WORKSHOP ON

THE GEOLOGY AND PETROLOGY OF THE APOLLO 15 LANDING SITE

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LUNAR AND PLANETARY INSTITUTE 3303 NASA ROAD 1 HOUSTON, TEXAS 77058-4399

WORKSHOP ON

THE GEOLOGY AND PETROLOGY OF THE APOLLO 15 LANDING SITE

Edited by

Paul D. Spudis
and
Graham Ryder

Sponsored by

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Contents

Preface

This report documents the "Workshop on the Geology and Petrology of the Apollo 15 Landing Site," held at the Lunar and Planetary Institute on November 13–15, 1985. This workshop was one of a series of workshops and topical conferences instigated by the Lunar and Planetary Sample Team (LAPST) to focus community attention on important and interesting topical problems in lunar science. Prior to the workshop, the conveners published a review paper on Apollo 15 site geology as it was then understood (P. D. Spudis and G. Ryder, *EOS, Trans. AGU*, v. 66, no. 43, pp. 721–726, 1985) and one of the conveners had produced a new, comprehensively annotated catalog of the Apollo 15 rock samples (G. Ryder, Catalog of Apollo 15 Rocks, *Curatorial Branch Publication 72*, NASA-JSC 10787, 1295 pp., 1985). Both of these documents set the stage for a lively and productive workshop that attempted to define and tackle some major lunar geologic problems and processes from the perspective of one of the most beautiful and fascinating lunar landing sites: the Hadley-Apennine region. The presence of both Dave Scott and Jim Irwin, the astronauts who explored the landing site, was an unprecedented and stimulating factor for such a workshop.

Workshop Rationale and Format

P. D. Spudis and G. Ryder

The geology of the Apollo 15 landing site has remained poorly understood, in contrast with that of the geology and samples of the Apollo 16 and 17 landing sites. The Apollo 15 site is on the rim of the Imbrium basin, the remains of a paramount event in lunar geologic history. It encompasses a remarkably complete stratigraphic section ranging from pre-Imbrian to Copernican, unique among Apollo sites. Within the Apollo 15 samples, site photographs, surface experiments, and crew reports is recorded a variety of lunar processes and historical events, many of which are at present only dimly perceived. The petrology and stratigraphy of site materials are relevant to lunar crustal composition, formation, and origin; the mechanics and ejecta depositional processes of craters ranging from large basins to secondary clusters; and a whole gamut of volcanic processes. However, the Apollo 15 mission was often felt to have received short shrift and to have been overshadowed by the succeeding Apollo 16 landing. It had never had a "conference of its own" at which multidisciplinary approaches could focus on its scientific opportunities. There was a perception that there were glaring deficiencies in our understanding that would be remedied by a multidisciplinary examination of the Apollo 15 landing site, especially in the light of the results from other missions. In the following paragraphs we summarize, in order of the workshop topics, some of the rationale and questions, perceived before the workshop, which it and subsequent studies might at least partly answer.

Sampling of the Apennine Front was the prime target of the Apollo 15 mission, yet its petrology has remained one of the major outstanding problems. The talus deposit on the lower slopes of Hadley Delta is dominated by mare debris and mare-rich breccias; highlands materials is generally cryptic or at least small. Small samples, including coarse-fines from the regoliths, were scantily regarded in the Apollo mission days, partly because of time constraints. These small samples are now a target for study. Why was so little highlands materials found? Is the Front dominantly very friable material? A rough average composition appears to be some form of low-K Fra Mauro (LKFM, a low-KREEP basaltic composition), and there are some impact melts of this broad composition; these might represent Imbrium basin impact melt. We do not know the range of compositions in the highlands, although igneous ferroan anorthosites, norites, and troctolites have been found. These cannot mix to produce the average; the LKFM composition has so far been found as non-igneous rocks, and its origin is a recurring question that investigation of the Front samples might solve. The regolith throughout the site contains highlands components, mostly in cryptic form. Up to the present, petrographic studies of particle populations and synthesis of chemistry (especially mixing models) have not been particularly directed at defining the highlands materials. Not until the terra components are identified can the events and processes that formed them be deciphered. The common pre-mission interpretation of massif materials forming the Front is of an Imbrium and Serenitatis basin origin. The sample suite is at present too poorly understood to adequately assess this interpretation, or whether other sources also provided Front material. Can material identified at the Apollo 17 site, e.g., the Serenitatis melt sheet, be identified among the Apollo 15 samples? Ejecta comprises older material; there are some deeply derived lower crustal (?) samples in the collection, but their significance has not been adequately discussed. Basin-related rocks and ejecta can provide much information about multi-ring basin formation.

Volcanic KREEP basalts were an unexpected discovery among the Apollo 15 samples. They are ubiquitous and numerous but small: Only two are individually numbered rocks, and the largest is 7.5 g. Their investigation is essential in shedding light on the development of KREEP on the Moon. They have crystallization ages of ≈3.85 b.y. and, according to Sr-isotopic studies, at least two distinct extrusions have been sampled. Their age cannot yet be distinguished from that of the Imbrium impact, but there is evidence that they are derived from the Apennine Bench Formation, hence are post-Imbrium. Was pressure-release significant in their genesis? The number of flows, their fractionation, and their origin is not yet known. How did they get distributed around the site as tiny fragments—from beneath the local mare units or delivered laterally by rays? Why are their rare earth abundances so much lower than the Apollo 14 (brecciated) KREEP? How does the much older zircon age of the quartz-monzodiorite clasts in 15405 fit in with KREEP petrogenesis? A few workers remain unconvinced of the origin of Apollo 15 KREEP as volcanic flows, suggesting instead that they are impact melts, perhaps from Imbrium itself.

The Apollo 15 highlands, once its composition and stratigraphy have been established, offer a perspective on lunar basins, especially with integration of information from other landing sites. One important potentially solvable question is the age of the Imbrium basin. Can we identify Imbrium basin ejecta at Apollos 14 and 16 and compare it with that of Apollo 15? What can cratering mechanics and remote sensing tell us about the target stratigraphy? Understanding the relationship between Apollo 15 KREEP basalts and the Imbrium basin is of fundamental importance in establishing crustal responses to large impacts and the thermal state of the Moon's crust at ≥3.9 b.y. ago. How did the pronounced layering at Silver Spur form? Cratering mechanics and the lateral and vertical redistribution of crustal materials are intimately related. Understanding of Imbrium ejecta and its distribution is a profitable approach toward understanding these problems.

Hadley Rille was an important target and has been well described, but its origin as a lava channel or tube is not undisputed. Even if it is a lava tube, the mechanism of its formation is unclear. It has not been clearly related to any of the sampled lavas. Can the features seen in its walls be adequately correlated with the known characteristics of the rocks, for instance the thickness of flows as determined from samples? The rille might expose unsampled lava types. If so, then we need to explain how Apollo 15 KREEP volcanics and the yellow volcanic glasses were distributed around the landing site without exposing them. Perhaps distinct mare volcanics do exist as small samples (e.g., coarse fines) but have not been recognized. There is a dark feature around the base of the massifs that has been disputably interpreted as a "high lava" mark. Is there an episode of lava ponding recorded within the mare basalt samples? The landing site lies upon a topographic ridge, and to the north is the raised mound of the North Complex, a planned sampling location not eventually visited. Are these features mare-related or older (e.g., Apollo 15 KREEP)? The inventory of basalt types has not necessarily been completed, because some small samples have not been adequately characterized and yet seem to be distinct. The olivine-normative and quartz-normative mare basalts are distinct in major element chemistry, yet have indistinguishable ages and isotopic systematics, and almost identical trace element patterns. The proper interpretation of this puzzling feature has never been addressed, yet surely is of deep significance for the petrogenesis of mare basalts in general. Several geochemists have suggested on the basis of small differences in trace element ratios that the two main mare basalts have subgroups. If the existence of these subgroups is verified, they have import for mantle processes or assimilations. Hadley Rille formation might include assimilation if it incorporated downcutting. Can recent suggestions that terrestrial komatiites assimilated older flows guide us in interpretations of Hadley Rille and the chemistry of the mare basalts? Where are the source vents for the lavas and what are they like? If the vents are some distance away, then it is quite likely that surface fractionation has occurred and that the magmas as erupted have not been sampled. If the flows came any great distance, one might not expect volatiles in sufficient abundance to have created the 30% to 40% vesicularity of many of the olivine-normative mare basalts. What were the volatiles and where did they come from? What is the basalt distribution and stratigraphy? Did the olivine-normative basalts form as a spillover from the rille? Several cooling rate studies, some rather quantitative, have been made on the mare basalts. Can these shed further light on the volcanic flooding history of the landing site?

Green glasses that are volcanic pyroclastics are common, apparently more so on the Apennine Front. On stratigraphic grounds they would appear to pre-date the lava flows and mantle the Apennines, although their radiometric ages are indistinguishable from the mare lavas. Green glass occurs as friable clods, some rather pure and likely to represent original deposits, yet the stratigraphy of green glass, the nature of eruptional mechanisms, depositional processes, and ultimate origin are still poorly known. Several slightly but significantly different compositions exist, but we do not yet know how they are related to each other, or whether they were deposited sequentially or simultaneously. Whether a single near-pure clod of glass contains one or more than one group has not been established; the relevant analytical work has not yet been performed. Other pyroclastic glasses, yellow and red, disseminated at the site are even more poorly understood. Relationships among glass groups and other geologic units have not been deciphered because of a lack of data on trace element chemistry, ages, and radiogenic isotopic ratios, and stratigraphic context.

Lavas are probes of the lunar interior, but how so is subject to interpretation. The pyroclastic glasses would appear to be the magma as extruded, hence the most primitive and more direct probes. However, even their interpretation requires assumptions about multiple or single phase saturation, fractionation during ascent, and wall-rock interaction. Their major and trace element chemistries can be and are being studied to place constraints on interior processes and mantle melting. Volatile species within the glasses are currently under investigation as guides to the lunar interior and lunar formation. Volatiles on the surfaces contain primitive lead and indicate the presence of primitive volatile reservoirs within the Moon. For lavas, the problem is compounded in that they are more fractionated and the lava, even as it first arrived at the lunar surface, cannot be unequivocally established. But a wide variety of mantle-derived materials is present at the Apollo 15 landing site and in synthesis can provide a useful guide to the composition, variation, and origin of the lunar mantle at a single spot.

The conjunction of the older steep highlands and younger flat mare makes the Apollo 15 site particularly appropriate for examining post-mare regolith development, the roles of lateral and vertical mixing, and talus development. This requires a critique and comparison of geochemical mixing models and their reality, as well as input from remotely sensed data of areas further afield. Drill cores can be especially useful; one drive-tube, collected at Spur Crater, has not yet been opened. Regolith at the lip of Hadley Rille is very thin, and this may be the only site on the Moon where bedrock blocks have been sampled almost *in situ*. What can compositional chemistry of regolith glasses tell us about the target and the glass-forming process?

A number of "recent" cratering events may be studied at the Apollo 15 site. Specific ray materials can possibly be identified among samples, if adequate criteria can be developed. Do exotic rocks (e.g., 15405) record major impact events, perhaps related to Aristillus or Autolycus? If ray deposits within core and drill sections are identifiable, perhaps we can use this information to decipher the mechanisms of ray deposition. The geology of the South Cluster has the potential to tell us about the formation of large secondary craters.

Apollo 15 is an important lunar site at which a remarkably complete lunar stratigraphic section may be studied. Aspects of all major lunar processes may be profitably studied from this single location.

The workshop was held at the Lunar and Planetary Institute on November 13–15, 1985. Conveners were Paul D. Spudis and Graham Ryder; other members of the organizing committee were A. Basu, B. R. Hawke, F. Hörz, and M. Lindstrom. Sixty-one registrants participated in the workshop (see Participants) and included experts in lunar petrology and geochemistry, cratering mechanics, photogeology, remote-sensing, geochronology, and regolith modeling.

The first morning session consisted of an overview of the regional geologic and geochemical setting of the Apollo 15 site and reviews of site-specific geology and returned samples (see Program). Apollo 15 crew members David R. Scott (Commander) and James B. Irwin (Lunar Module Pilot) participated in an hour-long "question-and-answer" session that not only sparked a lively discussion period, but also provided several key observations of the site geology that were repeatedly brought up in subsequent discussion sessions. An evening keg session brought the workshop participants face-to-face with the complexities of the Hadley-Apennine site, as an edited two-hour videotape of the three Apollo 15 surface traverses (EVAs) was shown.

The remaining workshop time was organized into six topical sessions covering the major questions posed by Apollo 15 site geology. Each topical session consisted of one (or more) keynote address, followed by contributed papers and general discussion. These discussion periods (see Discussion Summaries) were both lively and productive; while a consensus could not be achieved on all isues, there were points of general agreement and new directions for future research were pointed out. A special session on the last morning was an update on the JSC Lunar Initiative and a discussion of the relevance of the Apollo 15 site to future lunar exploration and utilization. The workshop ended with a summary session that reviewed the six topical questions and an open forum for workshop participants.

Program

Wednesday, November 13, 1985
Morning

INTRODUCTION
Conveners G. Ryder and P. Spudis

OVERVIEW OF THE APOLLO 15 LANDING SITE
Chairman: L. T. Silver

Geologic Setting of the Apollo 15 Landing Site
Selection of the Apollo 15 Landing Site
D. Wilhelms

Remote-sensing of the Hadley-Apennine Region
B. R. Hawke

Some Observations on the Geology of the Apollo 15 Landing Site
G. Swann

Samples at the Apollo 15 Landing Site: Types and Distribution
G. Ryder

Crew Observations
D. Scott and J. Irwin

Wednesday, November 13, 1985
Afternoon

TOPIC 1. APENNINE FRONT ROCKS AND THEIR SOURCES
Chairman: O. James
Summarizer: S. Simon

Petrology and Geochemistry of Highland Samples from the Apennine Front
M. Lindstrom

Contributed paper:
Highlands Impact Melts at the Apollo 15 Landing Site
G. Ryder and P. Spudis

Discussion

TOPIC 2. APOLLO 15 KREEP BASALT
Chairman: G. McKay
Summarizer: P. Warren

Characterization of the Apollo 15 Feldspathic Basalt Suite
R. Dymek

Contributed papers:
The Apennine Bench Formation Revisited
P. Spudis and B. R. Hawke

The Origin of Pristine KREEP: Effects of Mixing Between urKREEP and the Magmas Parental to the Mg-rich Cumulates
P. Warren

Discussion

Wednesday, November 13, 1985
Evening

Keg session and videotapes of Apollo 15 EVA's

Thursday, November 14, 1985
Morning

TOPIC 3. APOLLO 15 PERSPECTIVE ON LUNAR BASINS
Chairman: G. Schaber
Summarizer: B. R. Hawke

The Materials and Formation of the Imbrium Basin
P. Spudis

Contributed paper:
Spectral Reflectance Study of the Hadley-Apennine (Apollo 15) Region
P. Lucey and B. R. Hawke

Discussion

TOPIC 4. MARE VOLCANISM AT THE APOLLO 15 LANDING SITE
Chairman: G. Lofgren
Summarizer: L. Taylor

Hadley Rille, Lava Tubes and Mare Volcanism at the Apollo 15 Site
R. Greeley and P. Spudis

The Geologic History of Quartz-normative and Olivine-normative Basalts in the Vicinity of Hadley Rille (Apollo 15)
T. Grove

Contributed papers:
**Extraction of Information from Major Element Chemical Analyses of Lunar Basalts*
J. Butler

Apollo 15 Mare Basalts: Diverse Suite or Two Distinct Groups?
P. Salpas and L. Taylor

Discussion

Thursday, November 14, 1985
Afternoon

TOPIC 5. MARE ROCKS AND THEIR IMPLICATIONS FOR THE MANTLE BENEATH THE APOLLO 15 SITE

Chairman: M. Drake
Summarizer: J. Delano

Apollo 15 Mare Volcanism: Constraints and Problems
J. Delano

Contributed papers:
Apollo 15 Mare Lavas and Their Petrogenesis
A. Binder

Ultramafic Parent Magmas for Mare Basalts?
J. Longhi

Discussion

TOPIC 6. POST-MARE CRATERING AND APOLLO 15 REGOLITH EVOLUTION

Chairman: R. Morris
Summarizer: A. Basu

Chemical Components of the Apollo 15 Regolith
R. Korotev

Exotic Components at Apollo 15: A Relook at Secondary Cratering
P. Schultz

Contributed papers:
Regolith Erosion and Regolith Mixing at the Apollo 15 Site on the Moon
A. Basu

Comparison of Petrology, Grain Sizes, and Surface Maturity Parameters for Apollo 15 Regolith Breccias and Soils
D. Bogard, D. McKay, R. Morris, P. Johnson, and S. Wentworth

Apollo 15 Regolith Breccias and Soils: Comparative Petrology and Chemistry
S. Simon, J. Papike, and J. Laul

Discussion

Friday, November 15, 1986
Morning

SPECIAL SESSION: THE APOLLO 15 SITE AND FUTURE LUNAR EXPLORATION

Chairman: W. Mendell

Contributed paper:
**Apollo 15 Lunar Base Site: Steep Slopes as an Energy Resource*
J. Burke

Discussion

SUMMARY SESSION: MAJOR PROBLEMS FOR FUTURE APOLLO 15 RESEARCH
Chairmen: G. Ryder and P. Spudis

Summarizers review and identify outstanding problems and possible approaches to their solution

Open forum for all workshop participants

Adjourn, 12:00 noon

*Not presented.

