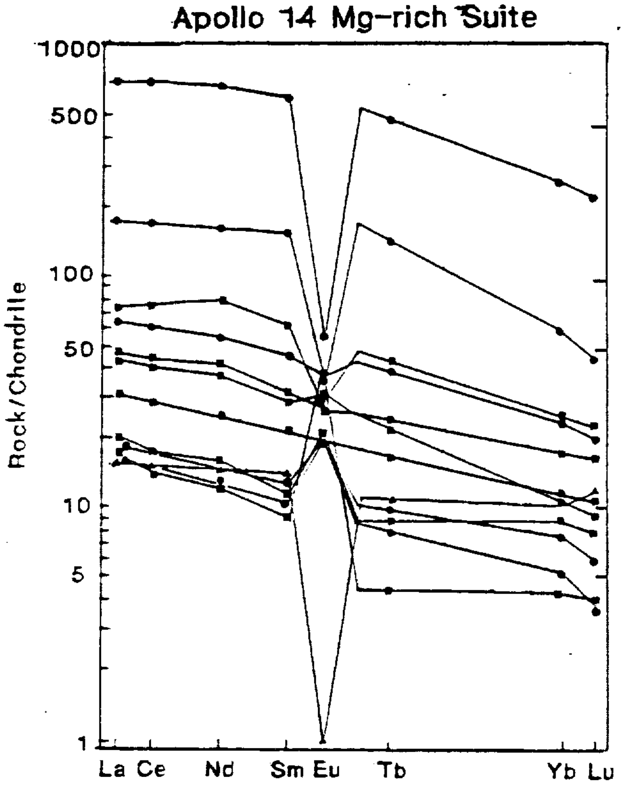

Figure 2. Chondrite-normalized REE patterns for Magnesian suite troctolites (squares), anorthosites (circles), and a dunite (triangle). After Shervais and Taylor, 1985.

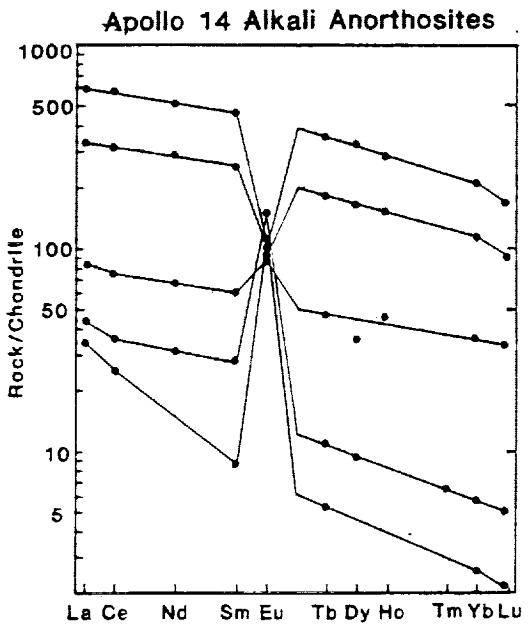

Figure 3. Chondrite-normalized REE patterns for representative alkali suite anorthosites and norites. After Shervais and Taylor, 1985.

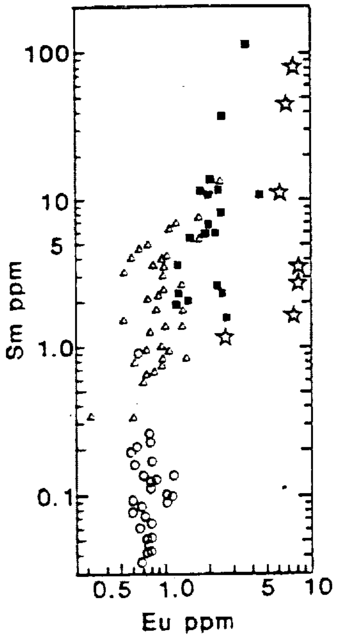

Figure 4. Sm vs Eu plot, with data for eastern ferroan anorthosites (open circles), eastern Mg-suite rocks (open triangles), western Mg-suite rocks (filled squares), and western alkali suite rocks (Stars). Western rocks are characterized by higher concentrations of Eu relative to Sm than equivalent eastern rocks.

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ISOTOPIC CONSTRAINTS ON THE PETROGENESIS OF APOLLO 14 IGNEOUS ROCKS. C.-Y. Shih[1] and L. E. Nyquist[2] ([1]Lockheed Engineering and Science Co., 2400 NASA Road 1, Houston, TX 77058; [2]NASA Johnson Space Center, Houston, TX 77058).

Recent petrologic, geochemical and isotopic investigations of igneous-textured clasts of Apollo 14 breccias, *e.g.* 14321, 14305 and 14304, have yielded several new lunar rock types. Among these are at least two, and perhaps as many as five, groups of aluminous mare basalts (1-3), VHK (very high potassium) basalts (4-7), a tridymite ferrobasalt (TFB) (2) and an olivine basalt or olivine gabbronorite (8), as well as evolved rocks, such as granites (9,10). These igneous rock clasts are pristine and have old isotopic ages in the range 3.9-4.2 Ga (*e.g.* 6-8,10,11), which are contemporaneous with KREEP basalts and some of the younger pristine Mg-suite rocks of the highlands. In this report, we summarize Rb-Sr and Sm-Nd isotopic data available for Apollo 14 igneous rock samples. Their ages and the corresponding initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios can provide useful information about their source materials as well as petrogenetic processes leading to their formation. In addition, these isotopic data can provide valuable informations about early mare basalt volcanism, differentiation of the lunar crust and mantle, and relationships among aluminous mare basalts and very early highland plutonic rocks.

Apollo 14 Aluminous mare basalts

The Apollo 14 aluminous mare basalts were divided into at least two and probably five groups, based chiefly on their REE (rare-earth element) distribution patterns and La vs. Hf abundances (1). The bulk major element chemistry and mineral compositions for the five basalt groups are very similar. Figure 1 shows the interrelationships between La (ppm) and mg-value (MgO/[MgO+FeO] in molar %) for the five groups of Apollo 14 aluminous mare basalts from a data base of 76 analyses reported in (1-3). The basalts were chemically grouped using the classification proposed by Dickinson *et al.* (1). Dotted lines representing linear fits for each basalt group are nearly parallel to each other and to the olivine (Fa_{25}) fractionation trend line shown near the top of the figure. These results suggest that the variations of mg-values within each group can be explained by moderate amounts (<15%) of olivine fractionation. However, the significant variations in La abundances between basalt groups, which can not be produced by near-surface olivine fractionation, are probably due to differences in degrees of partial melting, in source La abundances or in amounts of KREEP basalt assimilation (1,2). A complex process involving partial melting ± KREEP assimilation + olivine fractionation is probably unavoidable for the petrogenesis of Apollo 14 aluminous mare basalts. However, the recent AFC (assimilation-fractional crystallization) model of Neal *et al.* (3), shown in a solid-line curve, clearly can not explain the petrogenesis of all these basalts because the majority of the data points lie far from their proposed AFC trend.

Sr-isotopic data and implications

Rb-Sr ages and initial $^{87}Sr/^{86}Sr$ ratios for five groups of Apollo 14 aluminous mare basalts (11), represented by error parallelgrams calculated from uncertainties in their ages and initial $^{87}Sr/^{86}Sr$ isotopic compositions, are shown in Fig. 2. Also plotted are data for other Apollo 14 mare basalts including VHK and HK (high potassium) basalts, a tridymite ferrobasalt, an olivine basalt (OB), and young aluminous basalts from Apollo 12, Luna 16 and Luna 24 sites (12-14). At least four isotopically distinct groups (*i.e.* G5; G5'; G1, G2 & G4; G3) were identified for the five chemical groups of Apollo 14 aluminous mare basalts of Dickinson *et al.* (1). Except for the basalt G5', all groups of aluminous mare basalts lie on a single radiogenic growth curve for $^{87}Sr/^{86}Sr$ evolving from a primitive initial $^{87}Sr/^{86}Sr$=LUNI=0.69903 at 4.56 Ga ago in source regions having Rb/Sr~0.021. The Rb/Sr ratio for this source is very similar to that proposed by Nyquist *et al.* (15) for the undifferentiated portion of the moon. Thus, the isotopic data suggest that most groups of Apollo 14 aluminous basalts could have been extruded at different times from either a single mantle source in which the Rb/Sr ratio was ~0.021 or from different sources of the same Rb/Sr ratio but having different absolute abundances of Rb and Sr.

VHK and HK basalts

As shown in Fig. 2., the initial ^{87}Sr/^{86}Sr ratio for the VHK basalt is comparatively imprecisely determined because this basalt was distinctly more radiogenic than other mare basalts. However, its crystallization age is well defined. The HK basalts are younger than most of the Apollo 14 mare basalts, but significantly older than the VHK basalt. The Rb-Sr isotopic results suggest that VHK and HK basalts were genetically related to other groups of aluminous basalts and that all these basalts could have evolved from a common source region and formed at different times. In addition, the Rb/Sr ratios of VHK and HK basalts are enriched approximately ten-fold relative to their source materials. An assimilation model involving assimilation of the K-feldspar component of granitic crustal materials into ascending aluminous basalt magma could explain the chemical and isotopic characteristics of VHK and HK basalts (6,7).

Young aluminous mare basalts at Apollo 12, Luna 16 and Luna 24 sites

Aluminous mare basalts were not restricted to the Apollo 14 site. Young aluminous mare basalts of ~3.4 Ga have been reported at the Apollo 12, Luna 16 and Luna 24 sites (12-14). However, these young aluminous basalts have slightly lower mg-values (0.36-0.41) in contrast to mg-values of 0.41-0.58 for Apollo 14 basalts. As shown in Fig. 2, the time-averaged Rb/Sr ratios for sources of these basalts are ~0.004, about five-fold lower than those of Apollo 14 aluminous mare basalts. This ratio is even lower than those for the Apollo 11 and Apollo 12 mare basalt sources (*e.g.* 16). The extremely low Rb/Sr sources for these young aluminous basalts indicate that they were derived from cumulate sources depleted in LIL (large ion lithophile) elements and perhaps containing plagioclase.

Other Apollo 14 mare basalts (TFB and olivine basalt)

Tridymite ferrobasalt exhibits the most radiogenic initial ^{87}Sr/^{86}Sr ratio of all Apollo 14 mare basalts (11). The calculated Rb/Sr ratio for its source is ~0.035 which is significantly higher than that for aluminous mare basalts. This basalt is not directly related to the aluminous mare basalts. However, the isotopic data do not preclude assimilation of bulk granitic materials into aluminous mare basaltic magma to form the tridymite ferrobasalt. The bulk granitic materials would significantly increase amounts of REE, ^{87}Sr/^{86}Sr, K and Rb and would also decrease the mg-value of the parent aluminous mare basalt magma.