Summary of Questions Formulated by the Program Committee

I. Apennine Front Rocks and Their Sources

1. Which samples represent materials of the Apennine Front?
2. What is the average composition of the Apennine Front?
3. Why are distinctly highlands samples sparse even on the Front?
4. What does the low-K Fra Mauro (LKFM) composition represent?
5. Which material is basin ejecta? Which is basin melt?
6. Can Imbrium, Serenitatis, and pre-Serenitatis debris be distinguished?
7. What is the significance of aluminous samples such as 15415 "Genesis Rock" (anorthosite) and 15418?
8. Where do the Mg-suite pristine igneous rocks come from?
9. How were the Apennines emplaced?
10. What is the origin of the benches on Silver Spur?
11. Would opening drive tube 15009 be likely to be productive?

II. Apollo 15 KREEP Basalt

1. Are Apollo 15 KREEP basalts of volcanic or impact origin?
2. Is the Apennine Bench Formation KREEP basalts?
3. Is KREEP basalt present in the Apennine Mountains and backslope?
4. What is the age of KREEP basalts relative to that of Imbrium? Were there extended periods of emplacement?
5. What is the distribution of KREEP basalt at the landing site?
6. What is the provenance: lateral transport (exotic), or sub-mare excavation, or transport from the Apennines?
7. Has only one extrusive episode been sampled?
8. What is chemical range and fractionation process? What is relationship with quartz-monzodiorite?
9. What is the nature of their partially molten source, its history, and the cause of its melting? Is melting Imbrium-related?
10. Is there any connection between "Red Spots" in the Apollo 15 region and KREEP?
11. What is the reltaionship between the Apollo 15 KREEP basalts and KREEP-rich materials returned from other regions?
12. Does the North Complex have any relationship with KREEP basalts?

III. Apollo 15 Perspective on Lunar Basins

1. Which material is basin-related and to which basin?
2. Is there a stratigraphy of basin deposits at the site?
3. How do Apennine Front samples compare with Apollo 14 and 16 site materials?
4. What does the Apollo 15 region tell us about processes of lunar basin formation?
5. What is the age of the Imbrium basin impact?
6. What can cratering mechanics, remote sensing, and samples tell us about the target (crustal?) stratigraphy at Imbrium?
7. Is apparent layering at Silver Spur real, and if so, how did it form? Why do the Apennines lack horizontal ledges abundantly observed at Taurus-Littrow?
8. Are basin formation models adequate? How does present morphology relate to dimensions of the excavation cavity? How do rings form? Where did most of the Apennines form—in an Imbrium or Serenitatis scenario, if not both?

9. How much of the lunar crust was disturbed by basin impacts and how are these materials laterally and vertically redistributed? How much ejecta was molten? What does molten ejecta look like? Where does it end up?

10. What measurements should be performed from a Lunar Polar Orbiter to learn about basin formation and lunar crustal stratigraphy? What other studies need to be performed to improve our understanding of basin formation?

IV. Mare Volcanism at the Apollo 15 Landing Site

1. What is mode of formation of Hadley Rille? If lava channel or tube, which magmas used it? Why is it so big?
2. Where are source vents or fissures for lavas and volcanic glasses?
3. How are the olivine-normative and quartz-normative basalts stratified around the site? How are volcanic glasses distributed around the site?
4. How much fractionation in surface flows occurred?
5. How thick are the flows? How thick is the total pile? Was there any lava ponding or subsequent drainage?
6. Was flow chemistry affected by surface or subsurface assimilation?
7. Did Hadley Rille formation include erosion or assimilation?
8. Why do the two distinct lava types have indistinguishable ages, isotopic characteristics, and rare-earth element patterns? Do the main groups comprise subgroups? Are there other groups?
9. What were the volatiles that caused intense vesicularity of many olivine-normative mare basalts? Where did the volatiles come from?
10. Is the North Complex a mare construct or a pre-mare feature?

V. Mare Rocks and Their Implications for the Mantle Beneath the Apollo 15 Site

1. Can the chemistry of the lava flows as they were extruded be inferred?
2. Can subsurface fractionation and assimilation effects be inferred?
3. Are the volcanic glasses (green, red, and yellow) truly primary or near-primary magmas?
4. Are the assumptions linking high-pressure phase petrology of glass compositions to mantle petrologies adequately established for the lunar case?
5. Can both phase and trace element chemistry of mantle sources of volcanic glasses be reasonably inferred?
6. How complex is the petrogenesis of mare magmas? How complex was the evolution of their source mantle?
7. Can a petrologic column for the mantle beneath the Apollo 15 site be constructed?

VI. Post-mare Cratering and Apollo 15 Regolith Evolution

1. What rates of lateral migration of soil materials can be established, i.e., Front material mixed into mare soil and mass wasting at edge of Hadley Rille?
2. How good are chemical mixing models, end members, and petrologic reality?
3. What is the origin of layers in the drill cores—ejecta or slump?
4. What highland-mare geochemical gradients are observed remotely?
5. How and why are modal abundances of hand specimen, rake samples, coarse fines, and various soil fractions unlike each other?
6. Can agglutinate compositions be used as tracers of different sources?
7. Which surface features and events are dated reliably, e.g., South Cluster (Dune)?
8. Is there unequivocal evidence of ray material?
9. Why are mare basalts so scarce at the LM site?

Discussion Summaries

Prepared by: A. Basu, J. Delano, B. R. Hawke, G. Ryder, S. Simon, P. Spudis, L. Taylor, and P. Warren

Note: In the summaries, Mg′ = Mg/(Mg + Fe) atomic.

Topic 1: Apennine Front Rocks and Their Sources (O. B. James, Chair)

One of the major scientific objectives of the Apollo 15 mission was to sample the Apennine Front, which is part of the Apennine Mountain chain. These mountains are part of the rim of the Imbrium basin, and it was expected that the Front should consist largely of Imbrium ejecta (consisting of pre-Imbrian material) and possibly some Serentitatis ejecta.

In her keynote talk, Marilyn Lindstrom reviewed the samples from the Front, particularly the larger rock samples, and its regolith chemistry. The most abundant rocks are regolith breccias, and genuine highlands lithologies are rare and generally small. The highlands samples include anorthosite 15415, recrystallized and/or remelted anorthositic norite breccia 15418, and some impact melt fragments containing pristine igenous clasts including troctolites, spinel-troctolites, and noritic lithologies. KREEP basalt fragments are also present on the Front. The regolith breccias have an even greater variety of clasts, including anorthosites, granulites, mare and KREEP basalts, green glass, impact melts, and anorthositic norites. At present there is little data on clasts in regolith breccias. More information on clast populations and compositions is needed.

Compositions of materials, including pristine igneous rocks, breccias, and regoliths, on a Sm versus Sc plot (Lindstrom, this volume) form three trends from a central point: toward KREEP basalt, toward mare materials, and toward pristine igenous lithologies. The impact melt samples fall close to the central point, and there is a hiatus on the pristine igneous lithologies arm. The impact melts and the soils roughly correspond with the low-K Fra Mauro (LKFM) basalt composition as defined long ago. Understanding the components of this mixture, particularly in the melts, is difficult: Apollo 15 (or Apollo 14) KREEP only contributes 20% to 30% of the Sc (otherwise the Sm of LKFM would be higher) and thus a high-Sc component, unrecognized if it is not mare, is required.

In the discussion immediately following and apposite to Lindstrom's review, the LKFM problem was immediately focused upon. Delano noted that the problem was one of Ti-Sc-Fe in mixing, and he questioned why mare basalt was not acceptable, pointing out that the existence of old mare volcanism (4.2+ b.y.) had been established. Ryder noted that all clasts so far found in LKFM melts appear to be deep-seated rather than mare volcanic, but this did not preclude plutonic mare as the required component. Gordon McKay wanted to know why we did not see two point mixtures, e.g., KREEP-mare and or KREEP-anorthosite such as one would expect in random mixtures. Evidently the mixtures are not random. In response to the suggestion during the keynote talk that we need to study small fragments, e.g., breccia clasts, Basu pointed out the difficulty of representivity, but it was generally agreed that the attempt, if properly made, would be fruitful.

The main discussion period followed some headline questions posed by the Chair. The first—"Which samples represent Apennine Front subregolith?"—with a list of candidates, rapidly evolved into a discussion of the role of Apollo 15 KREEP basalt on the Front. Spudis, equating the Apennine Bench Formation and Apollo 15 KREEP, placed KREEP samples on but not in the Front, but said that orbital geochemical data required *some* KREEP type in the Apollo 15 highlands. In response to a query from S. R. Taylor, he said that the Apennines to the south have ~7.6 ppm Th, but at the site only 3.0 ppm Th. The problem of KREEP on the Front feeds back to that of the nature of LKFM. Korotev's note that KREEP was a "recent" addition to the Front (more common in coarse fines), Basu's that LM-8 soils have more KREEP basalts than in equivalent size-range Front soils, and Ryder's that KREEP at LM-8 is there with little other highlands contamination convinced most participants that Apollo 15 KREEP basalt is not an integral part of the Front, although it is in the regolith there. No one argued with other candidiates on the list, including ferroan anorthosites, LKFM melts, 15418 anorthositic norite, etc., accepting that the Front contained similar materials.

TABLE 1. Highland Rock Types at Apennine Front

Rock Type	Examples
Ferroan anorthosite	15415 15362 15437? 15361 } unstudied 15363 }
Granulitic breccia	15418 15364 15437?
LKFM fragment-laden melt rock containing Mg-suite clasts	15445 (Mg-Nor. + SPTR) 15455 (Mg-Norite) 15308? 15356? 15357? 15359?
KREEP Basalt	15382 15386
KREEPy fragment-laden melt with clasts of quartz monzodiorite, KREEP basalt, granite	15405 15358?

Following brief statements on current active work on Apennine Front samples, the Chair turned discussion to the origin of LKFM—at first specifically 15445/15455 ("black-and-white" rocks) and then to more general LKFM. Marilyn Lindstrom reported that ongoing INAA work on three subsplits of each rock shows that they indeed have similar chemistry. The Chair compared data for these rocks with other LKFM compositions and, with observations from Marilyn Lindstrom and Randy Korotev, demonstrated differences in LKFM compositions, e.g., different REE abundances, different Mg/Fe. Korotev noted that Warren and Wasson had analyzed two "pristine" norites in 15306, one of which was like LKFM. Warren hedged, saying that its pristinity was "marginal," but that, given the diversity of rocks on the Moon, it was likely that some pristine LKFM *does* exist. More importantly, he thought, was how much LKFM there is in the crust. Korotev felt that there were at least four different kinds of LKFM at the site, one of which was the original soil glass LKFM. At this point, Warren stated that there was an implicit assumption that basin melt compositions would be uniform in composition, and he wanted to know if that were reasonable. Vigorous discussion, quoting the largest well-studied terrestrial impact melt sheet from a heterogeneous target, failed to convince everyone that basin melts would be homogeneous. Intuition appeared to have as much credibility as terrestrial craters of inadequate size.

Ryder made a presentation on new chemical data for 13 Apennine Front impact melt samples (see Ryder and Spudis, this volume), showing a wide variety of compositions and possibly several clusters, one of which is roughly like the Serenitatis (Apollo 17 boulders) melt. Surprisingly, 15445/15455 compositions are not duplicated, but a group with higher REEs than the Serenitatis melts is strongly represented. Ages for nearly all of these melts are lacking.

Discussion on LKFM in general returned to the diversity of compositions, what they represent, and possible pristine varieties or components. James showed that the originally-defined LKFM composition from glasses was not a tight cluster. Drake questioned whether there was any sensible reason to believe that the glasses were rock compositions, and comments from Delano, Ryder, and Korotev made clear the fact that these glasses were impact melts, and that they were like and undoubtedly represented regolith compositions. Spudis felt that the original (glass) definition of LKFM was irrelevant; it is now applied to rocks, and the question is how such things were made. Given that all dated varieties are ~3.9 b.y. old, he proposed that LKFM = basin impact melt, and provides information about the lower crust. At issue then are the kinds of rocks we can imagine in the lower crust. LKFM is a loose term, a convenient way to characterize things.

David Lindstrom, noting the difficulties of modeling the LKFM composition, suggested that the problem could be turned around: Perhaps the *pristine* igneous rocks are anomalous. Warren felt that it was asking too much to expect to model complex mixtures with about four components, but Marilyn Lindstrom countered that only a mare-like component can account for the Sc and other transition metals. Warren suggested that the pristine sample suite may be missing a lot of gabbronorite ("mare-like"), but also suggested that the soils may contain cryptic, old mare materials, decimated because it was surficial. Spudis repeated that LKFM melts appear to sample deep-seated clasts; the only thing that samples LKFM is a big basin-forming impact, which melts it. Ryder thought that even then some pristine LKFM material should have been picked up, and therefore made the straw-man suggestion that LKFM existed as partial melt within a hot crust at 3.9 b.y. and was excavated as melt by impacts. LKFM compositions are cotectic. Grove emphasized that melting at the reaction point guaranteed such a composition, regardless of the source material, and that an impact would produce such a melt; Haskin, however, questioned that, because of the problem of separating the melt from the source during the short time of an impact event. In response to queries from Drake, Ryder affirmed that there was melting in the crust at 3.9 b.y. (Apollo 15 KREEP basalts, for instance), and repeated the proposition that LKFM could have been excavated as an existing partial melt of a plagioclase-pyroxene crustal source. Ryder also pointed out that the olivine mineral clasts in LKFM melts generally have high (0.8 to 0.10%) CaO, suggesting that the olivine cooled quickly; thus they were of shallow derivation, or the target was hot at the time of excavation. Dymek questioned the Ca abundances on the basis of his earlier work on Apollo 17 samples.

Returning to the components problem, S. R. Taylor noted that the extant mare basalts are a very small fraction of the crust, and that older mare basalts probably formed a similarly inadequate fraction to account for the Sc component in LKFM if there was much of the latter around.

The Chair turned the discussion to a comparison of the kinds of rocks found in the Apennine Front with their equivalents elsewhere, summarizing some similarities, e.g., the 15445/15455 norites' similarities to 78235 norite, and anorthosites being similar, except that Apollo 15 anorthosites appear to be richer in augitic pyroxene. Haskin, noting that there is probably no bedrock sampled directly, suggested that one should forget the context of the Apennine Front in such a discussion, replacing it with a general area. Grove echoed that, preferring to place the context as that of the highlands crust at a single spot, but Phinney interjected that some material might come from Serenitatis.

The Chair continued with specific rock comparisons, showing REEs for anorthosites; these are lower in abundance for Apollo 15, and Ryder noted that this was not really consistent with their more evolved nature in having high-Ca px, given that none appear to have trapped liquid; Haskin pointed out that such a perceived inconsistency is model dependent. There was discussion of the immediate geological context of "Genesis Rock" 15415.

Ryder commented that at Apollo 17 there were Mg-suite rocks only, at Apollo 16 there were almost only ferroan anorthosites, and that Apollo 15 had both, and the reason for such a distribution was an issue. Warren felt that it was a question of sampling. Ryder also noted the strong LKFM-Mg-suite tie: Apollo 17 boulders and Apollo 15 black-and-whites, but not much LKFM at Apollo 16. Spudis noted that the orbital data require some anorthosite in the Apennines, even though the regional bulk composition is roughly noritic. He said that there is no doubt about the existence of lateral variations on the lunar surface, but there is a question on vertical variations. While he leans strongly to a gross stratification, the details are not known. At Apollo 15 we sampled Imbrium, at Apollo 17 Serenitatis, at Apollo 16 probably Nectaris, all being different. If we sampled at different spots around a single basin, we would probably similarly get different things.

Discussion of the Apennine Front was terminated following Wilhelms asking if we could foreseeably get more Ar ages on the LKFM melt rocks, perceived as an important constraint on the origin of LKFM. It is a case of getting Ar labs to get interested enough in the problem to make the determinations.

Future Research

Much more sample work is needed to determine the dominant rock type(s) of the Apennine Front, the source of LKFM materials, and to distinguish between Imbrium, Serenitatis, and other impact melts. On account of the lack of large samples, the rake samples, coarse fines, and regolith breccias will have to be examined. Marilyn Lindstrom suggested that clast populations in regolith breccias should be studied, to look for associations between clast types. She also recommended a petrographic—compositional study of norite and anorthositic norite clasts in soils and regolith breccias. Finally, in order to identify melt rock groups, more petrographic, compositional, and age data are needed for Apollo 15 highland melt rocks.

As a result of new data presented on the Apollo 15 impact melts (see Ryder and Spudis, this volume), a particularly interesting problem may be addressed, i.e., the question of basin melt sheet homogenization. If it can be shown by additional data (e.g., Ir/Au ratios; ^{39}Ar-^{40}Ar ages) that group "C" of these melt rocks is indeed identical with the Apollo 17 poikilitic boulders (Serenitatis melts), this would be strong evidence for complete melt sheet homogenization, as the Apollo 15 site is on the opposite side of the Serenitatis basin from the Apollo 17 site.

Topic 2: Apollo 15 KREEP Basalt (G. McKay, Chair)

An unexpected find at the Apollo 15 landing site, and unrecognized until the preliminary examination of samples, was the ubiquitous presence of KREEP basalt. [The name "KREEP" refers to incompatible elements (K, REE, P, etc.) that are enriched in such rocks and have uniform relative abundance patterns at all landing sites]. The Apollo 15 samples have textures like extrusive igneous rocks and lack the siderophile contamination distinctive of impact generated rocks. Hence their importance lies in their not-universally-accepted origin as volcanic rocks, unlike virtually all other KREEP samples.

Dymek reviewed the mineralogy, petrology, and geochemistry of the Apollo 15 KREEP basalts (abstract, this volume). Most of the samples are small fragments or clasts weighing less than 1 g. The largest two are 15386 and 15382: 7.5 and 3.2 g, respectively. The few determined crystallization ages are ~3.9 b.y., and their model ages in several different isotopic systems are about 4.35 b.y. (similar to all other KREEP samples). Bulk-rock REE are typically 150-200× chondrites. Paradoxically, however, the Apollo 15 KREEP basalts also generally have moderate, not evolved, Mg′; bulk-rock values in the range 0.55–0.67 are most common, and the total measured range is 0.35–0.73. Texturally, these basalts are diverse, but typically they are subophitic, with the grain sizes of the major minerals mostly 0.05–0.5 mm. Unlike mare basalts, Apollo 15 KREEP basalts seldom contain phenocrysts or vesicles.

The dominant minerals in Apollo 15 KREEP basalts are low-Ca pyroxene and plagioclase. Pyroxenes are typically zoned from Mg-rich orthopyroxene cores to comparatively Fe-rich pigeonite or augite rims. Olivine is rare. Ilmenite is a late important accessory phase, frequently in the glassy, Si-rich mesostasis, which contains numerous minor phases including silica, Ca-phosphates, and Ba-K feldspars. A constraint from experimental petrology on the origin of these basalts is that most, if not all, plot close to a low-pressure cotectic of low-Ca pyroxene + plagioclase + melt. It seems difficult to link all of the Apollo 15 KREEP basalts to fractional crystallization of a single primary melt, however. The isotopic data demonstrate that little Rb/Sr or Sm/Nd fractionation occurred during the 3.9 b.y. event, virtually all having taken place at the model age of ~4.3 b.y.

Following some questions on the petrographic details of the basalts, the discussion focused on the fundamental problem of whether Apollo 15 KREEP basalts are "pristine" rocks (unaffected by meteorite-induced mixing) or impact melt rocks, in which case their compositions can only be indirectly related to magmas generated in the Moon's interior. S. R. Taylor asked how the textures compared with that of 14310, which is siderophile-rich and a generally accepted KREEP impact melt. Dymek offered that 14310 was similar but had heterogeneously distributed textural zones as well as relict cores for some plagioclases. The Chair mentioned that most Apollo 15 KREEP basalts were small particles in which textural heterogeneities might not be seen, but Dymek responded that several were quite big—of the order of several centimeters—and were homogeneous. Lofgren continued the discussion of textural variations, noting the role of heterogeneous nucleation and "seeding" in impact melts to produce distinctive textures. It was also pointed out that some (volcanic) mare basalts had heterogeneous textures (however, these observations do not refute the postulate that a homogeneous melt is volcanic). Warren remarked that 14310 has been observed, in post-Apollo heyday sawing, to contain a totally foreign breccia clast. He contended that the siderophile data are strong evidence for a volcanic origin for Apollo 15 KREEP basalts. Dymek countered that several terrestrial impact melts contain no detectable meteoritic siderophiles, but both Ryder and Warren contended that this was because terrestrial targets were poor in siderophiles whereas lunar targets were not. In other words, the impact event does not necessarily introduce many new siderophiles into the melt; they may be dominantly inherited from the target. The Chair asked whether there was any evidence for shock in Apollo 15 KREEP basalts; the response was that only post-formation shock features have been identified.

The Chair turned the discussion to the important question of a local or exotic origin. Dymek felt that the geological aspects discounted an exotic origin, such as had been commonly invoked in early studies, but deferred to Spudis. Spudis, a proponent of the idea that the basalts are from the Apennine Bench Formation and probably underlie the local mare basalts, pointed out that the targets for both Aristillus and Autolycus, the most likely sources of exotic ray material, are in the Apennine Bench Formation anyway. Ryder added that at least one of those craters should have introduced exotic mare basalts along with the KREEP, but that it was not clear that *any* such appropriate basalts had been found.

Paul Warren presented a model (abstract, this volume) to account for the paradox that the KREEP basalts, despite their high contents of K, REE, P, etc., have moderate Mg'. A long-standing model for the origin of KREEP holds that its ultimate precursor ("urKREEP") was the residual liquid from a primordial magma ocean. According to this model, urKREEP collected as a layer sandwiched between the floated anorthositic crust and sunken mafic cumulates of the upper mantle. A separate model holds that a major fraction of the crust (the Mg-rich cumulates) formed shortly after the magma ocean epoch, when highly magnesian melts produced differentiated intrusions within the older ferroan anorthosite (magma ocean) crust. Warren suggested that these highly magnesian melts tended to assimilate or admix urKREEP as they ascended through the crust/mantle boundary, and that the Apollo 15 KREEP basalts were derived from the resultant hybrid, high-*Mg* but REE-enriched, melts. S. R. Taylor noted that some liquid would have to remain as such for about 4 or 5 hundred million years, because the age of the KREEP basalts is 3.9 b.y. Warren did not consider this to be improbable, given the depth in the crust, the insulation, and the high incompatible element content. Taylor also noted that mare basalts must have passed through this region and should also be KREEP contaminated. As one response to this, Warren quoted Binder's models in which mare basalt chemistry is explained by assimilation of KREEP-related materials. The Chair then listed the important characteristics agreed upon as constraints on the genesis of the Apollo 15 KREEP basalts and other KREEP samples: (1) uniformity of rare-earth pattern, (2) high Mg', (3) cotectic phase relations, (4) crystallization age ≏ Imbrium age, (5) subchrondritic Ti/Sm, (6) Rb-Sr model age ~4.4 b.y.: early Rb/Sr fractionation, and (7) Sm-Nd model age ~4.4 b.y.: early Sm/Nd fractionation. Dymek thought that such characteristics in terrestrial basalts would lead one to invoke mantle metasomatism and wondered if such a process were indeed tenable on the Moon. The Chair remarked that the uniformity of KREEP characteristics ruled against metasomatism, because a global process was implied. The Chair emphasized a critical point, that of the Rb-Sr model age, which allowed only a very small Rb-Sr fractionation at 3.9 b.y. Thus in a straightforward partial melt model, the source contained very little plagioclase or was subjected to a high percentage of partial melting. In response to questioning from Drake, Warren emphasized that the ϵ Nd for both Apollo 15 KREEP basalts and Mg-suite rocks came from the urKREEP layer, not the mantle, and that mare basalts probably do get contaminated with the KREEP-residue.

Korotev turned the discussion to another fundamental aspect by questioning how volumetrically significant Mg-suite rocks are in the crust, which has a much lower Mg' (according to regolith mixing models) suggesting that Mg-suite rocks may be of much less significance than petrogenetic modeling studies assume. Warren thought that there might be a lot of rocks missing from the pristine suite, particularly Mg-gabbronorite rocks, but also that the crustal Mg' might be a little higher than believed by Korotev. The Chair wondered why similar KREEP *volcanics* are not found at other landing sites. Warren responded that KREEP volcanism, for the most part, was older and comminuted by bombardment, but Spudis felt that it was also a function of distribution and sampling locations—a landing at Aristarchus might have produced more KREEP basalt. Warren agreed. The orbital gamma-ray radioactivity signatures are easily masked by flows of mare basalt that would overlie KREEP basalts extensively in the Imbrium region. Drake wondered why igneous KREEP basalt is found inside the basin but not at the Apollo 14 site. Ryder responded that the KREEP basalts are post-Imbrium and therefore have no direct influence from Imbrium ejecta. S. R. Taylor noted that Imbrium and KREEP basalts have the same age, and Ryder thought that there could be a cause-and-effect of impact-induced melting, even though KREEP basalts were not impact melts. S. R. Taylor, pursuing the concept of KREEP basalt as (Imbrium) basin impact melts, brought up the Compston-Williams-Meyer U-Pb zircon age of 4.365 b.y. for the Quartz-monzodiorite (QMD) clast in 15405: Either this zircon is a residual, or this is the crystallization age of QMD, which would indicate the real crystallization age of KREEP. Thus it is more likely that the 3.9 b.y. ages reflect impact melting and that the Apennine Bench Formation is like the Maunder Formation (melt sheet) in the Orientale basin. Spudis disagreed with such an equation, noting that both the distribution and morphologies of the two units are different. Ryder noted that of three Apollo 15 KREEP basalts isotopically dated, there are two distinct initial Sr-isotope ratios; therefore they do not represent a single homogeneous melt sheet. In response to a question from the Chair, Ryder admitted that the QMD zircon was not likely to be a xenocryst, both on textural evidence and insofar as the QMD has a fractionated ("dregs") composition. This led to some discussion of the differentiation sequences and low-pressure experimental constraints on the KREEP basalts.

S. R. Taylor referred to the level of Th in the Apennines, believing it to be high and indicative of KREEP in the highlands, hence Imbrium ejecta, and also to the high KREEP of Apollo 14. Spudis responded that there are different kinds of KREEP, and that the Th levels do not necessarily indicate Apollo 15 KREEP basalts; indeed there is KREEP (low-K Fra Mauro; see section entitled Apennine Front) in the Apennines. Taylor wishes to keep the picture simple, but Spudis remarked that neither the Moon nor nature was simple. Hawke was compelled to correct the apparent impression many people still appeared to have that the Apollo 14 mission returned samples of primary Imbrium ejecta; he referred to several pieces of post-Apollo work that have lead to a consensus that the site is on Imbrium continuous deposits, but emplacement of such deposits incorporates material of local origin. Thus straightforward comparisons of materials at the Apollo 14 and 15 sites as ejecta at different radial distances from Imbrium may be incorrect.

The Chair wrapped up the session with the statement that we still do not really know whether the Apollo 15 KREEP basalts are volcanic or impact melts. It is clear that lines of work that can solve this fundamental problem to everyone's satisfaction must be drawn up. The present consensus appears to be that the KREEP basalts are local and volcanic. One important piece of data outstanding is a Sm-Nd age for the QMD, and more isotopic work on KREEP basalt fragments could clarify their origin.

Topic 3: Apollo 15 Perspective on Lunar Basins (G. G. Schaber, Chair)

The Apollo 15 site, located on the Apennine ring of the Imbrium basin, offers a perspective on the processes involved in the formation of lunar multi-ringed basins. The Apollo 15 site is the only Apollo site situated on the main (Imbrium) basin topographic rim and is thus important for comparison with the geology and samples of other landing sites. Discussion at the workshop made it clear that many issues are still unresolved.

P. Spudis presented a keynote talk (abstract, this volume) reviewing the regional geology and geochemistry of Imbrium basin deposits, a model for basin formation, and some possible implications for the highland geology at the Apollo 15 landing site. Imbrium deposits are subdivided on the basis of morphology into several units including inner basin and rim deposits (massifs), continuous deposits (the Fra Mauro and Alpes Formations and Apenninus material) and discontinuous deposits (the Cayley Formation and secondary craters). In contrast to some opinions, Spudis believes that Imbrium deposits are symmetric with respect to the main basin rim (see below), but noted a distinct bilateral symmetry of deposit morphology, with the Alpes Formation being confined to the northeast and southwest and the Fra Mauro Formation/ Apenninus material confined to the northwest and southeast sectors of the basin exterior.