The olivine basalt 14305,122 and a group 5 aluminous mare basalt 14321,1384 (G5') have the lowest initial ^{87}Sr/^{86}Sr ratio of all Apollo 14 mare basalts (8,11). The G5' basalt also has the lowest La abundance and the highest mg-value of all aluminous mare basalt. These two basalts are not isotopically related in a direct way to other groups of aluminous mare basalts. If assimilation of KREEP by a primitive magma such as G5' played a significant role in the petrogenesis of the other groups of aluminous mare basalts, it must have occurred in a manner to mimic the regular increase in ^{87}Sr/^{86}Sr which would occur in a source of fixed Rb/Sr ratio. The time-averaged Rb/Sr ratio for the source of the olivine basalt and G5' basalt is ~0.009, a value similar to that defined for the parental magmas of four pristine norites as shown in Fig. 3. (17). A petrogenetic link between these Apollo mare basalts and the Mg-suite crustal rocks is thus permitted by the age and initial ^{87}Sr/^{86}Sr data.

Nd-isotopic data and implications

The ages and corresponding ϵ_{Nd} values for lunar mare basalts are presented in Fig. 4. ϵ_{Nd} values represent the fractional deviation in parts in 10^4 (18,19) of the initial ^{143}Nd/^{144}Nd of rocks from a chondritic evolution line using the present-day values of ^{143}Nd/^{144}Nd=0.511847 and ^{147}Sm/^{144}Nd = 0.1967 (20-22). Most mare basalts have characteristic positive ϵ_{Nd} values, suggesting that their source regions had Sm/Nd ratios greater than chondritic (23,24). This result is compatible with cumulate-remelting models for mare basalt genesis (*e.g.* 25).

Aluminous mare basalts are shown in solid symbols (see also Fig. 5). Apollo 14 mare basalts have lower ϵ_{Nd} values relative to other mare basalts. Groups 4 and 5 aluminous basalts, the

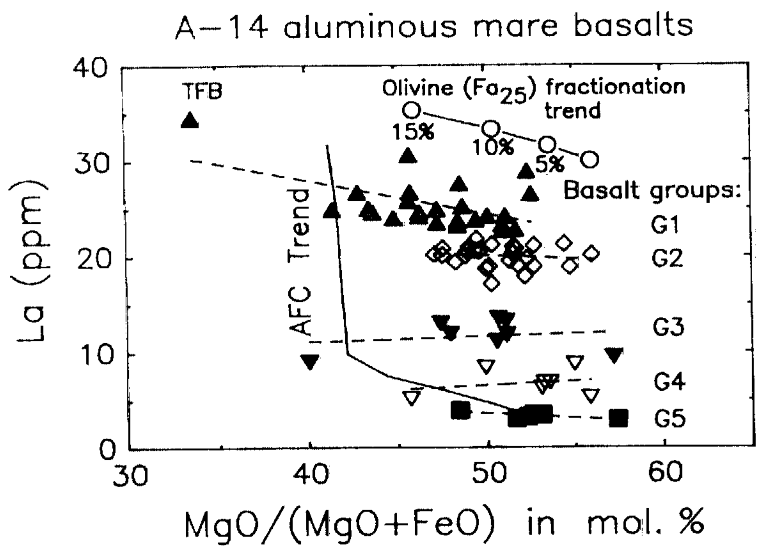

Figure 1.

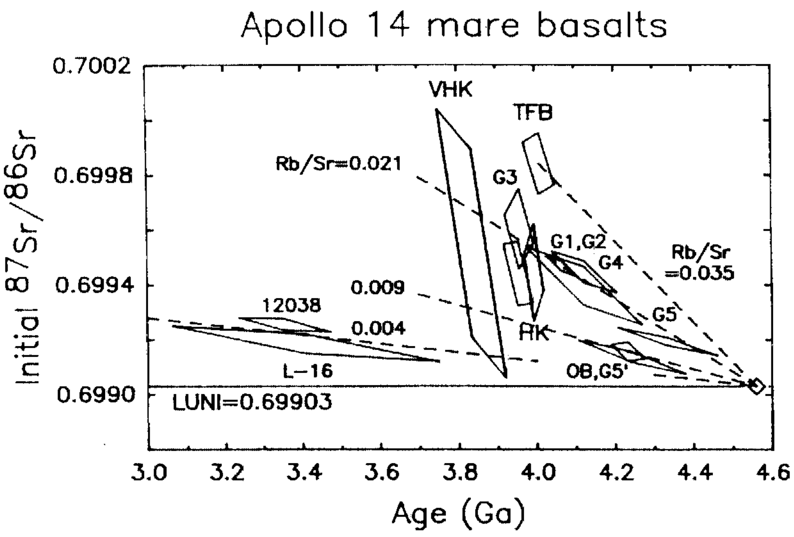

Figure 2.

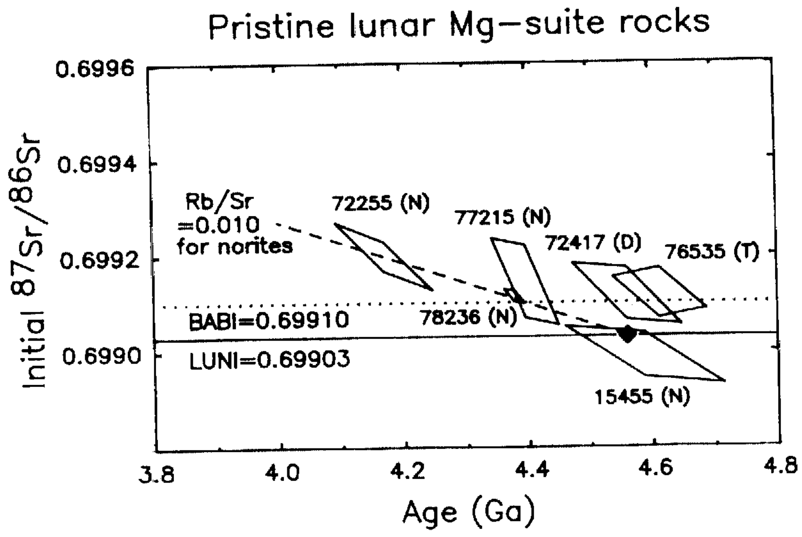

Figure 3.

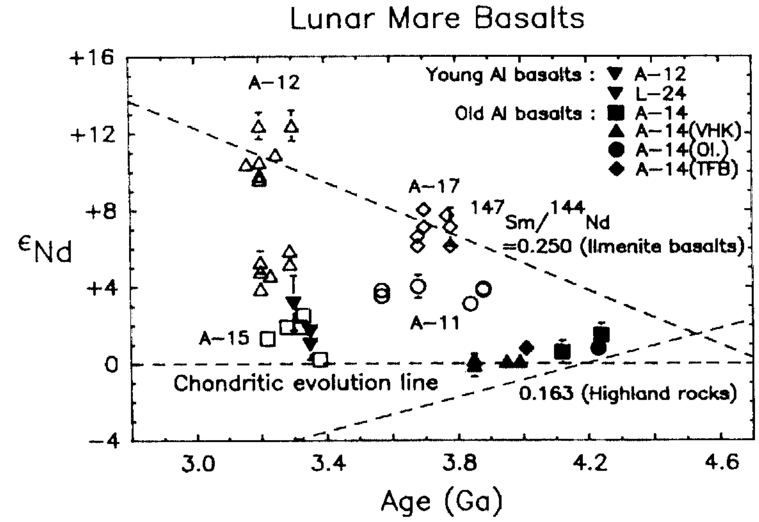

Figure 4.

olivine basalt and the tridymite ferrobasalt have similar and slightly positive ϵ_{Nd} values (11). Whereas both VHK and HK basalts lie on the chondritic evolution line of ϵ_{Nd}=0 (6,7). The chondritic ϵ_{Nd} values for VHK and HK basalts could have resulted from interaction of aluminous parent mare basalt magma of slightly positive ϵ_{Nd} values (*e.g.* G5' or olivine basalt) with old highland crustal materials having slightly negative ϵ_{Nd} values, such as granitic materials, as discussed in the previous section.

Apollo 12 and Luna 24 aluminous basalts have slightly higher ϵ_{Nd} values (12,14,24) than their Apollo 14 counterparts, which is consistent with their low initial $^{87}Sr/^{86}Sr$ ratios and also their cumulate sources.

The G5' basalt and the olivine basalt are similar to gabbronorites 73255,27,45 and 67667 (26,27) and troctolite 76535 (28) in ages and ϵ_{Nd} values (Fig. 5), suggesting that all these rocks were closely related and could be derived from a common source. This source was presumably located in the shallower regions of the lunar interior, *i.e.* the lower crust or uppermost mantle, relative to the deeper depleted source areas of mafic cumulates proposed for younger and more abundant high- and low-Ti mare basalts. The old mare basalt clasts found at the Apollo 14 site represent melts from the earliest mare basalt volcanism soon after lunar crustal formation. Crustal assimilation processes probably play a major role in the genesis of Apollo 14 aluminous mare basalts.

KREEP basalts

Ages and initial $^{87}Sr/^{86}Sr$ ratios of seven Apollo 14 KREEP basalts revealed that four different isotopic groups of basalts were sampled (29-33). However, no clear groupings were identified for KREEP basalts based on their Nd isotopic data (34,35). Figure 6 shows that KREEP basalts sampled at the Apollo 14 and Apollo 15 sites have similar ages and initial $^{87}Sr/^{86}Sr$ ratios (29-33,36,37). The Apollo 17 KREEP basalt represented by pigeonite basalt 72275,171 (38) is significantly older and has much lower initial $^{87}Sr/^{86}Sr$ ratios. The age and Sr isotopic datum for this basalt are indistinguishable from those for the G3 and HK aluminous mare basalts shown in Fig. 2. The initial $^{87}Sr/^{86}Sr$ values for KREEP basalts suggest that Apollo 14 and 15 KREEP were derived from high Rb/Sr source regions. A two-stage evolution model yields Rb/Sr ~0.05 for Apollo 14 and 15 KREEP sources and ~0.02 for the Apollo 17 KREEP source. The model also indicate that a significant Rb/Sr enrichment of ~4x occurred at crystallization for the Apollo 17 KREEP basalt. However, for Apollo 14 and 15 KREEP, the magnitude of Rb/Sr fractionation at crystallization is considerable less, ~1.6x. This result implies that the immediate precusors for Apollo 14 and 15 KREEP basalts were not only enriched in Rb/Sr but also in trace elements like REE.

KREEP basalts exhibit the lowest ϵ_{Nd} values (ϵ_{Nd}=~-1.5 relative to chondrites) of all lunar samples as shown in Fig. 5. Negative ϵ_{Nd} values suggest a low Sm/Nd or light REE-enriched source for the KREEP basalts. Data of major crustal components including anorthosite, norites, gabbronorites, troctolite, granite and KREEP basalts seem to follow a evolution trend corresponding to a subchondritic $^{147}Sm/^{144}Nd$ of ~0.163.

Evolved rocks-granite

Rb-Sr mineral isochrons of four granitic samples (12013,29, 12013,40, 73215,43, 14321,1062) have been determined so far (10,39,40). Their ages are in the range of 3.9-4.1 Ga. The Rb-Sr isochrons for 12013 and 73215 granites were reset and represent the time of brecciation (39,40). The age for the pristine granite clast 14321,1062 was determined to be 4.12 Ga (10). The young crystallization age suggests that this granite is probably not directly produced from the differentiation of the primordial magma ocean. Instead, it may have formed in a layered intrusion associated with Mg-suite rocks. The initial $^{87}Sr/^{86}Sr$ ratio for the granite clast is poorly defined because of the extremely radiogenic nature of the sample, however, the Rb/Sr of the parent liquid is estimated to be ~0.08. The source material of the granite could have had a similar Rb/Sr ratio as the source of Apollo 14 KREEP. A two-stage model calculation indicates that Rb/Sr fractionation during granite formation was ~20-30x. This extreme enrichemnt of Rb/Sr could be achieved only by a combination of feldspar crystal fractionation and silicate liquid immiscibility (*e.g.* 10).

Implications of early lunar differentiation

Age data for pristine lunar plutonic rocks (10,17,26-28,38-65) are summarized in a histogram presented in Fig. 7. These rocks are major constituents of the lunar crust. Ferroan anorthosites have ages ranging 3.9-4.5 Ga. The Mg-suite rocks comprised of norites, gabbronorites, troctolites and dunites exhibit a slightly wider range of 3.9-4.6 Ga clustered at 4.2-4.4 Ga. Evolved rocks including granites and quartz monzodiorite formed between 3.9-4.4. All the older age data, 4.2-4.4 Ga, of evolved rocks are Pb-Pb ages from zircons (61-63). According to the "magma ocean" hypothesis (*e.g.* 66), the Mg-suite rocks formed as layered plutons intruded into the old ferroan anorthositic crust. However, the age data show that ferroan anorthosites are not older than Mg-suite rocks. The model of lunar crust formation by "serial magmatism" proposed recently by Walker (67) seems to be more consistent with the age data obtained from the pristine crustal rocks.

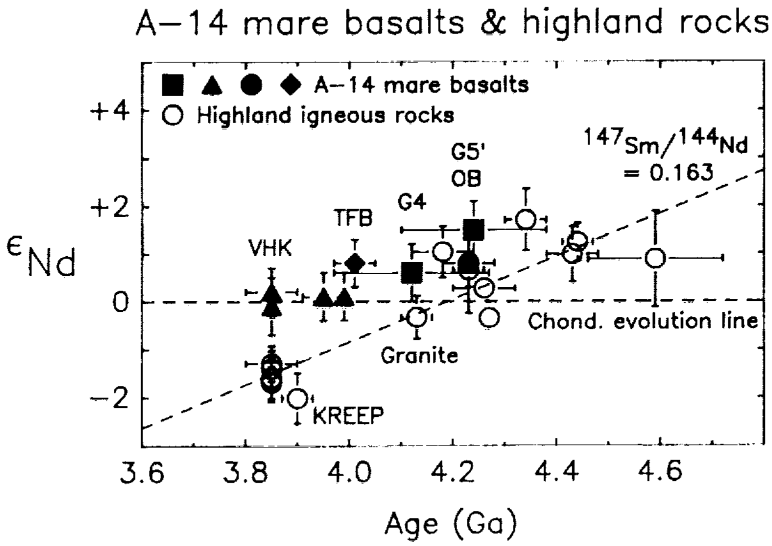

Figure 5.

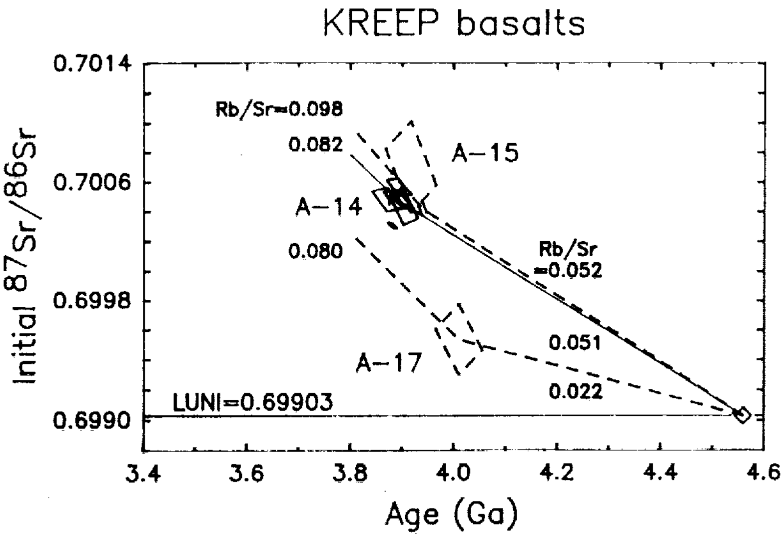

Figure 6.

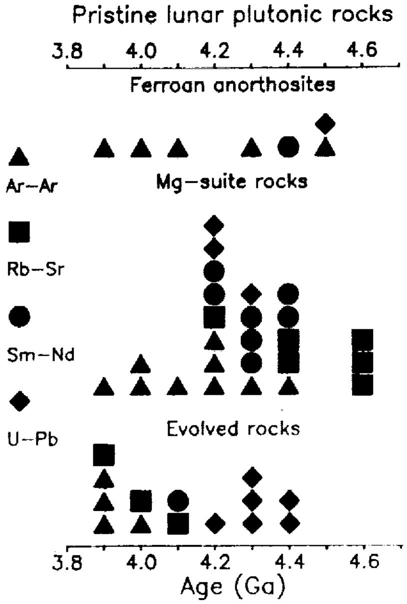

Figure 7.

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Fra Mauro Formation, Apollo 14: II. ^{40}Ar-^{39}Ar Ages of Apollo 14 Rocks

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As a contribution to the Cone-Crater-Consortium ^{40}Ar-^{39}Ar ages of 21 Apollo-14 samples were determined. Among these samples were 10 fragments from breccia 14063, which was collected only 20 m from the rim of Cone Crater. From impact mechanics it seems probable that this breccia is Cone Crater ejecta. This view is supported by the exposure ages of the fragments which range from 24 to 36 Ma which correspond to the assumed age of Cone Crater (25 Ma). The ^{40}Ar-^{39}Ar age pattern show remarkable high apparent ages (>4Ga) in the high temperature fractions in three of the 10 fragments. Figure 1 shows the K/Ca and the age pattern of fragment 14063,233. More than 50 % of ^{39}Ar is released in temperature fractions with apparent ages above 4 Ga up to 4.11 Ga. The ^{40}Ar-^{39}Ar age of 4.09 Ga is the highest so far found in the Apollo-14 rock-collection. The ^{40}Ar-^{39}Ar ages of the other fragments from breccia 14063 are scattered over a broad range (Fig. 2). Apparently the fragment ages are mixing-ages between the age of crystallisation of the individual fragment and the age of the breccia forming event. Consequently the maximum of the age distribution curve is of no chronological significance, but the left edge of the peak is an upper limit to the time of the breccia forming event.

The other dated Apollo-14 rocks according to their ^{40}Ar-^{39}Ar ages arrange themselves into three groups: Most samples have ^{40}Ar-^{39}Ar ages between 3.80 and 3.85 Ga (samples no. 14068, 14069, 14074, 14079, 14311, and 14431). In most cases their ^{40}Ar-^{39}Ar age pattern show well defined plateaux with the result that the errors are small (0.01 - 0.02 Ga). The samples 14179 and 14434 have higher ages, 3.97 and 3.92 Ga, respectively. And finally there are three samples with lower ^{40}Ar-^{39}Ar ages. The ages of 14051 (3.77 ± 0.03 Ga), 14140 (3.76 ± 0.05 Ga), and 14070 (3.73 ± 0.02 Ga) are the lowest among the examined samples. Perhaps the low ages are due to argon loss during the samples' residence close to the lunar surface. There is no obvious correlation between the ^{40}Ar-^{39}Ar ages and the mineralogy of the samples. Exposure ages vary from 18 to 528 Ma.

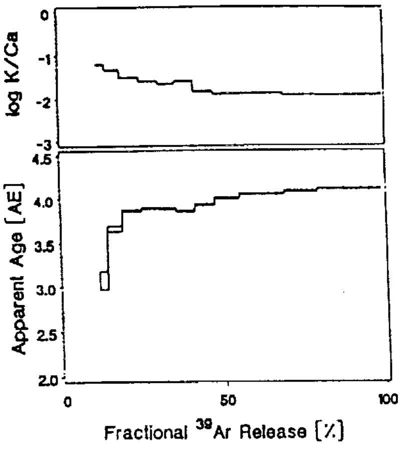

Fig. 1: ^{40}Ar-^{39}Ar age pattern and K/Ca pattern of sample 14063,233.

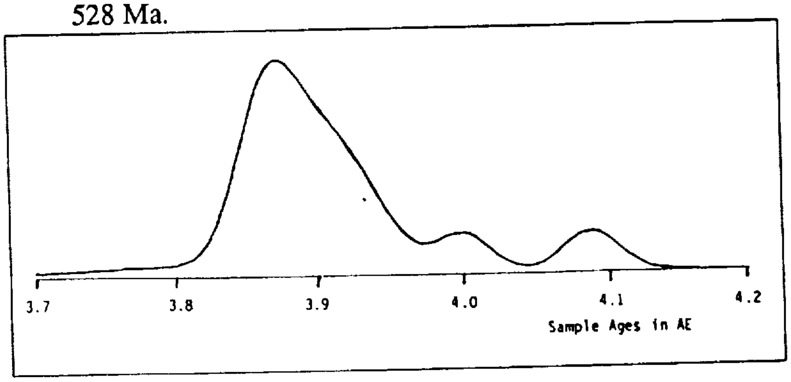

Fig. 2: ^{40}Ar-^{39}Ar age distribution of 10 fragments from sample 14063.

BRECCIATED NATURE OF THE APOLLO 14 LUNAR SAMPLE SUITE: A REVIEW.