Spudis next reviewed the controversy regarding the location and size of the main Imbrium topographic ring. This controversy centers on the location of the main ring north of the basin; some workers (e.g., Wilhelms) suggest that the north shore of Mare Frigoris represents the main rim, while others maintain that it is much smaller. Spudis indicated that his preference is to connect the western Alps and Iridum crater rim in the north with the Carpathian and Apennine mountains to the south; this results in a main basin rim 1160 km in diameter. A consequence of this configuration is that three large regional concentric patterns outside the Apennines are then easily explained as Imbrium basin-related, casting doubt on the reality of the proposed "Procellarum basin." Spudis believes that Imbrium is best explained as a six-ring basin (see abstract, this volume).

Spudis concluded by reviewing the regional composition of Imbrium deposits and basin-forming models. The composition of the Apennines derived from orbital geochemical data is regionally varied; data for the northern Apennines (near the Apollo 15 site, made up of Alpes Formation), are consistent with a broadly noritic bulk composition whereas data for the southern Apennines (Apenninus/Fra Mauro material), indicate a more feldspathic, KREEP-rich composition. Spudis suggested that the observed relations of Imbrium deposits are consistent with a proportional-growth basin-forming model. In this reconstruction, the Imbrium excavation cavity was about 680 km in diameter, had a maximum depth of excavation of 60–80 km, and excavated about 12×10^6 km^3 of material.

Following the keynote talk, S. R. Taylor asked about the effects that a thick, brecciated debris layer such as probably existed at the Imbrium basin target site would have on basin formation. Spudis replied that although a thick debris layer probably existed, at Imbrium basin size ranges the lower part of the cavity would probably extend into crystalline rocks. The discussion then turned to proportional versus non-proportional growth for basin-sized impacts. Wilhelms wanted to know why Spudis believes in proportional growth. Spudis replied that proportional growth satisfactorily explains craters that differ in size over 8 orders of magnitude (from laboratory scale to terrestrial complex craters) and nothing in the lunar data suggests that it is not valid for lunar basins. Wilhelms replied that evidence from terrestrial craters indicates shallow excavation. Spudis countered that it depends on what crater one considers, citing Rochechouart as a possible anomaly, but that data from the Ries crater is roughly consistent with proportional growth. Schultz suggested that Hörz prefers a shallower excavation cavity for the Ries than the proportional growth model would imply (F. Hörz *does* advocate proportional growth for the Ries Crater; see Hörz *et al.*, 1983, *Rev. Geophys. Space Phys.*, v. 21, pp. 1667–1725). Spudis said that proportional growth *is* consistent with shallow excavation, contrasting the deep *transient* cavity with the gravity-controlled *excavation* cavity. This controversy was not resolved and is unlikely to be in the near future.

It was asked how much crustal material was removed by the Imbrium impact and how thin the crust might be in the basin center. Spudis repeated his estimates of excavated volume, but said that his model only addressed the excavation stage of basin formation, i.e., prior to final modification. Thus he was unable to say how thick the crust was under the Imbrium basin, but noted that the excavation model would predict that lower crustal material was brought up closer to the surface in the basin interior. It was asked how thick are the mare basalts in the Imbrium basin. Spudis thought the basalts were less than 1 km thick near the edges of the main rim, but could be several kilometers thick near the center. Head suggested that the basalts average 2 km in thickness in the outer regions and 5–7 km thick in the basin center.

The discussion then turned to the significance of deposit morphology around the Imbrium basin. Binder wanted to know about the "bilateral symmetry" of Imbrium deposits. Spudis agreed that it was a feature of great significance, but that he had no explanation for it. He also pointed out that Imbrium displays no ejecta asymmetry, but it depends on how you draw the main basin rim. Wilhelms claimed it did fit the oblique impact model, where major portions of the ejecta are thrown out perpendicular to the flight path of the projectile. Spudis disagreed, saying that the extent of the Alpes Formation (up to 700 km from the basin rim) is unlike the observed "butterfly" patterns seen around craters such as Messier and in laboratory experiments. Binder wondered if the morphology of the deposits more likely reflected the physical nature of unit deposition, rather than composition or stratigraphic provenance. Spudis thought that it may be a combination, noting the chemical differences between the Alpes Formation and Apenninus material. Head suggested three possibilities: (1) a compositional difference; (2) differences in style of deposition; and (3) modification of the unit after deposition. He favors the last mechanism, whereby radially textured ejecta is deformed after deposition by movements on regional slopes. Wilhelms disagreed, claiming that the Alpes Formation was too extensive for that effect to be significant. Spudis concurred, saying that the Alpes looked like an ejecta facies and not a modified unit.

Ryder cautioned against comparing impact melt content in the Apollo 17 and Apollo 15 sample collections, saying that because of biased collection procedures (e.g., boulders at Apollo 17), there is no basis for assuming that Apollo 15 is deficient in impact melt. Spudis agreed, but also said that the proportional growth model merely predicts less total melt at Apollo 15 than should occur at Apollo 17, not the absolute amounts. Wilhelms wanted to know how much "true highlands" material was collected at Apollo 15. No answers were forthcoming.

Basu asked the reasons for using Apollo 14 KREEP rather than Apollo 15 KREEP in the mixing models of orbital data. Spudis replied that it didn't really matter which KREEP composition was used, its effect being to account primarily for Th. He also noted the geologic arguments for Apollo 15 KREEP being post-basin (see Topic 2) and therefore inappropriate for use in modeling the Imbrium ejecta. Basu then questioned the use of mare basalt as an end member in models of highland composition. Spudis said that this was represented in the highlands mostly by post-basin dark mantle pyroclastic deposits, but some mare basalt is probably within the Imbrium ejecta. Basu wondered how appropriate the chosen composition was, given the chemical diversity of post-Imbrium maria. Spudis agreed that we don't know how diverse the ancient maria were, but that all the mixing model requires is an Fe- and Ti-rich component.

Two contributed papers examined the composition of Imbrium deposits and cratering mechanics. Spectral reflectance data for the Hadley-Apennine region were presented by Hawke and Lucey. They concluded that the Apennine Mountains and backslope are composed of feldspar-rich rocks with abundant low-Ca orthopyroxene (norites and anorthositic norites), but the spectrum of at least one crater on the backslope appears to be dominated by olivine absorption. Spectra collected for highlands features inside the Apennine ring exhibit shallower, wider absorption bands centered at longer wavelengths than those typical of the Apennine Mountains and backslope. In some instances, this spectral difference can be accounted for by the presence of impact/volcanic glass or by a mixture of highlands and mare material. In others, a gabbroic composition for the highlands units in the Imbrium interior is indicated.

In a short but very interesting talk, Schultz presented the results of an extensive series of impact experiments performed at the Ames vertical gun facility. These results indicated that nonproportional crater growth may occur and that the controlling parameters are the impact velocities and sizes of the projectiles. He suggested that large projectiles impacting the lunar surface at a relatively low velocity (e.g., a projectile 100 km in diameter impacting at 10 km/s) would produce cavities that grow in a nonproportional manner and would have wide and shallow transient crater cavity depths. Wilhelms pointed out that Ralph Baldwin had proposed essentially the same model several years ago and was led to it to account for Imbrium sculpture, which Wilhelms believes is caused by low angle ejection of material. Schultz disagreed, saying his experiments indicated that an ejecta curtain (inclined at 45° to the surface) was responsible for basin ejecta deposition. Spudis noted that the key issue was whether basins are formed by larger, slower-moving objects or smaller, faster projectiles. Schultz agreed, noting that the impact of a small, fast-moving body would form a proportional growth cavity. It was generally agreed that both processes were operative during the era of lunar basin formation and independent criteria are needed to determine which mechanism applies to which basin.

Virtually all aspects of lunar basin formation and evolution remain contentious. At the Apollo 15 site, more work is required to identify which highland lithologies are Imbrium-related (see Topic 1). If Imbrium basin material can be confidently identified, we can attempt to understand both the basin excavation process and the nature of the Imbrium basin target. Continued work on the Apollo orbital geochemical data and, more importantly, on earth-based remote-sensing of Imbrium deposits is needed to determine the lateral and regional variations in ejecta composition. Continued experimental and theoretical work on the nature of cratering flow fields may yet lead to constraints on the formational mechanics of lunar basins. Dynamical models for the origin, source, and nature of the basin-forming projectiles could help us decide whether basins were formed by slow, big impactors or small, fast-moving bodies. A potentially important result lies in the confirmation or refutation of the idea that Serenitatis melts exist at Apollo 15. This postulate, based mostly on textural and chemical similarities, proceeds from the premise that large basin impact melt sheets are chemically homogenized (see "Future Research," Topic 1).

Topic 4. Mare Volcanism at the Apollo 15 Landing Site (G. Lofgren, Chair)

This section focused on the origin and nature of Hadley Rille, its role in the mare volcanism, and the petrology and spatial relations of the olivine-normative and quartz-normative basalts in the vicinity of Hadley Rille/the Apollo 15 landing site.

Paul Spudis reviewed the overall geology of Hadley Rille (abstract by Greeley and Spudis, this volume). From terrestrial analogs, it is generally agreed that this rille and similar lunar sinuous rilles are lava channels, parts of which were roofed to form lava tube segments. The dimensions of such lunar rilles are huge. The size of Hadley Rille exceeds the largest terrestrial tube/channel by an order of magnitude. At the Apollo 15 locality it is about 300 m deep and 1.5 km wide. The development of these rilles includes the formation of a tube roof or a crust on the channelized flow which retards heat and volatile loss from the active lava. This permits greater flow lengths and volumes. These factors, in addition to the low viscosity of the mare magmas, caused the lunar lavas to spread out in thin sheets from the rilles, leaving little evidence in the way of flow fronts. Evidence from terrestrial tube systems suggest that lava tubes can erode by both thermal (i.e., partial melting) and mechanical processes. Drainage of the tube/channel and collapse of the roof and bank segments can expose flow units of different textures and possibly different compositions. This trench at Hadley may be our "roadcut" into the sequence of mare basalt flows. The rille walls provide excellent exposure of several different mare units, including a massive 17 m thick flow. The Apollo 15 Field Geology Team proposed that this flow represents the local quartz-normative basalt (QNB), with the olivine-normative basalt (ONB) lying above.

During the following discussion, Head summarized the results of his work with Lionel Wilson on the erosional processes in sinuous rille formation. They find that the key factor in determining whether thermal erosion occurs or not is the mass eruption rate. Above a certain eruption rate value ($10^7 m^3/s$), turbulent flow of lava results in efficient heat transfer and substantial thermal erosion may result. Head estimates, comparing the volume of Hadley Rille with the volume of basalt in Palus Putredinis, that the rille could have formed by thermal erosion, incorporating about 1-2% of highland material into the emplaced basalt. Head further suggested that because rille source vents in the highlands are usually much larger, mechanical rather than thermal erosion dominates in these regions. Grove concurred that thermal erosion was likely, noting the need for a mafic, low-viscosity lava. Schultz pointed out the importance of effusion rate and topographic gradient, noting the extreme sinuousity of rilles elsewhere on the Moon. He suggested that the modest sinuousity of Hadley implied a greater effusion rate and that this may be evidence for thick flows at the Apollo 15 site.

The discussion then turned to the significance of the "high-lava mark" observed on the Moon by the Apollo 15 crew. Dietrich wanted to know what dammed the rille to produce a lava lake. Grove replied that a dam wasn't necessary. Spudis agreed, drawing an analogy to the high-lava "scum" observed around pre-existing topography on the Kilauea 1823 flow; this lava mark was caused by a sudden surge in the effusion rate and the lavas did not pond behind a dam.

The question of thermal erosion was brought up again by Lofgren, who wondered about heat balance and whether superheat in the erupted magma was required. Head repeated that the key factor was turbulence, bringing fresh lava into contact with material to be eroded. Grove thought that heat balance problems were not as important as they might appear and cited supporting evidence from terrestrial komatiite flows. Delano wondered if thermal erosion occurred during ascent of magma from the mantle. Grove thought that it did. Ryder noted that if Head's estimate of 1-2 percent assimilation was correct, superheat in the magma might not be required. The question was raised as to what happened to the material that was eroded during Hadley Rille formation? Spudis recapped the geology of the rille, noting its gradual shallowing and alignment with Apennine Bench structures to the north. He suggested that the eroded debris may be covered by the last phases of lava eruption.

Haskin and Schaber marveled at the size of Hadley Rille, wondering why it is so big. Head reemphasized lunar eruption rates as the explanation. Ryder asked if the presence of highly vesicular basalts many kilometers from the vent was consistent with a tube-emplaced origin. Spudis replied that, according to Greeley's work, lava tubes are extensions of the vent and retard both heat and volatile loss; vesicular basalts are found up to 20 km away from the vent in terrestrial tube systems. A brief discussion on the thickness of mare flows at the site ensued. Spudis argued for a relatively thin total accumulation of basalt, citing as evidence the paucity of mare basalt at the LM site. Ryder concurred, citing 15205, a regolith breccia formed from an immature regolith containing mostly KREEP and QNB basalt clasts. He suggested that the clast population of this rock indicates that the basalts in the site area are thin and directly overlie KREEP basalt flows.

Tim Grove presented a keynote talk on the mare basalts sampled at the Apollo 15 site, of which there are two types: quartz-normative (QNB) and olivine-normative (ONB). These are the rock types that were extensively studied using dynamic crystallization experiments (in the early 70s), wherein mineral textures, dimensions, morphologies, and chemistries were reproduced in the lab. Samples 15065 and 15085, collected at Station 1 (Elbow Crater), represent products of the slowest cooling rates determined; these samples are from the interior portions of a lava flow ~20 m thick. Application of cooling-rate data to samples from Dune Crater indicates a QNB flow about 3 m thick. If the samples at Elbow and Dune Craters come from the same flow, it would appear that the flow pinches out in a relatively short distance—Grove believes that the QNBs represent an overbank deposit with limited lateral extent and are the only basalts at the site directly related to Hadley Rille. This judgment, as well as others about the existence of lava ponds, is based on his recent work in northern California lava fields.

The typical relationship often cited for the QNB and ONB flows is that the QNB flow is continuous over the site with the ONB flow being directly above it. Grove presented a provocative treatment of the ONBs. He stated that it is notable that there are no vitrophyres of the ONB, and therefore no representatives of chill margins. This would not seem to be consistent with the sampling of simple lava flows. In addition, the plagioclase of the ONB often poikilitically encloses olivine and pyroxene, a texture reminiscent of thermal reprocessing. Grove feels that this rock type is not endogenous to the site. Instead, it represents an exotic component to this area transported to the site by an impact event, perhaps that which formed the Aristillus or Autolycus craters.