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Introduction. In 1971 Apollo 14 was the first mission to the moon returning rock samples which were predominantly polymict impact breccias. The interpretation of the brecciated nature of these rocks proved to be rather problematic since most workers at the time were not familiar with impact breccias. This explains why several attempts to classify and interpret the samples failed (1, 2, 3, 4, 5) leaving a confusing situation until about 1977 when the misconception of "thermal metamorphism" of Apollo 14 breccias (3, 4) was finally abandoned (6, 7, 8) and replaced by a generally accepted classification (9, 10) which was based on the experience with terrestrial impact formations. According to this classification the decimeter-sized samples are dominated by regolith breccias and impact melt breccias supplemented by a minor fraction of fragmental breccias and basalts. The current view is that the Fra Mauro Formation on which Apollo 14 landed, is a polymict breccia deposit (megabreccia) which contains a large amount of clastic rock material derived from the local brecciated bedrock (11, 12, 13, 14). The basic issue of this review can be put into the following questions: What has been learned from the brecciated nature of the Apollo 14 samples in terms of the composition, provenance, and mode of emplacement of the Fra Mauro Formation? What is the pre-Imbrian impact history of the lunar crust in the source region of the Fra Mauro Formation? What are the implications of the composition of the breccias for the evolution of the pre-Imbrian crust and mantle?

Classification and regional distribution of rock types at Apollo 14

The Apollo 14 collection comprises several types of samples which differ in size and mode of collection (15):

(a) Samples chipped from boulders which are in the size range from ~0.3 to ~5 m. A dozen boulders have been photodocumented and recognized as polymict breccias with clast sizes up to about 1.7 m (15),
(b) Handspecimen-sized individual rock samples ranging in size from centimeters to decimeters collected from the regolith surface; 141 samples have been registered and numbered,
(c) Soil samples (or regolith samples) which are available in 4 sieved size fractions (4-10 mm, 2-4 mm, 1-2 mm, and <1 mm),
(d) Drive tube samples taken from the regolith

These samples have been taken from 13 locations (stations) along a 3.5 km long traverse with 4 collecting areas located on the ejecta blanket of the 370 m diameter Cone crater (Fig. 1). Petrographic classifications of rocks are available for the large rock samples (types a+b), for the lithic clast population of polymict breccias (large rock samples), and for certain grain size fractions of the regolith representing sample types c and d (Table 1 and (16-21)). It is most characteristic for the abundance and regional distribution of the large rock samples at Apollo 14 that no plutonic rocks (anorthosites or rocks of the Mg-suite) are present and that fragmental breccias are restricted to the rim area of Cone crater (station C1). All types of "pristine" plutonic rocks so far recognized at Apollo 14 are confined to the lithic clast population of polymict breccias in contrast to the other highland landing sites. A comparison of the abundances of rock types among lithic clasts of breccias and regolith is given in Fig. 2 for the Apollo 14 and 16 landing sites. The relative abundance of the various types of igneous lithic clasts is not well known for most types of polymict breccias exept for the fragmental breccias from Cone crater (Table 2 and (18)). Table 3 shows that the total frequency of plutonic igneous clasts is about 25% (16% anorthosites and 9% noritic-gabbroic-troctolitic rocks) in the Cone crater basement breccias compared to 38% in Apollo 16 North Ray crater basement interpreted as Descartes Formation (22).

Textural and petrologic characteristics of impact-induced lithologies

All four major groups of breccias which have been recognized moon-wide - regolith breccias, fragmental breccias, impact melt breccias, and granulitic breccias - are present in the Apollo 14 sample collection. Among these groups the fragmental and impact melt breccias are genetically most important for the origin of the Fra Mauro Formation and the evolution of the pre-Imbrian crust. In principle, they represent the two major allochthonous breccia units of large impact craters, namely the polymict continous ejecta deposits and the coherent impact melt deposit (melt sheet), respectively.

The grain size characteristics of the impactoclastic detritus in both types of polymict breccias (19, 26) indicates that it underwent multiple impact reworking. It is intermediate in "maturity" between "mature" regolith and the clastic material produced in a single impact event (e.g. terrestrial suevite). The modal composition of the mineral clast population is feldspathic with a plagioclase: mafic minerals ratio ranging from 1.5 to 2.3 in contrast to loose regolith and regolith breccias where this ratio ranges from 0.6 to 1.25

(Fig. 3). The lithic clasts in fragmental breccias and impact melt breccias are dominated by a variety of fine-grained impact melt lithologies and coarser-grained subophitic "basalts" which are in part impact melt rocks. The proportion of fine-grained intergranular melt breccia clasts ranges up to 84% in these breccias ((19, 26); compare also Fig. 2). The lithic clast modes and the chemical composition of the mineral clasts indicate that the protolith(s) of the clasts were composed of a variety of different rock types (6) including impact melt breccias, high alumina basalt, mare basalt, anorthosite, noritic-gabbroic-troctolitic rocks, dunite and granulitic lithologies. KREEP is a dominant component in the impact melt lithologies.
Considering the nature of the <u>melt matrix</u> it becomes obvious that the Apollo 14 impact melt lithologies with crystalline matrix represent a unique group of such rocks which differ from all other highland sites in composition, texture, and frequency. Compared to the seven textural types at Apollo 16 (22) the large rock samples at Apollo 14 fall into two types only: (a) fine-grained, clast-rich intergranular melt breccias, and (b) coarse-grained subophitic melt rocks which are clast-poor or free of clasts (type 14310). Among the lithic clasts of the fragmental breccias (14063, -64, -82/83) the textural variety of impact melts is somewhat larger representing a broad range of cooling rates. In addition to the two types (a and b) very fine-grained to crypto-crystalline variolitic and porphyritic types occur.
The modal composition of the matrix of the intergranular melt breccias is more mafic than the mode of the mineral clasts (26, Fig. 3). The matrix texture is very heterogeneous on a small scale due to the variable clast content of the melt (light and dark matrix texture).

The <u>chemical composition</u> of the melt matrix of the various impact melt lithologies falls near to the ternary peritectic in the olivine - anorthite - silica system but into different fields of primary crystallization. The intergranular melt matrix may have plagioclase, pyroxene, or olivine as liquidus phase whereas in the subophitic feldspathic melt matrix plagioclase crystallizes first. Some of the porphyritic melt matrix types (eg. 14068 and clasts in 14063, -64, -82/83) display olivine and spinel as phenocrysts. The bulk chemistry of all types of impact melt lithologies suggest the presence of five chemical groups: (a) KREEP rich melt breccias, (b) KREEP-rich aluminous melt rocks, (c) KREEP-rich, high Mg-, low K-melt breccias, (d) KREEP-poor, low Mg-, medium to high K-melt breccias, and (e) KREEPy high Ti-melt breccias. The latter three are exclusively found as lithic clasts in the fragmental breccias of Cone crater (13, 17, 18). The chemistry of the rare granulitic lithologies at Apollo 14 is also unique if compared with other highland sites. One sample (14179) is KREEP-rich and a small clast from fragmental breccia 14063 is KREEP-free as most granulites from Apollo 16 and 17 are.

<u>Breccia genesis and implications for the origin of the Fra Mauro Formation and for the evolution of the pre-Imbrian crust</u>

The Apollo 14 breccias were formed by multiple cycles of pre-Imbrian and Imbrian cratering events in which impact melts and clastic rock debris were mixed in very variable proportions. The observed textural variation can be explained by the model given in Fig. 4. Clast-poor or clast-free melts not shown in Fig. 4 lead to subophitic coarse-grained impact melt rocks (type 14310) as part of a coherent melt sheet. Clasts incorporated into coherent melt in schlieren-like agglomeration or mixed interstially into melt agglomerates cause a two-stage cooling of the super-heated melt (27) which can explain the observed textural variation and the light-dark matrix texture of the most common intergranular impact melt breccias at Apollo 14. The light matrix represents coarser grained clast-rich regions where crystallization started first. The mixing of small amounts of melt with clastic material or just mixing of solid clasts forms fragmental breccias as represented by the Cone crater breccias. The clastic nature of the impact melt lithologies in these breccias speaks in favor of the latter process. It is possible that the intergranular melt breccias of Apollo 14 may have been part of one single melt sheet. The fragmental breccias are best explained as parts of an allochthonous polymict ejecta deposit.
In a local and global selenological context the following conclusions can be drawn from the presently available data:

1. The subregolith basement of the Apollo 14 landing site is a polymict clastic megabreccia which is extremely rich in clasts of impact melt lithologies of restricted chemical variety compared to other highland sites. These clasts are as young as 3.75 AE (13, 29) which therefore is the lower limit for the age of the Fra Mauro Formation (29).
2. A group a fragmental breccias near Cone crater rim obviously represents a discrete older stratigraphic subunit whithin this megabreccia as demonstrated by the composition and age of impact melt clasts (28, 14) which are all older than 3.9 AE.

3. The younger group of impact melt lithologies (Nectarian) is uniformly KREEP-rich and has been formed in an impact-processed protolith composed of KREEP-rich rocks (mainly impact melt breccias and possibly KREEP-basalts), aluminous basalts, mare basalts and minor amounts of anorthosotic (Mg- and alkali type), noritic-gabbroic, and troctolitic igneous rocks.
4. It is highly probable that the Nectarian melt breccia or melt rock clasts were once part of one or two impact melt sheets produced in local Nectarian craters (11) and were incorporated into the Fra Mauro Formation by secondary mass wasting during the Imbrium basin event (12).
   The older breccia unit excavated by the Cone crater event may represent a megablock derived from the allochthonous surficial ejecta deposits of a local pre-Nectarian crater again reworked by the emplacement of Imbrium ejecta. The lithological nature of the primary Imbrium ejecta is still not clear.
5. The Apollo 14 samples are representative only of the upper section of the Fra Mauro Formation to a maximum depth of about 35 m (excavation depth of Cone crater (30)) which according to most photogeologists is only a fraction of the total tickness of this formation (31).
6. The frequency statistics of the lithic clasts in the various polymict breccias requires a crust composition at the time of the formation of the oldest impact melt breccias (>3.9 AE) which was free of ferroan anorthosites and dominated in its igneous rock component by rocks of the Mg- and alkali suites (Mg-anorthosites, norites, troctolites, gabbronorites, dunites, alkali anorthosites, and alkali gabbronorites). Clearly, the volumetrically largest fraction of the pre-Nectarian crust were KREEP-rich impact melts derived from extrusive or intrusive volcanics or from KREEP ejected from the base of the pre-Nectarian crust by any of the old multi-ring basins in the general area of the present Imbrium basin (e.g. South Procellarum or Procellarum (11, 31)). This scenario does not exclude the possibility that the primordial ferroan anorthosite crust was present prior to these basin impacts also in the western lunar frontside.

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Table 2: Number frequency (%) of 2476 lithic clasts (>ca. 100 µm) of fragmental breccias 14063, 14064, and 14082/83 (data from (18)) and other breccias of Apollo 14 (19, 32)

Type	Fragmental breccias n=2476 (18)		Large rock samples n=65 (15, 32)	Regolith breccias (19)	Crystalline melt breccias (19)
Igneous rocks	26.4		15.3	1.2	3.5
anorthosite		15.9			
norite		3.25			
troctolite		5.65			
basalt		1.2			
granophyr		0.4			
Metamorphic rocks	3.7		1.5	45.1	16.4
granulitic breccia		0.7			
granulitic rock		3.0			
Impact melt lithologies	69.9		83.1	53.7	80.1
impact glasses		1.5			
impact melt breccias (mafic)		53.6			
impact melt breccias (feldspathic)		14.8			

Table 1: Number frequency of rock types among large rock samples at the Apollo 14 sampling stations (see Fig. 1); based on (15, 16, and 32)

	A	B	Bg	C'	C1	C2	Dg	E	F	G	G'	H	LM	un-known	total	%	%
regolith breccia	6	2	2	-	-	-	-	7	-	1	2	3	11	1	35	25	34
crystalline melt breccia	-	-	-	3	1	-	1	-	1	3	-	4	26	3	42	30	41
crystalline melt rock	-	-	-	1	-	-	-	-	-	1	-	-	-	1	3	2	3
"glassy" melt breccia	-	-	-	-	-	-	-	-	-	-	-	1	8	-	9	6.3	8.5
polymict breccia (undetermined)	-	-	-	-	-	-	-	-	-	1	-	-	33	4	38	27	-
fragmental breccia	-	-	-	-	3	-	-	-	-	-	-	-	-	-	3	2	3
granulitic rock or breccia	-	-	-	-	-	-	-	-	-	-	-	-	1	-	1	0.7	1
basalt	-	-	-	2	-	1	-	-	-	4	-	-	3	-	10	7	9.5
															141	100	100

Table 3: Number Frequency (%) of pristine plutonic rocks in the lithic clast population of polymict breccias of Apollo 14, Apollo 16 and lunar meteorites as measured in thin sections

Site/Breccia type	Number of clasts	Anorthosites	Mafic rocks (Mg-suite)	Total plutonic rocks	Ratio of anorthosites to Mg-suite rocks
Apollo 14					
Fragmental breccias (18) (Cone crater)	2476	15.9	8.9	24.7	1.8
Apollo 16					
Fragmental breccias (22) (North Ray crater)	2213	38.0	0	38.0	∞
Regolith breccias (23)	1895	19.3	11.0	30.3	1.8
Lunar meteorites					
ALHA 81005 (24)	460	28.8	0.8	29.6	36
Yamato 791197 (24)	245	20.3	0.5	20.8	41
Yamato 82192/193 (25)	397	22.2	0.7	22.9	32
Yamato 81032 (18)	127	7.7	10.7	18.4	0.7

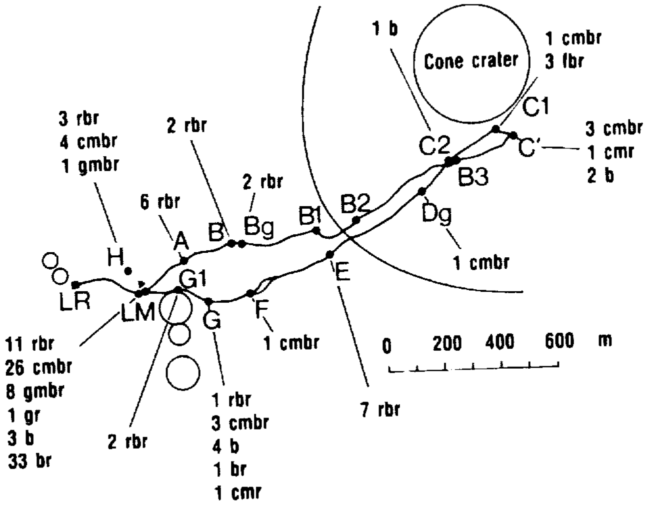

Fig. 1: Apollo 14 landing site with sampling traverses and stations (A-H); LR = ALSEP-station; LM = lunar module; circles = craters; rbr = regolith breccia, fbr = fragmental breccia, cmbr = crystalline impact melt breccia, gmbr = "glassy" impact melt breccia, br = polymict breccia (undetermined), gr = granulitic rock, b = basalt; curved line = outer limit of Cone crater ejecta blanket

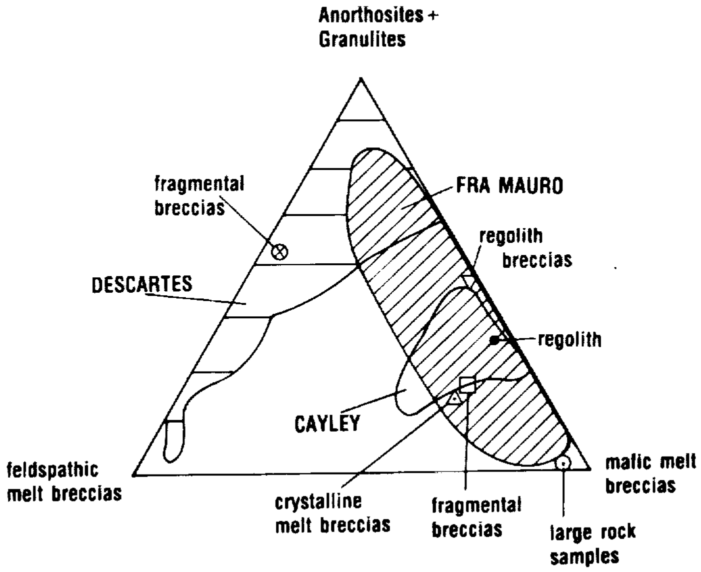

Fig. 2: Modal composition of lithic clasts (> ~ 0.4 - 0.1 mm) of breccias, regolith and large rock samples of Apollo 14 and 16 in the ternary system anorthosite + granulites - feldspathic melt breccias - mafic melt breccias; Apollo 14: hatched area = lithic clasts in breccias (total variation in thin sections of fragmental breccias 14063, -64, and -82/83); data for regolith breccias and crystalline melt breccias from (19), others from (18); Apollo 16: hatched area = lithic clasts in fragmental breccias of Station 11, North Ray crater (total variation in thin sections), circled cross: average; Cayley field: large rock samples from all stations in the Cayley plains; Apollo 16 data from (22)

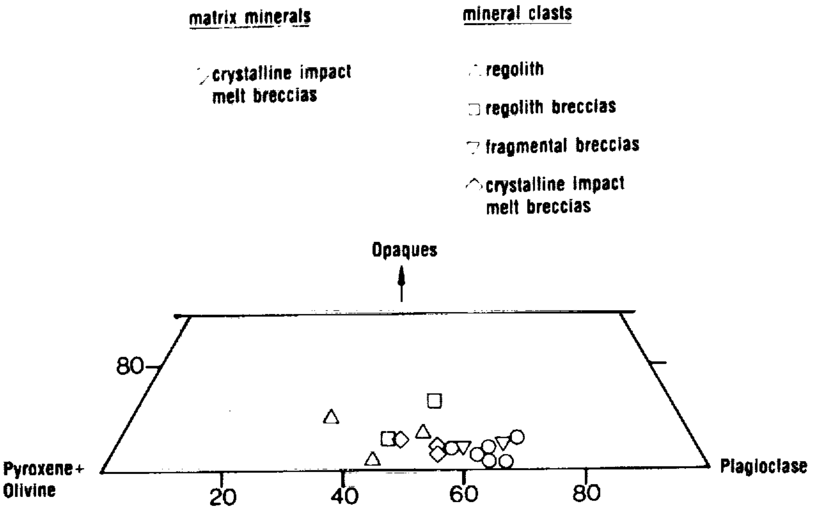

Fig. 3: Modal composition of mineral clasts in breccias and regolith and modal mineralogy of the crystalline matrix of intergranular melt breccias (Apollo 14)

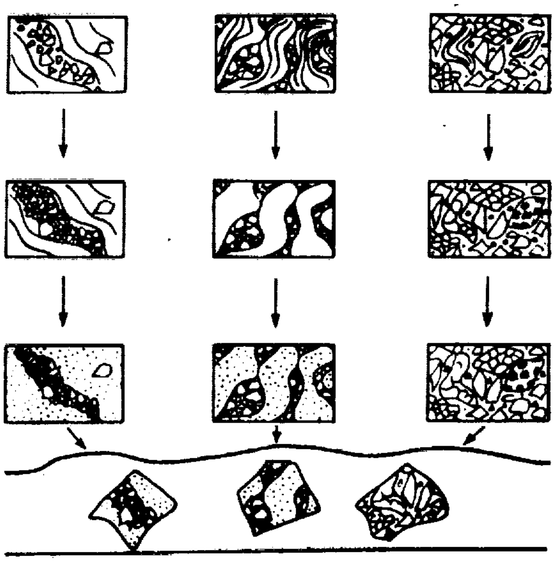

Fig. 4: Evolution of textural characteristics of Apollo 14 breccias; from left to right: clast-laden melt, melt agglomerates with interstitial clastic debris, and mixture of clasts and melt particles ("suevitic"); from top to bottom: melt-clast mixing, crystallization in clast-rich regions, crystallization of clast-poor melt, and fragmentation by subsequent impacts and incorporation into Fra Mauro Formation (from (9); see text)

FRA MAURO FORMATION, APOLLO 14: IV. SYNOPSIS AND SYNTHESIS OF CONSORTIUM STUDIES.

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Introduction. The aim of this paper is to discuss the results of a consortium study of Apollo 14 rocks (1, 2, 3) and their bearing to the genesis of the Fra Mauro formation and the composition and formation of the pre-Imbrian lunar crust in the wider area of the Imbrium basin. The discussion is based on the generally accepted assumption that the Fra Mauro formation sampled by the Apollo 14 mission is part of the continuous ejecta blanket of the Imbrium impact basin but contains a very large amount of rocks derived from the vicinity of the sampling site by the process of secondary mass wasting (4). The interpretations and models presented here are based on textural, mineralogical, chemical and isotope analyses of samples described in (1, 5) and presented in (1, 2, 3, 5, 6). The approach of this consortium is identical to our Apollo and lunar meteorites consortium studies (7, 8, 9). Therefore, relations to the Apollo 16 and other highland sites will be presented here.

Lithological and stratigraphic characterization of the Apollo 14 site. As defined by the photogeology and morphology of the sampled region we distinguish two surface units in the Apollo 14 region: (a) the ejecta blanket of the 25 m.y. old Cone crater and (b) the smooth older terrane around the landing site. The total population of samples from (a) and (b) which we checked microscopically (100 handspecimen (large rocks), 2500 lithic clasts in polymict fragmental breccias, and 100 lithic clasts from a soil sample), can be classified into regolith breccias, fragmental breccias, igneous lithologies, granulitic lithologies, and impact melt lithologies (1). On the basis of the relative abundance, chemical composition, and the absolute ages of these rock types it is possible to define two distinctly different lithological units which are related to the two sampling areas described above. The composition of the first unit denominated "Subregolith basement megabreccia" has been either obtained with some error from the bulk composition of the regolith and from a weighted average of the large handspecimen samples collected throughout the sampled area. The second unit is represented by the bulk or the lithic clast population of the fragmental breccia boulders ("white rocks" 14063, -64, -82/83) near Cone crater and may be denominated "Cone crater basement megabreccia". The essential differences between the two units are summarized in (1, 2, 3, 5, 6).