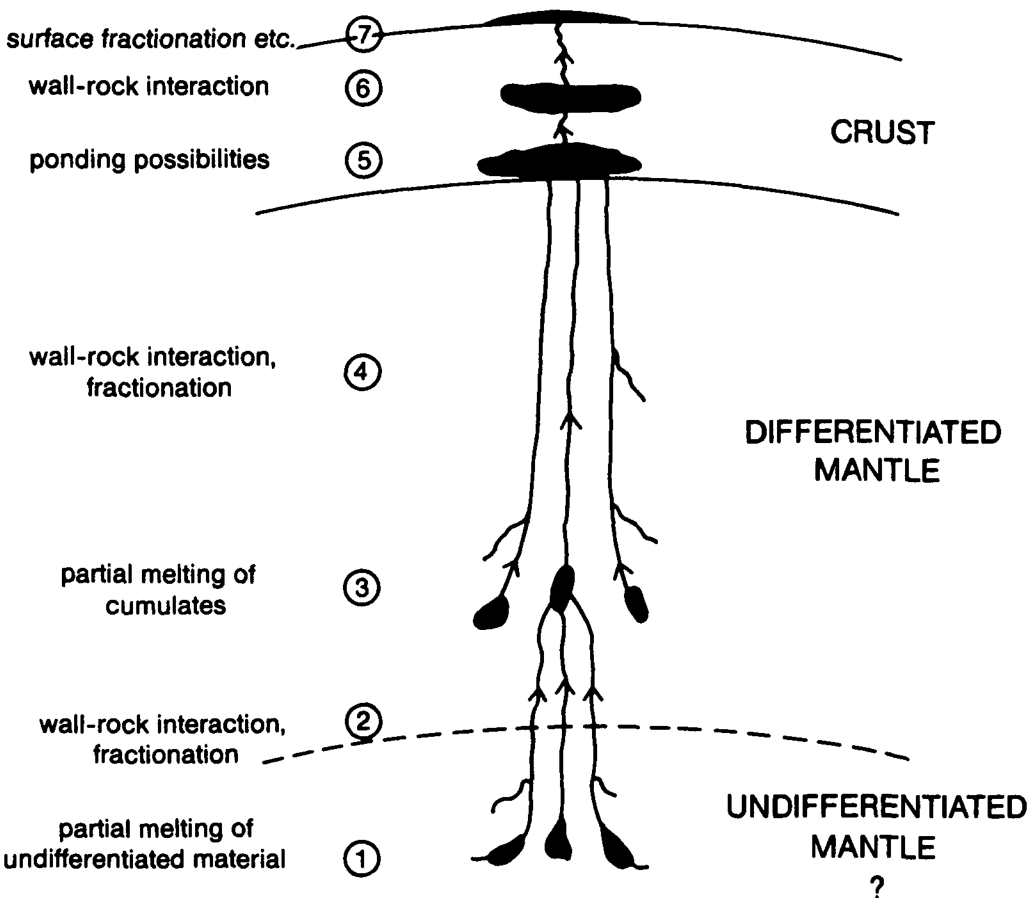
Ryder objected to Grove's interpretation of the ONB flows on three grounds: (1) that regolith development would destroy the postulated upper chill margin; (2) that the Station 9A rake sample consists almost entirely of ONB, suggesting that it is a major, local rock type and not exotic; and (3) that soil mixing models throughout the site require large amounts of ONB (but little QNB), again suggesting that it is a widespread, local lithology. In regard to the first point, Grove replied that even though there is a thick regolith, we should see lower margin chilled specimens in the Station 9A rake sample. Regarding the last two points, Grove thought the ray explanation was adequate. Ryder disagreed, noting that the composition of basalts in the Aristillus region, determined by remote-sensing, did not seem to be like the ONB at the site. Swann pointed out that considering the limited time spent at the rille during the mission, it would be sheer chance if we got chilled ONB samples anyway. Lofgren thought that the results of Grove's presentation presented problems for a local, rille-related origin for the ONB, but he did not elaborate. Basu asked if Grove would apply his argument about the Apollo 15 ONB to plagioclase-poikilitic basalts elsewhere on the Moon. Grove replied not necessarily, as he hadn't yet considered the context of other mare samples. Dietrich asked how the Medicine Lake Highlands (California) data applied to the question of thermal erosion at Hadley Rille. Grove said that he thought that at Hadley we sampled late-stage activity, and therefore he could not directly address the issue.

The QNB and ONB sampled at the site represent two rock types that are chemically and mineralogically distinct. Peter Salpas gave a presentation (abstract by Salpas and Taylor, this volume) in which it was stressed that the major and trace element chemistries indicate that samples from neither of these rock types represent one lava flow. It is not possible to derive the various samples of either rock type from a common parent by simple fractionation of olivine and/or pyroxene. That is, attempts to find coherent subgroups within the overall rock types was not successful. There are several different flows represented by these samples. Binder cautioned that because of the use of data from different labs, no meaningful conclusions could be drawn from this study. Ryder pointed out that many of the basalts studied were fairly coarse-grained and thought that many analyses were not representative enough.

In summary, it was agreed that there certainly is room for a reassessment of mare basalt petrology at Apollo 15, particularly in light of all the developments, discoveries, and renewed interest in mare basalt petrogenesis in general. We are still not certain of the relation of mare basalts to Hadley Rille. A detailed reexamination of mare site geology and petrology, coupled with the results of dynamic crystallization experiments, could determine which basalts (if any) are rille-related, how the various textural varieties of the ONBs are related (if they are) and test the hypothesis of a possible lava lake at the site. A resolution of the problem of total mare basalt thickness at the Apollo 15 site may be forthcoming, if local versus exotic components in the regolith can be isolated (e.g., if KREEP basalts at the LM site are locally derived through vertical mixing, mare basalt flows, at least there, are thin). More work is needed on the abundant mare basalt fragments found at the Front (in coarse fines and rake samples); until this is done, the relation of these basalts to mare samples from the plain will remain problematical. Continued work on lunar magmatic eruption conditions and modeling of rille formation by both thermal and mechanical erosion is needed to fully apply such a model to the formation of Hadley Rille.

Topic 5. Mare Rocks and Their Implications for the Mantle Beneath the Apollo 15 Site (M. Drake, Chair).

Basalts are generally agreed to be partial melts of a planet's interior, hence their characteristics, properly interpreted, can provide information on the interior. The Chair began the session by providing conferees with an informative overview of igneous processes and the geochemical behavior of elements during crystal/liquid fractionation. The genesis of basalts is really a difficult detective story comprising several possible steps (diagram), and we need to convince ourselves that we understand each step. In some cases we can draw some compositional conclusions because of insensitive behavior, e.g., for elements with solid/liquid coefficients of ~1, such as Ge, or where ratios remain constant, such as U/Th.



Delano, in his keynote address (abstract, this volume), summarized the chemical information on Apollo 15 mare samples, *after first discussing the criteria by which volcanic glass is distinguished from impact* glass. Ten distinct magmatic compositions are at present known. Two of these occur in the form of crystalline mare basalts (i.e., olivine-normative and quartz-normative), while the remaining eight occur as pristine, high-Mg glasses of volcanic origin. The abundance of TiO_2 in these ten Apollo 15 magmas ranges from 0.2 wt % to 13.5 wt %. The ages for five of the magmas have been determined and found to range between 3.6 and 3.3 b.y. The large chemical diversity among the mare magmas collected suggests that the mantle beneath the Apollo 15 site is a heterogeneous assortment of mafic cumulates formed during the global differentiation event. Whether these cumulates occur as neat stratigraphic layers, as density-graded cumulates (see Binder abstract, this volume), or as a melange of units that have been stirred by solid-state convection is not generally agreed upon by investigators. What is clear, however, is that the Mg′ of the residual ferromagnesian phases(s) in the mare source-regions varied by only about 10% (i.e., 0.76 to 0.84), even though the Ti-abundance in the magmas varied by a factor of about 60. This limited Mg′ is thus a *lunar* problem, not just a *KREEP* problem (see Topic 2).

Delano emphasized that the *depths* of the mare source-regions remain contentious. If two (or more) types of minerals were present in the residue, then experimental phase studies show that the pristine, high-Mg glasses were derived from depths of at least 400–500 km, independent of their Ti-abundance. However, if olivine were the only residual phase, then the source-regions would have been located at shallower levels (e.g., ~200 km; see Binder, abstract this volume). The eruption of the mare magmas was accompanied by the release of indigenous lunar gases containing the following elements: B, C, F, Na, S, Cl, Ar, Cu, Zn, Ga, Br, Ag, Cd, In, Sb, Te, I, Xe, Au, Hg, Tl, Pb, and Bi. The nature of the component within the Moon from which these volatile elements were derived remains elusive but potentially important.

Summarizing, Delano thought that the most important remaining questions were as follows: (1) the exact depths of the source regions, (2) whether there are more magma varieties to be found, and (3) the nature of the component that contained the volatiles.

Warren questioned the analogy Delano had made between KREEP and green glass when their LIL-element contents are so different. Delano reemphasized the point that in the entire spectrum of mare compositions, TiO_2 and LIL-elements range up to 100 × chondrites but the Mg′ changes by a factor of less than 10%. There is a lunar problem of high Mg′ with high incompatibles. Warren noted that the actual percent variation is a function of calculation; for instance, Mg/Fe instead of Mg′ would show more variation. Haskin wondered if the defined different green glass compositions showed any distributional characteristics; Delano responded that he had found all varieties in each of the three thin sections he had studied (but see Ryder's comments, below). Basu offered that he had found no difference among different size fractions.

S. R. Taylor, accepting the evidence (e.g., Eu anomaly) for a differentiated source for green glass, wondered where the primitive volatiles then come from. Delano referred to U-Pb data on orange glass (Apollo 17) by Wasserburg's group, which showed a line running through the eruption age and 4.6 b.y. rather than the 4.4 b.y. intersection of most lunar materials. So the orange glass volatiles apparently have no memory of a "magma ocean" stage. The implication is of preserved primitive reservoirs. Taylor suggested that the volatiles might have been in sulfide pods during whole-Moon melting, but Delano emphasized that the glass coatings are a mixed bag of volatiles, most of which are not chalcophile. The Chair offered two contrasting thoughts: (1) Whole-Moon melting does not necessarily lead to complete devolatilization, depending on time-scales; and (2) Ge has a near-constant abundance in terrestrial rocks, but among Apollo 15 samples it scatters. The most straightforward interpretation is that the Moon has preserved heterogeneous pockets, perhaps inconsistent with whole-Moon melting. Dymek felt that some rare minerals could be the hosts; Delano agreed that they could, but emphasized that the significant feature was that isotopic data showed that the volatiles were primitive. Warren, continuing with the theme of whole-Moon melting, noted that the seismic data indicate that the Moon at depth has incipient melting, inconsistent with whole-Moon melting, which would have extracted the radioactive elements. Binder countered that the Moon is in a conductive, not convective, state, and that only the outer few hundred kilometers would have cooled off. The Chair cut off the argument, noting that at least one respected geophysicist believes that the Moon is in a convective state, but also that no process was so efficient as to expunge the heat-producing elements completely from the interior.

Head produced the geological point of the widespread distribution of glass volcanics; volatiles would be important in the eruption and fire-fountaining. Longhi asked the provocative question: How do we *get* primary, undifferentiated, unaltered magmas from 400 km depth? Delano agreed that it was difficult to understand, but made the observation that mid-ocean ridge basalts came from a similar *pressure* of 25–30 kb. Longhi pursued the possibility of xenoliths as providing information, but in fact we don't have any. The Chair pointed out that we actually know little about the entrainment of xenoliths in terrestrial magmas anyway. Head noted that fissures were very important in getting magmas out, and that we do have them in the upper part of the Moon, e.g., basin rims.

Longhi wondered if there was any evidence of an impact at about 3.3 b.y.; Spudis was not aware of any big enough to produce large-scale impact melting or impact-induced melting. Archimedes is a possibility, but is probably a little older.

The Chair returned the discussion to depth estimates, inquiring if there was any firm petrological or chemical evidence that two or more minerals were residual to the glasses. Delano said that no one had produced any definitive ideas, but quoted Binder's work suggesting olivine control, i.e., single phase. Drake questioned Binder on whether he could distinguish a *holding* chamber, following production from a deeper source, from his model; the answer was no.

Ryder made a short presentation on green glass microprobe data, first confirming the chemical variation shown by Delano, and then showing that the rather pure green glass clod 15426,26 consisted dominantly (though not entirely) of Delano's Group A. Thus different clods have different proportions and presumably different groups were erupted separately. Basu felt that different groups would have different size frequencies and means (from separate eruptions), but Ryder could not tell that from his data; Group A was present at all sizes. Delano emphasized the difference in proportions found by him and by Ryder. David Lindstrom wanted to know what we know about the distribution of the clods and deposits; was there once a deposit all over the site, or were clods subsequently brought in by impacts? Ryder said that it was impossible to say from the samples, but green glasses are found all over the site. Pure clods, however are rare.

The session finished with some short contributed papers. Binder first showed his Monte Carlo modeling of very low-Ti glass compositions, claiming that the actual trend was consistent with olivine-control, not cotectic control. Elthon commented that olivine-control did not distinguish fractional crystallization, a common and expected feature of basalts, from partial melting with an olivine-only residue. Binder stated that he accepted Delano's arguments that these are primary glasses, unfractionated. He also pointed out that a cotectic model for melting would have produced a spread in the first place, roughly perpendicular to an olivine control line, and this is not observed. Grove said that since all the glasses were in the olivine phase field the Monte Carlo modeling cannot be used as a test for the petrogenetic modeling; it is not unique. Binder disagreed. Following further argument, Warren clarified the phase diagram: The cotectic moves with pressure, and therefore as a melt rises, crystallizing cotectically, its trace on the phase diagram will mimic olivine control. This question of olivine control was unresolved.

Binder followed with a contribution on the genesis of Apollo 15 mare units (see abstract, this volume), outlining his multifaceted model for the production of basalts. He has been able to successfully duplicate the observed abundances of trace elements (Co, Ni, Ba, Rb, Sr, K, REE), Sr-isotopes, and Nd-isotopes in most magmas by: (1) 30 ± 2% partial melting of source regions at depths of 200 km in the presence of residual olivine, (2) 0–30% olivine fractionation during emplacement, and (3) 0–11% assimilation of incompatible-element-enriched liquid produced by 7–8% partial melting of urKREEP at the base of the highlands crust.

John Longhi (abstract, this volume) presented a chemical comparison between crystalline mare basalts and the 25 varieties of pristine, high-Mg glass reported by Delano. He concluded that none of the basalts was produced by simple fractionation of the magmas represented by these glasses. Although this mismatch may merely result from inadequate sampling of mare units on the Moon, it may also be a petrogenetically significant observation that warrants further study. Marilyn Lindstrom suggested that some basalts might represent the ultramafic parents and were worth looking at, e.g., feldspathic peridotite. Longhi felt that the parent samples would be vitrophyric or at least fine-grained. Binder said that the lost olivine in his model was at depth (so ultramafic parents were not expected at the surface), and that increasing time in the magma chamber allows not only more olivine, but also more volatiles, to be lost. Thus fractionated basalts lost the impetus for fountaining. Grove wondered about the mafic rock from Apollo 14, "Average olivine-vitrophyre," but most of those familiar with it thought that it was an impact melt, to be considered warily. Dymek briefly talked about inclusions of vitrophyres and other materials in green glass clods; most thought that these were a result of local impact mixing and were not genetically related.

The Chair ended the session by stating that the case has been made that the glasses are volcanic from the lunar interior, but that we only dimly perceive how to interpret the details of the processes involved in their production.

The session revealed that major questions remain concerning mare petrogenesis and the chemistry of the lunar mantle.

1. How deep were the mare source-regions located within the Moon?
2. Was KREEP assimilation important during mare petrogenesis?
3. Were mare basalts differentiates from high-Mg magmas?
4. What are the ages, trace element abundances, and isotopic compositions of the magmas represented by the pristine, high-Mg glasses?
5. What is the nature of the component within the Moon that contained the volatiles emitted during mare volcanism?
6. What are the chemical and isotopic characteristics of lunar gases?

Topic 6. Post-mare Cratering and Apollo 15 Regolith Evolution (R. Morris, Chair)

All lunar samples have been collected from the lunar regolith. Therefore it is important to understand regolith processes in as much detail as possible if we are to correctly interpret the geology of different landing sites and that of the Moon from sample studies. One criterion for evaluating the quality of our understanding of the geology of any lunar landing site is whether we can construct a geological cross-section and relate it to the rest of the crust of the Moon. Regolith studies of the Apollo 15 site should allow us to construct cross-sections that are local in scope; understanding regolith evolution may enable us to draw cross-sections of the Apollo 15 landing site for different times, from pre-Imbrian to the present. Drill core data may be immensely helpful in this regard. However, we must understand and be able to quantify a few basic regolith processes. We need to know how the regolith was produced; how much of the regolith is non-local in origin; how the regolith was mixed, and in what proportions and rates; how the regolith, especially the samples, was modified and at what scales. The part of the session on regolith petrology and dynamics suffered in that a keynote talk by D. McKay was cancelled because of his illness.

The difficult task of modeling the chemical components of Apollo 15 soils and regolith breccias as petrologic reality was attempted by Korotev in his keynote address. He showed that four local physical entities, *viz.* mare basalt (mostly olivine normative), green glass (mostly group A of Delano), KREEP basalt (medium-K as in 15382), and the least mafic soils from the bottom of station 2 drive tube core (15007), are sufficient to model the compositional variation of Apollo 15 soils. This mafic-poor soil [which Korotev named "Apennine Front Soil Composition (AFSC)]" is itself a mixture of many subcomponents that may or may not be fully represented by the rocks collected at this site. Nevertheless, if this soil is a well-mixed, fine-grained end member present in all Apollo 15 soils, it appears to be quite invariable as a component throughout the site. Plots of Sm-Sc show that some regolith breccias from Stations 2, 6, and 7 are distinct from the average soils of these stations. It is likely that random variation in small amounts of KREEP component, rich in Sm, cause this dissimilarity (Fig. 1 of Korotev, this volume).

The methodology of data analysis via mixing calculations was discussed by Korotev. He emphasized the model dependent nature of mixing calculations and drew attention to the fact that an apparent numerical improvement of a statistical fit [to data] does not necessarily make a model more realistic than others. There may be local cases, Korotev showed, where a realistic end member may itself be a mixture of more pristine components.

Following this presentation, it was asked how realistic was Korotev's use of 67215 as an end member in the mixing calculation. Korotev replied that it is the only ferroan anorthositic norite in the collection of pristine rocks and he used it just to test its applicability to the mixing problem. Haskin noted that Korotev's KREEP component seems more like Apollo 14 KREEP, rather than Apollo 15 pristine KREEP basalt. Spudis commented that the value of mixing models was not to determine what is in the soil, but as a tool within which to view chemical data in a petrologic context. He also suggested that Korotev's new term for the Apollo 15 highlands composition (AFSC) was really no better than LKFM; it merely replaces one polymict component with another. It was generally agreed that this problem largely reflects the inadequate sampling of lunar rock types.

David Lindstrom suggested that the best mixing models were the ones that used the fewest end members. Korotev disagreed, noting that although a mathematically correct model could be performed on Apollo 15 soils using three end members, his preference is for a four-component model. Ryder thought that his new data for Apollo 15 impact melts might contain an appropriate new end member for mixing model studies. He also asked if Korotev could macroscopically identify KREEP basalts in the soil sample for which he did individual particle analyses. Korotev replied that they looked like crystalline rocks, some with glass coats; these coats are included in his analyses. The Chair asked which mare basalt type was at the LM site. Korotev replied that his models were unconstrained until we define the highlands component, but noted that published models indicate ONB as the dominant basalt type at this location.

The importance of modeling and extrapolating experimental data to lunar scale, in the altogether different context of secondary cratering, was emphasized by P. Schultz in his keynote talk. It was generally felt that such scaling is acceptable at the present time, and provides a relative estimate of the expected amount and size of exotic material that could be ballistically transported to the Apollo 15 site from neighboring craters. New cratering experiment results suggest that bombardment by clusters of primary ejecta produce some secondary craters. For any given mass of impactor, the cratering efficiency of clustered bodies of impactors is much less than that of a single strong body. This increases the probability of transporting primary material over long distances. More importantly, a part, if not a concentration, of primary ejecta is ricocheted downrange and is deposited near the surface. Post-depositional processes will dilute but may not totally obscure the exotic "primary" ejecta.

Scaling these experimental results to the Moon and allowing a few pertinent assumptions, one could perhaps estimate the amount of ray and/or exotic material present at the Apollo 15 site. Unfortunately, it is not yet possible to assign an absolute amount of the Apollo 15 material as "exotic," although such deposits should exist. This view contrasts with both the pre-Apollo view of ray formation and later views that considered only cratering efficiency. Calculations indicate that of the large craters (diameters greater than 20 km) within a radius of 200 km from the Apollo 15 site, Aristillus, Autolycus, Hadley C, and Hadley B would contribute more than 75% of all exotic material. It is also likely that such ejecta would consist of small particles; blocks or boulders transported to this site from secondary craters would be a minor mass fraction.

Basu asked how much primary ejecta from distant craters could be at the Apollo 15 site. Schultz replied that his model assumes isotropy, but in reality, because of anisotropy it could be anywhere from zero to "a large amount." The Chair asked if the ONB could be exotic ejecta (as suggested in another session by Grove), and whether anyone has looked at Apollo 15 ropy glasses as possible exotic ejecta. Schultz replied that although he hasn't looked at the specific problems, his ray emplacement model could explain large amounts of exotic material. Bogard said his group had looked at the ropy glasses, but they are apparently 3.5 b.y. old.

Haskin asked if these results could be interpreted to mean that there was *no* local material at the Apollo 15 site. Schultz replied no and reemphasized his depositional model, whereby exotic debris is concentrated downrange of observed secondary craters. Spudis, noting Korotev's results suggesting the recent addition of KREEP to the Station 6 soils and that station's position downrange of the South Cluster from Aristillus/Autolycus, wondered if this KREEP could be primary exotic ejecta. Ryder thought Aristillus/Autolycus were too old for such an origin for coarse soil particles. Delano asked whether Aristillus/Autolycus might be simultaneous impacts, which could lead to unusual ejecta deposition processes. Schultz replied that stratigraphic and morphologic evidence suggested that these craters were formed in two separate impacts.

In a short presentation, Basu discussed his attempts to use regolith information to construct a geologic cross-section of the Apollo 15 landing site. Assuming that disaggregation of regolith breccias into soils is a dominant process on older regoliths, he reconstructed the LM to Rille subsurface geology, accounting for the enrichment of LM soils in KREEP as a consequence of the destruction of a pre-existing regolith developed on the underlying Apennine Bench Formation (KREEP basalts). The Chair asked if Basu saw any evidence for comminuted, old regolith samples in the LM soils. Basu replied that he did, noting that some LM area KREEP particles possess edge characteristics that suggest that they were originally in soil breccias.

A method of extracting new information on the irradiation ages of soils forming regolith breccias was reported by Bogard and others. Because the ratio of $^{40}Ar/^{36}Ar$ at or near the surface of the Moon has descreased over time, Bogard showed how the abundances of surface correlated ^{40}Ar and ^{36}Ar could be used to estimate the pre-compaction time when the soil components of the breccia were irradiated at the lunar surface. Bogard observed a systematic difference between regolith breccias collected from the rim of a Station 6 crater and breccias collected some distance from the rim. Regolith breccias apparently ejected from near-surface regions of the crater and deposited away from the crater have similar $^{40}Ar/^{36}Ar$ ratios to the nearby surface soils. Breccias collected near the crater rim and presumably ejected from the deeper parts of the crater have higher $^{40}Ar/^{36}Ar$ ratios than the local soil. FMR data are apparently consistent with this interpretation.

Following this presentation, it was asked whether the older-than-Apollo 15 assembly age implied for Apollo 16 regolith breccias was real or apparent. Bogard replied that it is indeed real and attributed it to a higher impact flux in the interval from 3.9 to 3.3 b.y., which is the age difference of surface units between Apollos 15 and 16. It was asked whether the differences in Ar content of regolith breccias might be somehow related to breccia composition. Bogard repeated that they were looking at surface-correlated (trapped) ^{40}Ar on surface grains, not the product of radioactive decay, and therefore composition is not a factor.

Simon made a presentation suggesting that the geological significance of chemical similarities can be best evaluated by mixing model calculations. Although the results of mixing calculations varied drastically with the choice of end members, the use of one algorithm with one set of end members provides a normalized means for comparison (Figure 6 of Simon *et al.*, this volume). Direct comparison of the petrography of regolith breccias and surface and drill core soils are probably helpful in understanding the nature and causes of dissimilarity between regolith breccias and surface and drill core soils. Simon suggested that the older regolith lost to the rille (as the rille margin receded) must have been more highland-rich than the rille edge regolith of today. Basu asked why Simon's mixing models of the Station 2 soils indicated no green glass when green glass is present and also questioned the use of 15205 as a representative breccia from this station. Simon replied that there is green glass in the soil, but they found none in the regolith breccia thin sections that they studied (15205). Korotev said that the Station 2 soils were not like 15205, which appears to be exotic, and Spudis suggested that study of regolith breccias from the Station 2 rake sample might be more appropriate. The Chair asked what kind of mare basalt occurs in the regolith breccias. Simon said that he didn't know, but probably both types. Warren asked if Simon could predict what Bogard might find in a given regolith breccia based on petrographic classification. Simon said probably yes, because their petrographic types were in general agreement. Ryder questioned Simon's interpretation regarding the highland-rich nature of older rille soils, believing that over time the opposite trend might be seen. He also pointed out that the chosen LKFM end member (62295) for mixing models was probably unrealistic.

In summary, there was a general consensus that the abundance of exotic material at the Apollo 15 site, in the form of a ray or otherwise, must be quite low on average; however, pockets of unusual concentration may be present. It was also generally agreed that chemical mixing model calculations are useful for comparative purposes but cannot substitute for petrologic reality. Questions remain as to the rates of vertical, horizontal, and downslope movement of the regolith at this site. A few topics that were not discussed at all include size-composition relationship of the regolith and agglutinate composition. Drill core data, especially any macroscopic layering and their origin, were virtually neglected. Some of the questions on the rates of regolith motion could perhaps be answered if age dating by $^{40}Ar/^{39}Ar$ ratios could be done on soil samples, especially in agglutinate separates.

ABSTRACTS

REGOLITH EROSION AND REGOLITH MIXING AT THE APOLLO 15 SITE ON THE MOON; Abhijit Basu, Department of Geology, Indiana University, Bloomington, IN 47405, U.S.A.

Regolith samples from the Apollo 15 landing site provide an opportunity to trace soil mixing on a horizontal scale of about 1-5 km. Pure mare basalt occurs on one side of the landing site and presumably highland materials are piled up on the Apennine Front on another. If the local regoliths were to be composed of comminuted products of exclusively local crystalline rocks, the question of mixing would not arise. If these were to be mixed by processes of simple gravitational mass wasting and/or by micrometeoritic bombardment, the mixing process would have been relatively easy to understand. However, other complicating processes and/or events make the overall process of regolith mixing at this site much more challenging to understand. Fire fountaining event(s) deposited green glass spherules that are distinct from all mare basalts. There are craters of impacts that have excavated substantial proportions of one and more kinds of substrate--e.g. Dune excavating mostly mare basalts, St. George excavating crystalline highland material, and Spur excavating green glasses. There is a possibility of the existence of a ray from an exotic source emplacing non-local material (KREEP basalts?) at this site. Regolith mixing at this site, therefore, must be understood in terms of the surface features and other photogeologic interpretations of this site [6,8].

Mixing model calculations [9] have been performed on the chemical compositions of many soils from different stations. The results provide a good guide for models that are dependent on intelligently chosen end members. We are testing an approach using only the modal abundance data on crystalline fragments and green glass spherules. We have constructed a pseudo-fence diagram of the Apollo 15 site showing the distribution of major lithic fragments actually present at the various sampling stations (Fig. 1).

The diagram shows that:

(a) KREEP basalt is uniformly distributed on the Front and through the high grounds near the ALSEP/LM location.

(b) Occurrance of green glass is dominantly a Spur crater phenomenon; green glass has been redistributed by post-mare cratering events from this point source.

(c) Highland rock fragments are uniformly distributed on the Front; St. George crater has not affected the present day distribution of highland rock fragments in the Apollo 15 soils.

(d) Abundance of mare basalt fragments is controlled not only by the distance from mare-highland boundary [cf. 9] but also by the downslope movement of regolith near the rille [cf. 7] and by the depth of penetration by local cratering events (e.g. Dune).

KREEP basalt enrichment in Apollo 15 soils in a linear fashion extending from ALSEP/LM location through Station 6 on the Front may give the appearance of the presence of a ray rich in KREEP basalt fragments. However, we prefer a different scenario on the basis of the modal data as represented in the pseudo-fence diagram. Assume that KREEP basalt is local and that the pre-mare regolith on the Apennine Bench Formation (or, at least the one before the last major lava flooding of the Apollo 15 embayment) was uniformly rich in KREEP basalt fragments. Sprays of green glass spherules from fire fountain events covered the surface in an irregular fashion; eruption of mare basalt was both simultaneous with this event and also followed immediately. Into this embayment flowed one (or more) low viscosity mare basalt lava that