The age data summarized in Fig. 1 clearly put these two petrographically and chemically different geological units into distinctly different stratigraphic positions with the Cone crater basement megabreccia being older than the subregolith basement megabreccia. According to the principle that the youngest clast of a polymict clastic matrix breccia determines the age of the breccia-forming process, the older breccia has an absolute age of 3.85 b.y. whereas the younger breccia which forms the subregolith basement is 3.75 b.y. old. These two ages coincide exactly with the ages we have recently proposed for the Nectaris and Imbrium impacts respectively (7, 10).

Relations of the two stratigraphic units of the Apollo 14 site to the local and global geology. The interpretation of the younger stratigraphic unit (subregolith basement) is straightforward. The rock samples taken from the regolith outside the ejecta blanket of the young Cone crater display a wide range of exposure ages (11, 12). They were brought to the surface by impact reworking of a substrate megabreccia unit through nearby post-Imbrium small-scale impact craters as discussed in (7 and 10). Because of the observed crater size-frequency distribution near Apollo 14 (10) the majority of samples must originate from very shallow depths of only a few meters below the regolith. Samples of the clastic matrix of the subregolith megabreccia are lacking in the surface sample collection because they did not survive the regolith gardening process because of lack of coherence. Such samples can only be expected at very young craters. Cone crater is such a case where bulk samples of the basement megabreccia in the form of large boulders ("white rocks" 14063, -64, -82/83) can be found in the rim ejecta. These boulders originate from a maximum depth of 32 m (5, 6, 13). This leaves two options for the stratigraphic and structural position of the parent megabreccia unit of these boulders which is older than the subregolith basement megabreccia (Fig. 2): (a) the Cone crater basement megabreccia forms a sublayer of the Fra Mauro formation and represents an ejecta layer of a pre-Imbrian crater, or (b) it forms large megablocks from such a pre-Imbrian ejecta layer which were incorporated into the Fra Mauro formation by secondary mass wasting of the local basement during the emplacement of the Imbrian Fra Mauro formation. The latter appears more probable to us because the former would allow not much more than about 20 m total thickness for the Fra Mauro Formation at the Apollo 14 site (Fig. 2). The question remains whether the source crater for the Nectarian megabreccia unit exposed in the basement of Cone crater can be identified. The distribution and size of possible candidate craters has been studied by (14). It appears probable that one of the nearest large pre-Nectarian or early Nectarian (Phase IB of (14)) craters has produced the megabreccia unit sampled by Cone crater.

Composition of the primordial parental crust of the two stratigraphic units of the Fra Mauro formation. As outlined in an companion abstract (3), the igneous precursor rocks of the secondary Apollo 14 lithologies have been deduced by means of mixing calculations. According to the results of these calculations (3, 6), the Imbrian megabreccia is derived from a crust section in which the primordial igneous rocks are dominated by noritic to gabbroic lithologies whereas the Nectarian megabreccia unit is typified by non-ferroan, evolved anorthosites and by troctolites and only minor amounts of noritic-gabbroic rocks. Both units are typically poor in ferroan anorthosites which are the dominant igneous lithology of the parental crust of the Apollo 16 formations and of the source regions of lunar meteorites (Table 1). In addition, the latter crust sections are extremely poor in troctolites. These model compositions are compatible with the observed ratios of anorthositic to noritic-gabbroic-troctolitic-dunitic rocks (Mg-suite) as given in Table 2. The higher ratios in Table 2 are probably due to the fact that the Mg-suite rocks are the main mixing components of all secondary lithologies which appear in the form of their igneous rock components in Table 1.

Model of the history of the primordial crust in the Imbrium and Procellarum region. The question whether the pre-Nectarian Procellarum impact basin existed or not (15) plays an important role for the deduction of a model history for the primitive crust of the frontside of the moon. The main thesis of this paper is that the Apollo 14, 15 and 16 data are in favor of the existence of the Procellarum basin which according to (15) has a rim diameter of 3200 km (?). This basin which may have an excavation depth of more than 150 km, must have exposed a very large section of the lunar mantle and lowermost crust so that mafic (noritic) and ultramafic rocks and KREEP formed the basin floor of Procellarum (Fig. 3). The basin floor was probably also flooded by aluminous basalt flows at later times. Consequently, a mixture of KREEP and mafic lithologies either formed as a product of the magma ocean, in layered intrusions or as volcanic flows constituted the target rocks for many generations of Nectarian craters. Apollo 14 appears to be located at the edge of the Procellarian KREEP layer where layered intrusions rich in alkali- and Mg-anorthosites and troctolites were exposed. This may be the source region for the Nectarian (Cone crater basement) megabreccia unit. The emplacement of the Imbrian Fra Mauro formation lead to a megabreccia unit dominated by Nectarian impact melt lithologies which were mainly derived from craters located on the KREEP-rich parts of the Procellarum basin floor (Fig. 3). An important implication of this scenario is that the ferroan anorthosite crust (of magma ocean origin) was primarily present also in wider Procellarum area but had been removed by Procellarum before the Imbrium basin was formed.

Table 1: Abundances of primordial igneous rocks in the parental crustal regions of various highland formations based on mixing calculations (3, 6)

	Imbrium Region				Apollo 16 region		Meteorites'parent regions			
Rock type	Imbrian megabreccia (a)	(b)	Nectarian megabreccia (c)	(d)	Descartes Formation (7)	Cayley Formation (7)	791197	Yamato 82192	81032	ALHA 81005 (8)
Anorthosite, ferroan	14.5	-	5	-	86	82	72	56	66	62
Anorthosite, magnesian and alkali	43.5	24	54	60	-	-	-	-	0.3	0
Troctolite	0	0	38	30	0.1	2	0	0		
Norite - Gabbro	42	75	0	3	11	13	28	44	34	33
Dunite	0	1	3	7	3	3	0	0	0	5

a = based on bulk Apollo 14 regolith (3); b = based on a weighted average of large rock Apollo 14 samples (6); c = based on the bulk composition of breccia 14063; d = based on a weighted average of lithic clasts in 14063

Table 2: Frequency of pristine rocks in the lunar highlands (statistics based on the exclusion of regolith and fragmental breccias)

	Anorthosites (%)		Mg-suite (%)		Total (%)		Ratio of anorthosite to Mg-rocks (%)
Apollo 16 (7)	25.8		3.0		28.8		8.6
Apollo 14							
subregolith basement (16)	0		7		7		0.0
Cone crater basement (3)	15.8		8.8		25		1.8
Lunar meteorites							
ALHA 81005 (8)	28.8		0.8		29.6		
Yamato 791197 (8)	20.3	23.7	0.5	0.7	20.8	24.4	35.0
Yamato 82192/193 (9)	22.2		0.7		22.9		
Yamato 81032	7.7		10.7		18.4		0.7

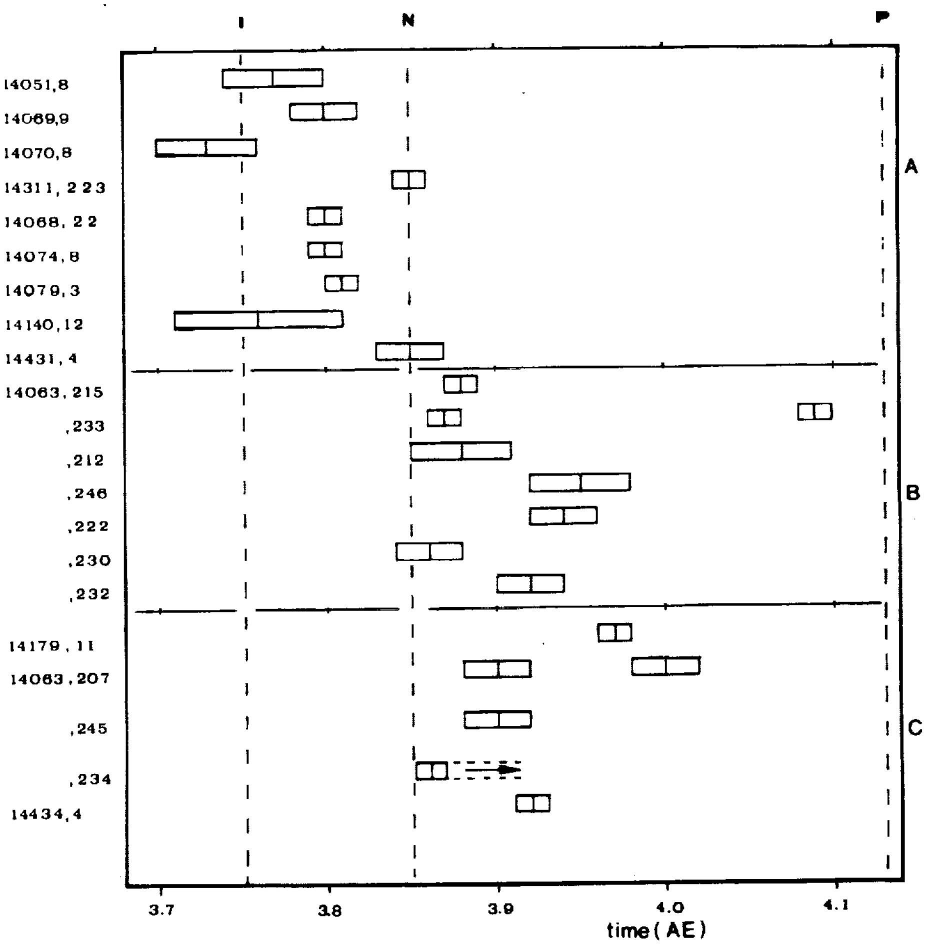

Fig. 1: ^{39}Ar-^{40}Ar ages of Apollo 14 rocks; block A - large rock impact melt rocks and -breccias; block B - lithic clasts of impact melt breccias from 14063; 14179, 14063,207 - granulites; 245 - plagioclase single crystal; 234 - noritic anorthosite, 14434, 3 - gabbronorite, I, N, P - Imbrium; Nectaris, and Procellarum (?) events (10); vertical line in bars and width of bars indicate ages and errors

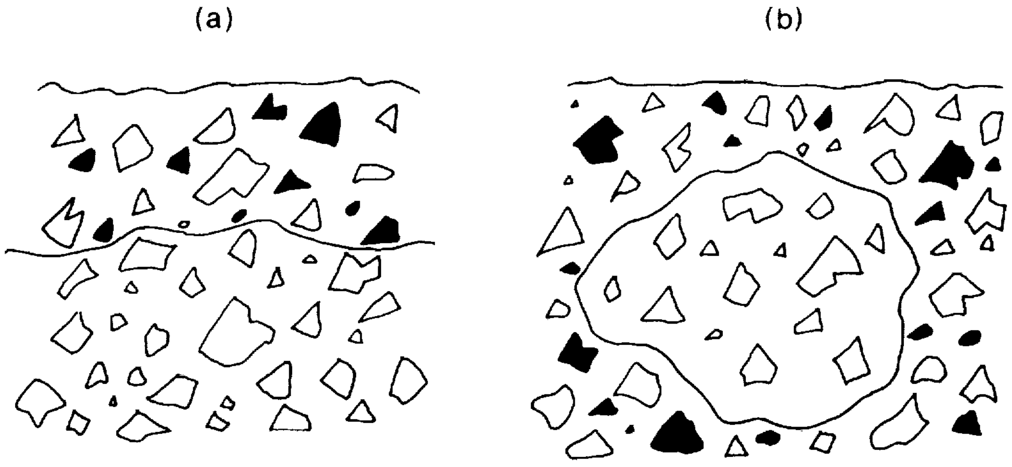

Fig. 2: Stratigraphic relation between Imbrian (subregolith basement; with black clasts) and Nectarian (Cone crater basement) megabreccias; see text

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KREEP: MAJOR-ELEMENT DIVERSITY, TRACE-ELEMENT UNIFORMITY (ALMOST)

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For the distinctive lunar rock type affectionately known as KREEP, the Apollo 14 landing site is essentially the type locality, albeit KREEP was first recognized, as "K,P glass," among highlands samples from Apollo 12 [1]. An old synonym for KREEP is "Fra Mauro basalt" — named after the Fra Mauro Formation, which the Apollo 14 mission extensively sampled. Since the vast majority of KREEP samples are actually impact melt breccias, and thus not truly basalts, "Fra Mauro basalt" is a term with misleading connotations. (Before the Apollo 14 mission, the Fra Mauro Formation was assumed to represent a layer of nearly pure ejecta from the Imbrium basin. Today, the Fra Mauro Formation is more commonly interpreted as a mixture of mainly local material, sculpted by Imbrium ejecta. The vast majority of the rocks at the Apollo 14 site are polymict impact breccias.) In rare instances where KREEP rocks are found in monomict or "pristine" form (mainly, if not exclusively, among rocks from missions other than Apollo 14), they range in major-element composition at least from basaltic (MgO = 8.4 wt%) to quartz-monzodioritic, and perhaps all the way to granitic. They range in texture at least from glassy to coarse-subophitic [2].

The two definitive traits shared by all KREEP rocks are: (a) highly enriched concentrations of incompatible trace and minor elements (ITE), such as K, P, REE, Th and U; and (b) ratios among ITE close to those characteristic of the "type" KREEP samples — e.g., the soils and typical breccias from Apollo 14. Another way of stating criterion (b) would be that the ratios among ITE must be close to those for an average composition of *all* ITE-rich lunar highlands rocks, because the KREEP "component" appears to account for nearly the entire budget of ITE in the lunar crust. Very little material seems to exist that is ITE-rich without also being KREEPy, in the sense of criterion (b). The main exceptions, rocks that are ITE-rich but *not* KREEPy, are rare granites and some of the "alkali" type cumulates. Arguably, a third criterion should also be applied, (c): the texture (or major-element composition) of the sample should not give indications of origin as an igneous cumulate. Criterion (c) is mentioned because the "KREEP" classification should probably be restricted to rocks formed by solidification of KREEPy melts (or by impact-mixing of such rocks). An igneous cumulate could conceivably derive a KREEP-like trace element pattern through complexities associated with accumulation from a nonKREEPy melt. Possible examples of this sort include a few of the most REE-rich alkali anorthosites. However, some models for the origin of alkali anorthosites favor accumulation from KREEPy melts.

A widely-held model of early lunar evolution suggests that primordial heating engendered a magma ocean, or magmasphere, which produced the earliest crust by flotation of ferroan anorthosite (and in some models additional nonmare rock types as well), thus accounting for, among other things: (a) the hyper-magmatic average Al_2O_3 content of the upper lunar crust; (b) the total absence, due to deep burial during magmasphere crystallization, of "ferroan" mafic cumulates expected to have formed as complements to the near-monomineralic ferroan anorthosites; and (c) the remarkable compositional uniformity (in terms of ratios among ITE, especially REE) displayed by ITE-rich lunar rocks, i.e., by KREEP [3]. Clearly, key constraints on the origin of KREEP, and thus on the origin of the lunar crust in general, can be derived from a careful assessment of the composition of KREEP. Both the average composition, and evidence for systematic compositional diversity among KREEPy rocks (e.g., compositional effects linked to the "field" provenance) are of interest.

With this aim in mind, I have compiled an extensive data base for the compositions of ITE-rich lunar rocks (using data from far too many literature sources to be specified here), and fine-tuned the Warren and Wasson [3] "KREEP component" composition. A better name for this composition is high-K KREEP. KREEP is remarkably uniform, and no convincing evidence for compositional clustering into genetically distinct low-K, medium-K and high-K subclasses has been adduced (except for clustering produced by limited sampling of a compositionally diverse lunar crust). The simplest assumption would be that a continuum exists from low-K to highest-K KREEP. Nonetheless, a range of enrichments does occur, and (as we shall see below) even for ITE ratios, differences exist between the extremes of this range. Also, confusion arises between the "KREEP component" of Warren and Wasson [3] and their separate "urKREEP" material — the hypothetical residual melt from the magmasphere, posulated to be at least indirectly parental to all KREEP. This confusion should be reduced by renaming the KREEP composition "high-K KREEP."

I follow the approach used (at least for most elements) by [3], and model the "high-K KREEP" composition not as a simple average, but rather by interpolation (or for some elements upward extrapolation) along correlation trends shown by the element in question, when plotted vs. ITE, especially REE. Warren and Wasson [3] arbitrarily defined their "KREEP component" to have 49 μg/g of Sm — for the sake of consistency with earlier proposed compositions, and because available samples are seldom ITE-enriched enough to allow estimation (except by extensive extrapolation) of a "KREEP" composition more "high-K" than one with 49 μg/g of Sm. I have likewise arbitrarily defined "high-K KREEP" to have 10.0 μg/g of Tb. For most REE, this results in virtually the same composition for my high-K KREEP as for the "KREEP component" of [3]. Rather than plotting all other elements vs. Tb (in many analyses Tb is determined poorly, or not at all), I plot the elements vs. an average ITE ratio, *KR*. The *KR* ratio is arbitrarily defined as the average of sample/KREEP ratios for a large set of ITE, where for the present compilation the "KREEP" composition used was that of [3], except with Ce revised to 280 μg/g. Two different *KR* ratios were calculated for each sample: one based on light REE (La, Ce, Nd, Sm, Gd, Tb and Dy) alone, and the other based on these same light REE, plus Rb, Ba, Er, Lu, Ta, Th and U. Data for the element in question are plotted vs. *KR* (using both *KR* ratios, shown by different symbols, on the same diagram), and the intercept of the data trend (which ideally is linear) at $KR = 1.0$ (i.e., Tb $\approx$ 10.0 μg/g) defines the composition of high-K KREEP.

Results for a few ITE and the *mg* ratio are shown in Fig. 1. On these diagrams, the filled symbols represent samples from Apollo 14, the unfilled symbols represent samples from all other sites. Results for La and Lu are unsurprising: well-defined intercepts at $KR = 1.0$ agree precisely with the "KREEP component" composition of [3]. However, results for a few other elements present some surpises. For example, Th shows a $KR = 1.0$ intercept clearly defined to be at least 22 μg/g, i.e., 22% higher than the value suggested by [3]. Major revisions also seem advisable for Li, Mg, Y, Zr, Nb, Cs (revised by a factor of two), Ta, W and U (Table 1). In general, the element (or ratio) vs. *KR* diagrams show little distinction between Apollo 14 KREEPy samples and those from other sites, except for a tendency for Apollo 14 samples to have medium-high *KR*. Note, however, that the trend for La (Fig. 1a) appears distinctly shallower in slope for Apollo 14 samples. This difference in slope is consistent with the observation of McKay et al. [4] that KREEPy rocks from Apollo 14 tend to have slightly more "concave up" chondrite-normalized REE patterns than KREEPy rocks from other sites.

A few other apparently distinctive traits of the Apollo 14 KREEPy rocks are also noteworthy. In comparison to non-Apollo-14 rocks of similar *KR* ratio, those from Apollo 14 tend to have systematically higher Mg contents (a disparity that is almost equally apparent from their *mg* ratios: Fig. 1d), and slightly lower Si contents. Also, far more scatter is seen among Apollo 14 rocks for alkali elements (Li, K, Rb and Cs). The higher Mg and lower Si make sense when considered vis-a-vis the predominance of troctolitic lithologies (and surprising scarcity of norites) among the few pristine nonmare rocks from this site. Apparently, after a noritic form of KREEP (unfortunately not yet found in clearly pristine form), the second most abundant pristine component in the Fra Mauro Formation is troctolite. Two possible explanations come to mind for the greater alkali scatter: (a) the data for Apollo 14 samples tend to be older than the data for other nonmare samples, and thus some of the scatter might be caused by inferior analyses; (b) granitic and alkali-cumulate lithologies appear to be unusually abundant in the Apollo 14 region, and these non-KREEPy rock types may account for major proportions of the total alkali element contents of typical Apollo 14 breccias. Of these two factors, (b) is probably the most important.