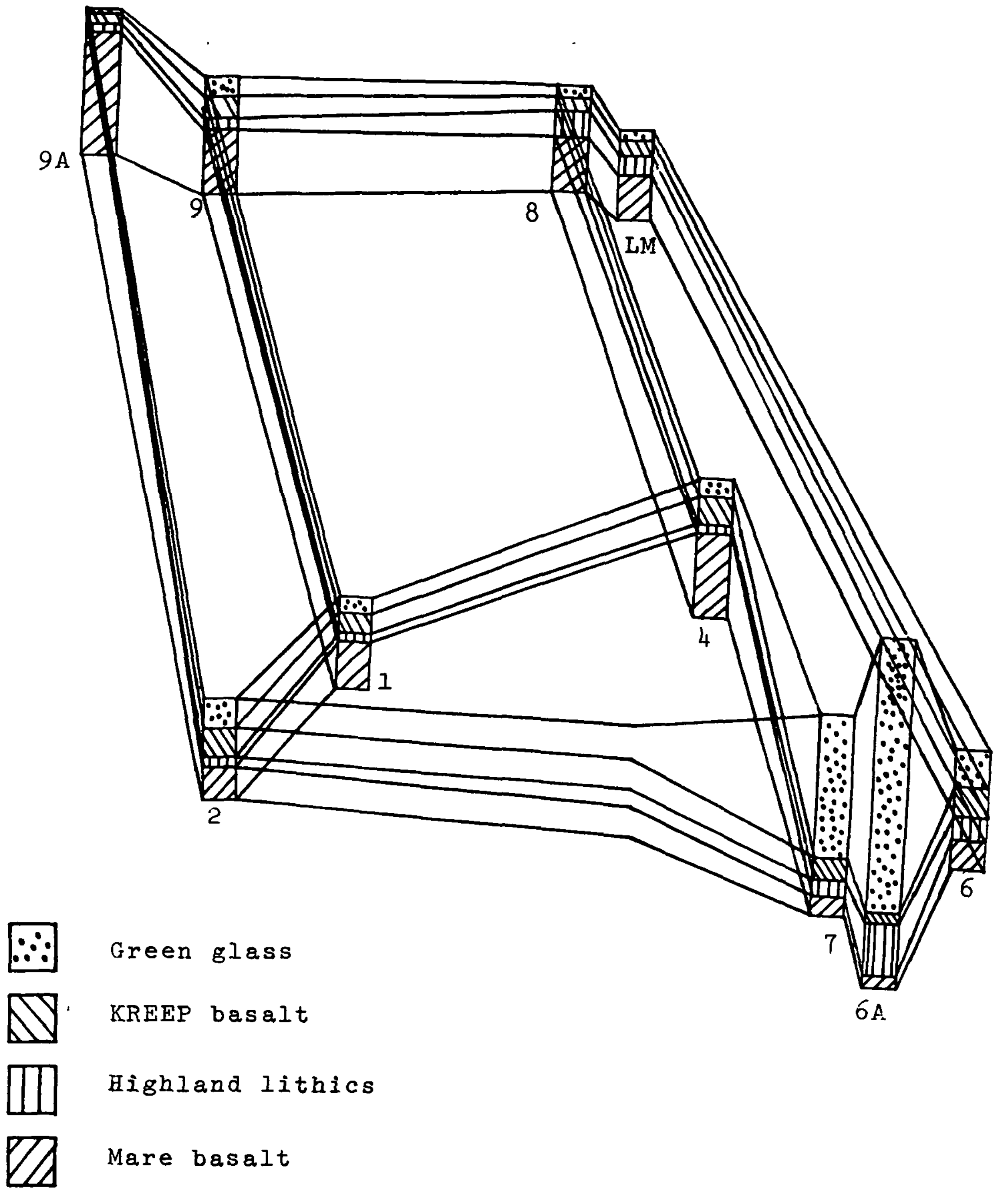


Figure 1. Pseudo-fence diagram showing the major modal abundances of major lithic particles in Apollo 15 soils. Both surface and drill core modal analysis data have been used. Station numbers are at the bottom of the modal bar graph for each station.

not only carved out the Hadley Rille, but also eroded part of the then regolith in the embayment. All green glass spherules, except those deposited on relatively high grounds (e.g. Station 6A), were swept away by the mare basalt flows. The eroded bench was irregular in shape and is now represented by Stations 9A, 9, 1 and 4. The bench had a veneer of mare basalt that thins in the direction of all high grounds (Fig. 2). Post-mare cratering comminutes the thin veneer of the mare basalt, mixes KREEP basalt fragments from below and produces a regolith to which is added material from the Front including the green glass ejected from Spur crater.

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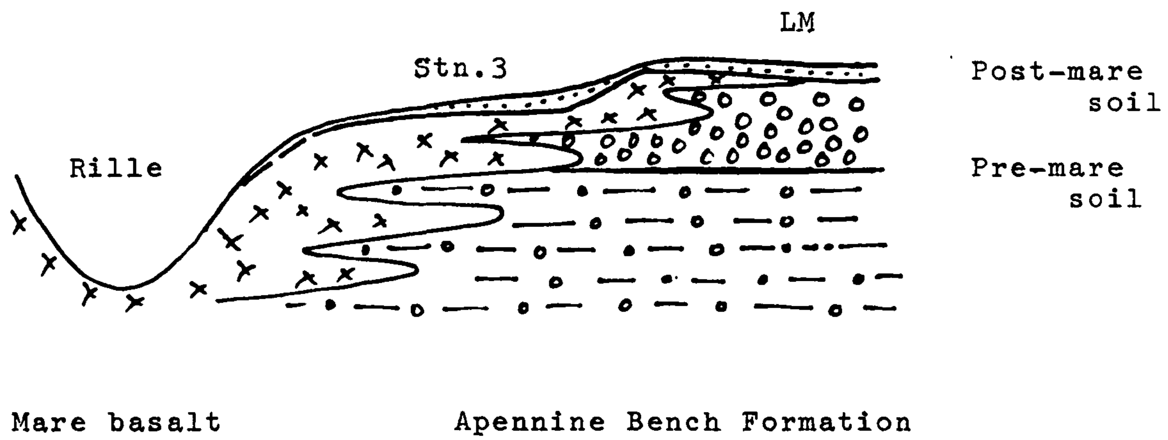

Figure 2. Simplified and schematic cross-section from Hadley Rille through Station 3 and ALSEP/LM. Pre-mare soil and mare basalt in reality are likely to be intercalated with many flows and very thin syn-mare soils. Post-mare regolith is thinner on slopes than it is on relatively flat ground.

APOLLO 15 MARE UNITS AND THEIR PETROGENESIS; A.B. Binder, NASA Johnson Space Center, Houston, TX

Samples from some 15 different mare units have been identified (in some cases tentatively) among the Apollo 15 collection. Of these, 8 are pyroclastic glass units (5 VLT green glass units, 1 LT yellow glass unit, 1 HT orange glass unit, and 1 VHT red glass unit, Delano and Livi (1)), one is an impact (yellow) glass unit derived from a LT mare basalt flow (2), and the remaining 6 are all regular LT mare basalt units. The latter 6 units were initially defined by Dowty et al. (3) on the basis of textural characteristics of rake samples and broad beam microprobe analyses. The majority of the Apollo 15 mare basalts belong to 4 of these units, i.e., the pyroxene phyric unit, the olivine phyric unit, and two olivine microgabbro units (A and B). All of these pyroclastic glass and mare basalt units belong to Delano and Livi's (1) Array I materials, except for the Array II LT yellow glass unit. In addition, Dowty et al. identified two rake samples (15385 and 15387, these are the most olivine-rich mare materials thus far found) from a feldspathic peridotite (in reality a picrite basalt) unit and one rake sample (15388, which has a positive Eu anomaly and 42% plagioclase (4)) from a feldspathic microgabbro unit.

As shown in Fig. 1, as an example, the Apollo 15 mare units lie along a series of compositional trends defined by the entire suite of pyroclastic and mare basalt magmas. These, and similar plots, quite clearly show that all mare materials were produced by a common petrogenetic sequence from a common set of source materials, as depicted in Fig. 2 (5,6). The fact that all mare materials lie along common compl trends rules out all proposed petrogenetic models in which each unit, or a few units, is considered to have both an individually tailored source region and genesis needed to to explain some subset of the petrological, chemical, and/or isotopic data. Given the general model of the mare basalt source regions and of mare basalt genesis derived from a synthesis of the major oxide/major mineral [Pl(Or,Ab,An), Py(Wo,En,Fs), Ol, Ilm, and Chr], compatible siderophile (Co, Ni) and incompatible (K, Rb, Sr, Ba, and REE) trace element data and the isotopic ratios of the Rb/Sr and Sm/Nd systems (5,6), the genesis of the Apollo 15 mare units is briefly as follows:

The primary magmas of all 15 units were derived by about 30% olivine controlled partial melting of their source regions which are located at depth of less than 200 km, Fig. 2. The normative compositions of source region of each of the 5 VLT pyroclastic green glass units are within about 1 Wt% of 6.1% $Or_{0.6}Ab_4An_{95}$, 14% $Wo_{18}En_{62}Fs_{20}$, 78.5% Fo_{76}, 0.2% Ilm, and 1.1% Chr. The normative composition of the LT (Array I) yellow glass unit is 7.3% $Or_{-}Ab_{16}An_{84}$, 12.6% $Wo_{21}En_{56}Fs_{23}$, 76.5% Fo_{71}, 2% Ilm, and 1.2% Chr. The normative composition of the HT Orange glass is within 1 Wt% of 5% $Or_3Ab_{17}An_{80}$, 12.6% $Wo_{23}En_{57}Fs_{20}$, 76.3% Fo_{74}, 5.7% Ilm, and 1.4% Chr. The normative composition of the VHT red glass unit is 4.1% $Or_6Ab_9An_{85}$, 12.5% $Wo_{20}En_{59}Fs_{21}$, 72.6% Fo_{74}, 9.4% Ilm, and 1.6% Chr. The normative compositions of the source regions of the 7 LT mare basalt units are within 1 to 2 Wt% of 5.7% $Or_1Ab_{11}An_{88}$, 11.8% $Wo_{20}En_{58}Fs_{22}$, 79.9% Fo_{73}, 1.2% Ilm, and 1.2% Chr.

These 30% primary melts rose to the crust-mantle boundary where they pooled in one or more magma storage chambers, Fig. 2. However, the primary magmas of the pyroclastic glasses remained in their magma chamber(s) only a short time and therefore lost no olivine (as reflected by their high normative Ol, Co, and Ni contents) or volatiles (as reflected by the volatile coatings on the glass beads and their low $^{238}U/^{204}Pb$ ratios) and assimilated little or no urKREEP residual from the storage chamber(s) wall rocks. The trace element pattern of Ma et al. (7) of the green glass units shown in Fig. 3 (there are no trace element data for the other Apollo 15 pyroclastic glass units) is accounted for if the 30% primary melts assimilated no urKREEP residuals. If green glass pattern of Taylor et al. (8) is correct, then the primary magmas assimilated a minute amount (0.07%) of fractional melt from the urKREEP wall rocks. In either case, the low incompatible trace element contents of the green glass magmas is due to their have assimilated little or no urKREEP residual wall rocks during their short stay in the magma chamber(s).

In contrast to the pyroclastic glass units magmas, the primary magmas of the other Apollo 15 units remained long enough in the storage chamber(s) so that they cooled and lost olivine via fractional crystallization, as reflected by their relative positions in the quaternary phase diagram and their decreasing Co (Fig. 1) and Ni contents. Specifically the amount of Ol lost by each of the primary magmas in the storage chambers is: olivine microgabbro unit A, 21%; olivine microgabbro unit B, 25%; olivine phyric unit, 28%, and the pyroxene phyric unit and the yellow impact glass unit each 31% (the amount of olivine lost from the picrite basalt and feldspathic microgabbro units can not be determine since the magma compositions of these units are not accurately defined on the basis on only 1 to 2 samples). As these primary magmas cooled and lost olivine, they also assimilated urKREEP redisuals from the wall rocks. The amounts of incompatible trace elements in the basalts, their trace element patterns (Fig. 3), and isotopic ratios (Fig. 4) are accounted for if the magmas of the olivine phyric and olivine microgabbro units A and B each assimilated about 0.4% of urKREEP residual, that of the pyroxene phyric unit assimilated about 0.5% of the residual, and that of the yellow impact glass unit assimilated 10.5% urKREEP residual (again, until their magmas are accurately defined, the amount of urKREEP residual assimilated by the primary magmas of the two remaining units can not be accurately defined). In all cases, the urKREEP resiuals assimilated by the Apollo 15 mare basalt magmas was formed by 7-8% fractional remelting of the parental urKREEP materials. Since all the magmas obtained the bulk of their incompatible trace element from the <u>same</u> type of urKREEP residual, this indicates that either the magmas all used (sucessively) the same magma chamber or the individual storage chambers were close enough together that the spatial variation in the composition of the residuals was of no significance in the case of the Apollo 15 basalts.

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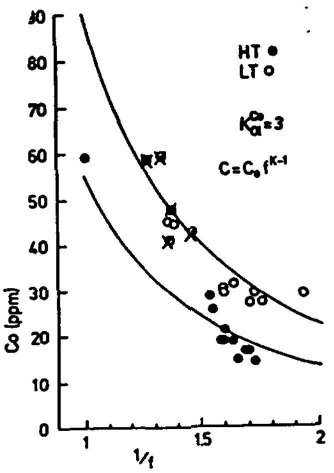

Fig. 1. Observed (open and filled circles for low and high Ti magmas, respectively; the Apollo 15 magmas are also indicated by an x) and calculated (curved lines) variations of the Co contents of the mare basalt magmas as a function of their degrée of olivine fractionation (1-f) in the shallow magma chambers shown in Fig. 2.

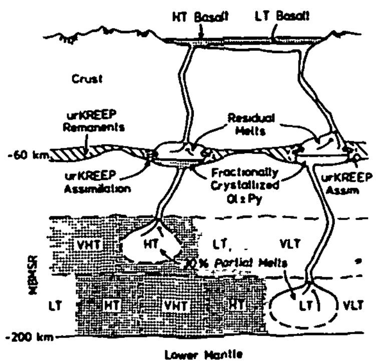

Fig. 2. Schematic representation of the density-graded bands of the mare basalt source region, the magma storage chambers, and the major steps in the genesis of the mare basalt magmas.

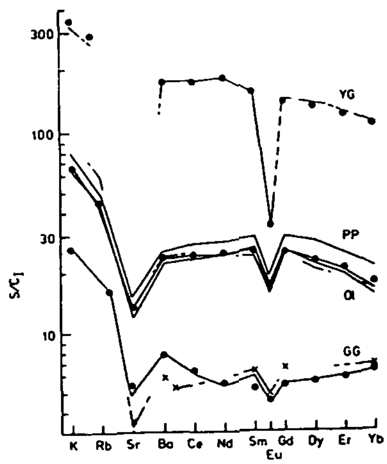

Fig. 3. Observed (lines) and calculated (X's and filled circles) incompatible trace element contents of the Apollo 15 units. The units are: YG - yellow glass unit, PP - pyroxene phyric unit, Ol - the very similar olivine phyric and microgabbro units, and GG - the green glass units (the continuous line are the data from (8) and the broken line are those from (7)). The calculated values given along the Ol curves is a average fit to all the Ol and PP data together.

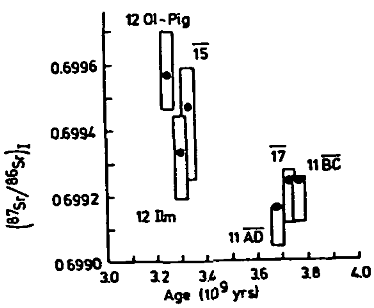

Fig. 4. Observed (rectangles) and calculated (filled circles) initial $^{87}Sr/^{86}Sr$ values of various mare units as a function of age.

COMPARISON OF PETROLOGY, GRAIN SIZES, AND SURFACE MATURITY PARAMETERS FOR APOLLO 15 REGOLITH BRECCIAS AND SOILS. D.D. Bogard, D.S. McKay, R.V. Morris, P. Johnson[1], and S.J. Wentworth[2], Code SN4, NASA Johnson Space Center, Houston, TX 77058 ([1] also Northrup Services Inc.; [2] also Lockheed/LEMSCO)

Introduction: We have analyzed 28 Apollo 15 regolith breccias for their petrographic and textural properties and for the surface exposure indices solar noble gases and I_s/FeO. These data, along with compositional data determined for the same breccias by R. Korotev, permit detailed comparisons to be made between Apollo 15 soils and Apollo 15 regolith breccias which were formed by lithification of soil components. Two breccias, 15265 and 15086, were disaggregated by either freeze-thaw or ultrasonic techniques and sieved into several grain size fractions in order to examine the soil material that pre-dated breccia formation. The purpose of these experiments is to examine similarities and differences in compositional components and irradiation history between regolith breccias and local, present day soils. A similar study of Apollo 16 regolith breccias is reported by (1), and earlier reports on Apollo 15 breccias were given by (2,3).