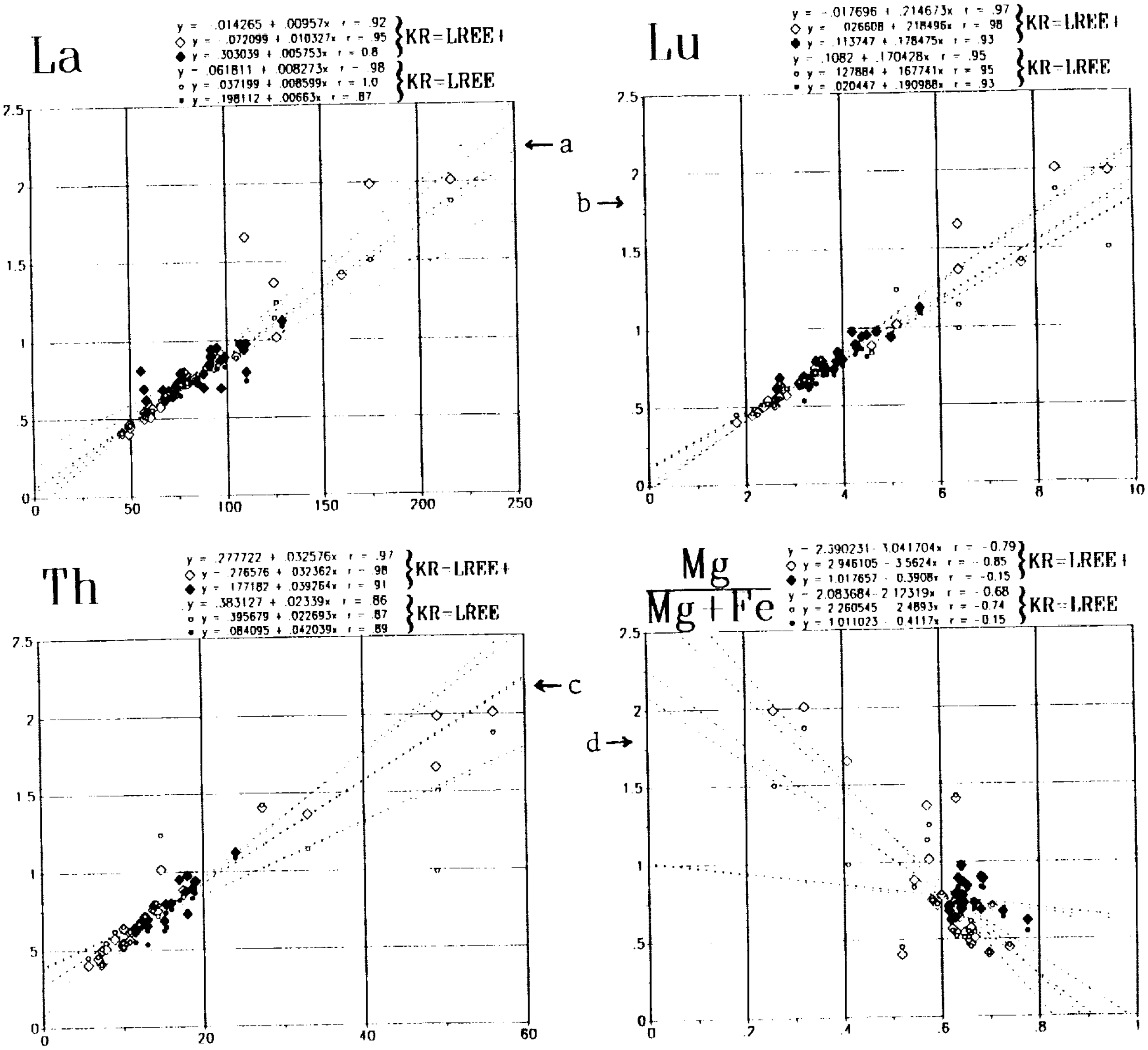

Figure 1.

This study has also revealed some surprising ITE differences between low-*KR* KREEP and high-*KR* KREEP. The ratio Zr/Th shows a clear negative correlation with *KR* (Fig. 2). The ratio Ta/Hf shows a weak positive correlation with *KR*. However, the ITE compositions of KREEPy rocks are more remarkable for their uniformity than for their diversity. Of course, most relevant in this connection are the compositions of unmixed, pristine KREEPy rocks. Unfortunately, except for Apollo 15, most sites have provided few or no samples of pristine KREEP. Few, if any, KREEPy rocks are incontrovertibly pristine. The main grounds for deeming a few KREEPy rocks pristine are low siderophile element contents, indicating a lack of meteoritic involvement in their genesis. However, Ryder [2] argues that the most common variety of ostensibly pristine KREEP, the KREEP basalts from Apollo 15, often show signs of multi-stage cooling; and Ryder interprets these complex cooling histories as a result of meteoritic-impact disaggregation of the cooling lavas (nevertheless, Ryder remains confident that these rocks are pristine). Other samples of probably pristine KREEP that have been analyzed for ITE are a set of quartz monzodiorite clasts in Apollo 15 breccia 15405 [5], and a set of pigeonite basalt clasts in Apollo 17 breccia 72275 [6]. Also, arguably a pristine granitic clast from Apollo 14 breccia 14304 [7] might be considered to have KREEP affinity. The contents of a number of commonly-determined ITE in these samples are shown normalized to high-K KREEP (Table 1) in Fig. 3. Also shown for comparison is an apparently polymict melt lithology from Apollo 16 breccia 67975 [8], included because it is far more REE-rich than any other Apollo 16 lithology; and a pristine granite clast from breccia 14321 [7]. These data suggest that the correlations between the Zr/Th and Ta/Hf ratios and *KR* are not restricted to polymict samples. However, compared to other REE-rich pristine lithologies, such as the 14321 clast, the ITE patterns (and especially the REE patterns) of pristine KREEPy rocks are flat.

The general uniformity of the ITE patterns among KREEPy rocks (and most significantly among the pristine ones), despite their great diversity of major-element compositions, suggests derivation of nearly all of the ITE budget of the lunar crust from a common parental material — presumably the residual melt of the primordial magma ocean, i.e., urKREEP [3]. The paradox that all but the very highest-K varieties of KREEP have moderate *mg* ratios (Fig. 1d) is readily explained as a consequence of mixing between urKREEP and early-post-magmasphere Mg-rich intrusions into the region of the lower crust [9].

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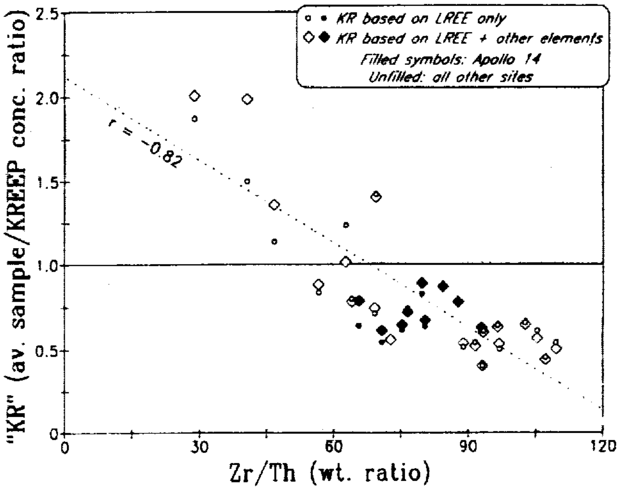

Figure 2.

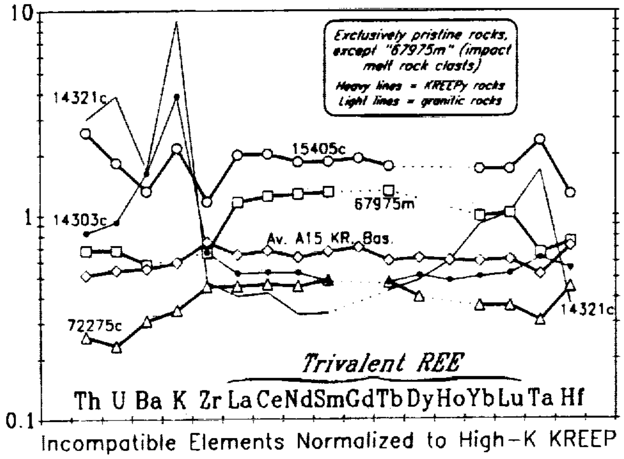

Figure 3.

KREEP

Warren P. H.

Table 1. The composition of high-K KREEP, as compiled by Warren and Wasson (1979), and proposed revisions.

		W&W '79 KREEP (av. high-K)	This work KREEP (av. high-K)	Strength of correlation with "KR"	High-K KREEP/CI wt. ratio	Uncertainty class* (see below)
Li	µg/g	56	40	moderate +	25	III
Be	µg/g	not est.	10	moderate +	370	(II)
B	µg/g	not est.	25	moderate +	21	(IIII)
F	µg/g	not est.	100	weak + (?)	1.56	(OM)
Na	mg/g	6.4	7	moderate +	1.43	II
Mg	mg/g	64	50**	moderate -	0.52	II
Al	mg/g	88	80	weak -	9.3	I
Si	mg/g	224	235	weak + (?)	2.24	I
P	mg/g	3.4	3.5	moderate +	3.4	III
S	mg/g	1.1	1.1	none	0.02	(IIII)
Cl	µg/g	not est.	100	v. weak + (?)	0.15	(OM)
K	mg/g	6.9	8	weak +	14	III
Ca	mg/g	68	70	weak -	7.6	II
Sc	µg/g	23	23	none	4.0	II
Ti	mg/g	10	12	v. weak +	29	III
V	µg/g	43	40	weak -	0.73	II
Cr	µg/g	1.3	1.2	weak -	0.45	II
Mn	µg/g	1.08	1.05	none	0.55	II
Fe	mg/g	82	80	weak +	0.44	II
Co	µg/g	33	25	weak -	0.05	IIII
Cu	µg/g	20	20	weak + (?)	0.17	(OM)
Zn	µg/g	3.6	5	none (?)	0.02	OM
Ga	µg/g	7.5	9	weak +	0.92	(III)
Ge	ng/g	40	500	none (?)	0.02	OM
Br	µg/g	not est.	120	moderate +	0.03	IIII
Rb	µg/g	22	22	weak +	9.9	III
Sr	µg/g	200	200	v. weak +	25	I
Y	µg/g	300	400	strong +	278	(II)
Zr	µg/g	1700	1400	strong +	368	III
Nb	µg/g	80	100	moderate +	370	(III)
Cd	ng/g	15	100	none (?)	0.15	(OM)
Cs	ng/g	2000	1000	weak +	5.46	III
Ba	µg/g	1200	1300	strong +	565	II
La	µg/g	110	110	v. strong +	466	
Ce	µg/g	270	280	v. strong +	455	I
Pr	µg/g	not est.	37	v. strong +	398	I
Nd	µg/g	180	178	v. strong +	389	
Sm	µg/g	49	48	v. strong +	322	
Eu	µg/g	3.0	3.3	moderate +	59	I
Gd	µg/g	57	58	v. strong +	294	
Tb	µg/g	10	10.0	v. strong +	282	
Dy	µg/g	65	65	v. strong +	265	
Ho	µg/g	14	14	strong +	256	I
Er	µg/g	39	40	v. strong +	250	
Tm	µg/g	not est.	5.7	v. strong +	231	I
Yb	µg/g	36	36	v. strong +	226	
Lu	µg/g	5.0	5.0	v. strong +	204	
Hf	µg/g	37	38	strong +	317	I
Ta	µg/g	4.0	5.0	v. strong +	313	II
W	µg/g	2.0	3.0	strong +	30	(III)
Pb	ng/g	not est.	11	weak +	4.6	III
Bi	ng/g	not est.	230	weak +	2.1	III
Th	µg/g	18	22	v. strong +	759	I
U	µg/g	5	6.1	strong +	744	I
Molar Mg/(Mg+Fe)		0.64	0.59**	moderate -		II
Molar Ca/(Ca+Na)		0.86	0.84	moderate -		II

*Estimated uncertainties for the av. high-K KREEP composition, expressed as maximum expected percentages of deviation between "true" average and estimates: blank = 5%, I = 10%, II = 20%, III = 30%, IIII = 40%, OM = Order of magnitude. Parentheses denote elements for which extrapolation to high "KR" is required.

** Mg concentrations appear to be systematically higher in Apollo-14 KREEP vs. KREEP from other locales.

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