Surface Maturity: Various indicators of the duration of exposure of fine-grained material at the lunar surface (surface maturity) show considerable similarity between these regolith breccias and soils and cores returned from the Apollo 15 site. The parameter I_s/FeO, a normalized measure of the quantity of fine-grained metal produced by micrometeorite bombardment at the lunar surface, shows a range in these breccias that is typical of Apollo 15 immature and submature soils, although I_s/FeO for the breccias do not completely overlap the range for soils at the most mature end of the scale. Mean I_s/FeO for 28 regolith breccias is 25.0 whereas for 25 surface soils the mean is 59.8, more than twice as high. Core soils are intermediate; the mean I_s/FeO is 39.2 for 46 evenly space samples from the deep drill core (4). Of the 28 regolith breccias analyzed, all but one (15688) contain noble gases implanted by the solar wind in concentrations that are typical for Apollo 15 soils (Fig.1). Agglutinate concentrations for these breccias correlate roughly with I_s/FeO, although some breccias (e.g. 15295 and 15505) have few identifiable agglutinates, yet contain appreciable I_s/FeO and solar gases. These observations indicate that most Apollo 15 regolith breccias contain a sizeable component that resembles lunar soil, and that most breccias are somewhat less mature than typical soil. No significant compositional difference seems to exist between the solar gases trapped in these breccias and in typical soils. Averaged elemental ratios (and one sigma undertainty of the mean) of trapped noble gases in 27 of these breccias are: $^{4}He/^{36}Ar=161\pm75$, $^{22}Ne/^{36}Ar=0.35\pm.18$, $^{84}Kr/^{36}Ar=4.6\pm1.2 \times10^{-4}$, and $^{132}Xe/^{36}Ar= 0.86\pm.35 \times10^{-4}$. The last three of these ratios are similar to trapped ratios shown by a large number of bulk soils of different surface maturities from the Apollo 15 drill core (5). The He/Ar ratios for the breccias are considerably lower than the range of values shown by drill core soils, and suggest that greater He loss has occurred from the breccias, probably during mild heating that accompanied breccia formation.

Comparison of Disaggregrated Breccias with Soils: Breccia 15086 disaggregated by freeze-thaw has a grain size distribution indistinguishable from a typical Apollo 15 submature soil such as 15071. Other disaggregated breccias including 15265, 15298, and 15565 also resemble soils in their grain size parameters, although some differences exist between the freeze-thaw and ultrasonic versions. A comparison of disaggregated breccia with typical soils from Apollo 15 show very similar properties. For example, disaggregated breccia 15086 contains 41.5% monomineralic fragments in the size range 20-500 um and soil 15601 contains 41.6 percent monomineralic fragments in the same size range. The plagioclase/pyroxene ratio in this breccia is 0.31 in this size range compared to 0.19 in soil 15601. The greatest difference is in the more abundant KREEP basalt in the breccia (10%) compared to this soil (1%), and the lower agglutinate content in the breccia (5%) compared to this soil (28%). As the surface maturity of soil decreases, the noble gases and fine-grained metal are observed to be preferentially enriched in the finest size fraction of the soil. We measured concentrations of solar gases and I_s/FeO in the <20 um and 90-150 um grain sizes of disaggregated breccias 15265 and 15086, and these data offer further evidence that the pre-breccia material was irradiated as finely disseminated grains. The ratios of concentrations of these maturity parameters in the two grain sizes are compared to core soils in Table 1. Because noble gases in the 90-150 um grain size were not measured for these core soils, we compare to the bracketing size ranges of 75-90 and 150-250 um measured for the soils. Comparison of gas concentrations of whole rock and grain size data show no evidence of appreciable loss of solar gases during the disaggregation. The five noble gases and I_s/FeO have very similar concentration ratios for a given disaggregation experiment, e.g. the ratios are all about four for the freeze-thaw disaggregation of 15265. The concentration ratios for 15265 disaggregated by freeze-thaw are somewhat lower than the ratio of about 7 expected from core soil data, and the ratios for 15265 disaggregated by ultrasonic and 15086 disaggregated by freeze-thaw are somewhat higher than those shown by the soils. These concentration ratios are known to vary with soil maturity and relative retentivity of solar gases (6,7). Lower ratios could result if the disaggregation caused breakage of larger grains and production of small grains with a deficiency of original grain surfaces enriched in solar gases. Higher enrichment factors could result if the disaggregation did not fully break the breccia into its original soil component so that some fraction of the larger grains contain solar gases on interior surfaces. Completely random breakage of the breccia during disaggregation without regard to the original soil grains is expected to produce a concentration ratio of one.

Breccia-Soil Differences: Comparisons of petrologic components, grain size distributions, surface maturity parameters, and chemical composition (8) show that the Apollo 15 regolith breccias are quite similar to Apollo 15 soils. Korotev (8) found the chemical composition of breccias and soils recovered from the same collecting station to be even more correlated. In spite of these similarities, several breccias show significantly higher trapped $^{40}Ar/^{36}Ar$ ratios than the soils, which suggests that the breccias were formed at significantly earlier times when this ratio was larger at the lunar surface (e.g. 9,1). The five breccias from station 8 have $^{40}Ar/^{36}Ar$ ratios <1, as do local soils. Five breccias from station 7 near Spur Crater have ratios of 3.3-5, far greater than local surface soil with a ratio of 0.7. Five breccias collected at station 6, some distance from a small crater, have ratios of 0.6-1.3, similar to local soils, whereas, breccias collected near the crater rim, including two chipped from boulders, have ratios of 1.4-2.4. Apparently deeper and older breccias were deposited near the crater rim. One breccia collected at station 9 at some distance from the rim of Hadley Rille has a ratio identical to local soil (0.6). Three breccias collected on the rim of the Rille have $^{40}Ar/^{36}Ar$ of 1.4-2.3, considerably higher than the range of 0.6-1.1 seen in soils of the 15010/11 core also collected at the rille rim. Higher Ar ratios in these breccias and in the less mature soils of the core are consistent with older regolith being exposed by downslope movement of regolith into the rille.

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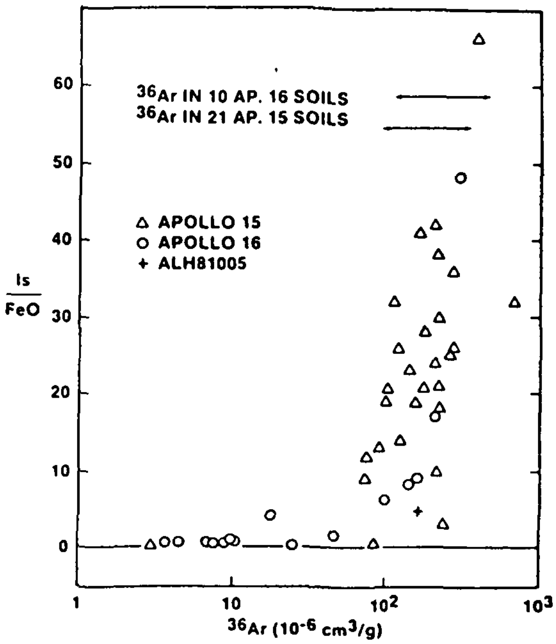
Table 1. A Comparison of I_s/FeO and Noble Gas Concentration Ratios as a Function of Grain Size for Disaggregated Breccias 15265 and 15086 and for Twelve 15010-11 Core Soils

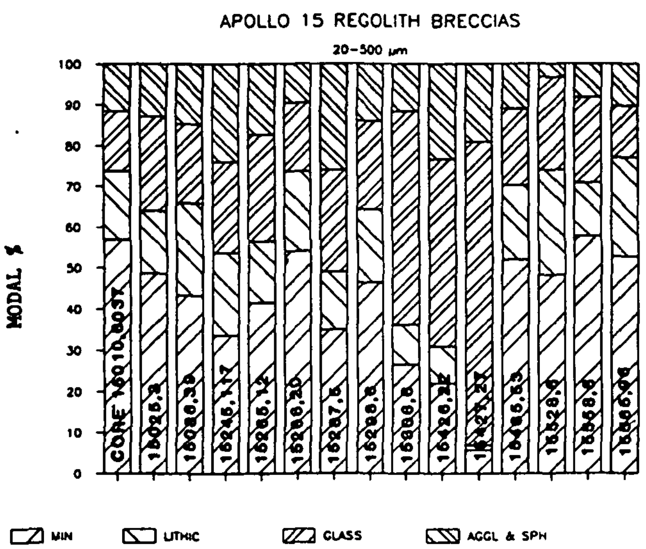
ELEMENT	BRECCIA 15265		BRECCIA	CORE SOILS 15010-11	
	<20/90-150		15086	<20/75-90	<20/150-250
	FT	US	FT		
^{4}He	4.3	11.7	12.0	7.7 ±1.0	12.4 ±1.9
^{22}Ne	3.4	9.8	10.0	6.2 ±0.6	9.7 ±1.1
^{36}Ar	3.5	9.8	10.7	6.1 ±0.9	8.5 ±1.9
^{84}Kr	4.4	10.3	--	5.0 ±0.8	8.5 ±2.0
^{132}Xe	4.2	9.3	--	5.0 ±0.8	7.2 ±1.7
I_s/FeO	3.7	11.5	9.4	4.5 ±2.9*	

* I_s values are <20/90-150 for 5 drill core soils.
FT= freeze thaw; US= ultrasonic

Fig. 1 (below left) I_s/FeO versus solar ^{36}Ar for Apollo 15 and 16 regolith breccias

Fig.2 (below right) Modal percents of major components in several Apollo 15 regolith breccias





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APOLLO 15 LUNAR BASE SITE: STEEP SLOPES AS AN ENERGY RESOURCE, J. D. Burke, Jet Propulsion Laboratory/California Institute of Technology

1. Introduction

If it is decided to build a lunar base at an Apollo site, the choice is likely to be between Apollo 15, Hadley-Apennine, and Apollo 17, Taurus-Littrow, because these two sites offer more variety than do the other landing sites. Apart from their visual interest and good scientific characterization, the Apollo 15 and 17 sites offer the prospect of varied and accessible lunar resources. One such resource is provided by steep natural slopes. This paper discusses the potential benefits and hazards associated with these slopes.

2. Types of steep slopes near the Apollo 15 site

Figure 1 (AS15-0585) shows the surroundings of the Apollo 15 site, with North at the top. Crater Hadley, at center, is 5.7 km across. Figure 2 (AS15-0585, 86) is a stereo pair that provides an exaggerated sense of the topography. Even without exaggeration, it is clear that steep slopes are plentiful within 50 to 100 km of the landing site. The LM descent stage, rover and ALSEP instruments rest just to the East of the "elbow" where Hadley Rille departs from the Apennine Front and begins to wander toward the northwest. At least four kinds of steep slopes can be recognized at the scale of these orbital photos: (1) walls of relatively recent impact craters, (2) the walls of the rille and its source cleft, (3) slopes of the Apennine Front ranges, and (4) the (less steep) sides of apparent tension fractures near the top of the picture. On closer examination it is seen that all of these slopes have suffered mass wasting, as shown by patterned ground, boulder tracks, and basal talus deposits. However, considerable slope areas are still at or near the angle of repose (Ref. 1). Our purpose here is to examine what use can be made of this fact.

3. Slopes as an energy resource

Earth-moving (or perhaps one should call it Moon-moving) is a difficult but essential task in any of the lunar base concepts that have been studied to date. An early base is usually depicted as a set of cylindrical containers, covered over with soil to protect the inhabitants from the lunar environment. The required thickness of cover is set by the need to shield against ionizing radiation and is usually considered to be at least one meter, preferably two. The base module must be buried in a trench, or else soil must be piled over it as is done for explosives-storage igloos on Earth. Either way, a lot of material must be moved, lifted and deposited, so artists' lunar base concepts usually include something like a skip-loader to do the work. Lunar mining, of course, may demand similar and much greater efforts. An obvious question to ask is whether or not natural features can be exploited to make these tasks easier. A minimum-energy concept would involve placing items to be covered at the bottom of a slope existing at the angle of repose, and then kicking loose small landslides. While this might work, it would be risky because the slides would probably include boulders. Figure 3 (AS15-84-11287) shows house-sized rocks in the bottom of Hadley Rille. A safer way might be to place the object to be covered at a safe distance from the bottom of the slope and launch soil toward it ballistically by means of rotating wire brush or equivalent device.

A qualitative idea of this process can be gained by observing the dust plumes thrown up by the Apollo rover's wheels.

For mining, where the boulder hazard is not so severe, pulling a dragline bucket up and down a steep slope should be both practical and efficient on an energy basis, because the heavy loads are all going downhill.

4. Mechanical properties of slope materials.

The mechanical characteristics of the lunar regolith (its depth, particle size and shape distributions, density, cohesiveness, and hence its bearing and shear strength) differ with the age and morphology of the surface exposed. On steep slopes, where thermal creep and downslope ballistic transport operate to keep the near-surface material stirred up and relatively fresh, the soil is softer and less cohesive than it is in flat regions where the soil can become gradually more mature, settled and compacted (Ref. 2).

Steep slopes are therefore hazardous from a trafficability standpoint, even without considering dislodged boulders. On the other hand, the relative weakness of slope soils contributes to the ease of excavating and transporting lunar material. Slopes may therefore be interesting sites for prospecting in early resource surveys around the Apollo 15 site. For this purpose, measurements of regolith depth and the gradients of density and particle size with depth would be desirable. The seismic and electromagnetic techniques demonstrated on previous Apollo missions could be used. However, characteristics of the substrate are probably not as favorable for such measurements on slopes as they are, for example, on flat mare surfaces, because there is no reason to expect strong layering parallel to the surface. Indeed some of the Apollo 15 photos show layering almost perpendicular to exposed slopes, as on Silver Spur (Figure 4-AS15-84-11250). If remote methods prove unrewarding it will be necessary to use direct mechanical probes (penetrators) which can be carried and inserted by a person or a mobile robot. This would be analogous to the probing and sampling of snow on Earth, and it need not go to great depth because plenty of material for shielding an early base can be obtained by draglining only the top meter or so of the soil. For quantitative sampling, probes similar to the (later, improved) Apollo drive tubes could be used but are probably not needed for the gross evaluation of slope soils as a shielding resource.

5. Conclusions

The abundance of steep slopes near the Apollo 15 site, due evidently to several different geological causes, is an invitation to the lunar base designer and resource prospector to use ingenuity in benefiting from what nature has provided. This paper has intended to open the subject and point the way to possible uses and needed exploratory measures. Further exploration of these concepts appears warranted by the need to keep the engineering simple and all energy demands as low as possible, at least in the early stages of a lunar base build-up. The Apollo 15 site, with its several different kinds of steep natural slopes, appears well suited to this use. Therefore, a careful assessment of the prospect, with due attention to its evident hazards, should be among the early activities of the next humans to visit the Hadley-Apennine region of the Moon.

Ref. 1 Apollo 15 Preliminary Science Report. NASA SP-289, 1972.

Ref. 2 Bazilevskii, et al (1984) Dependence of the physicomechanical properties of lunar soil on relief features and processes in the region of operation of Lunokhod-2. Kosmicheskie Issledovaniya 22, 2, 243-251.

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FIG. 1

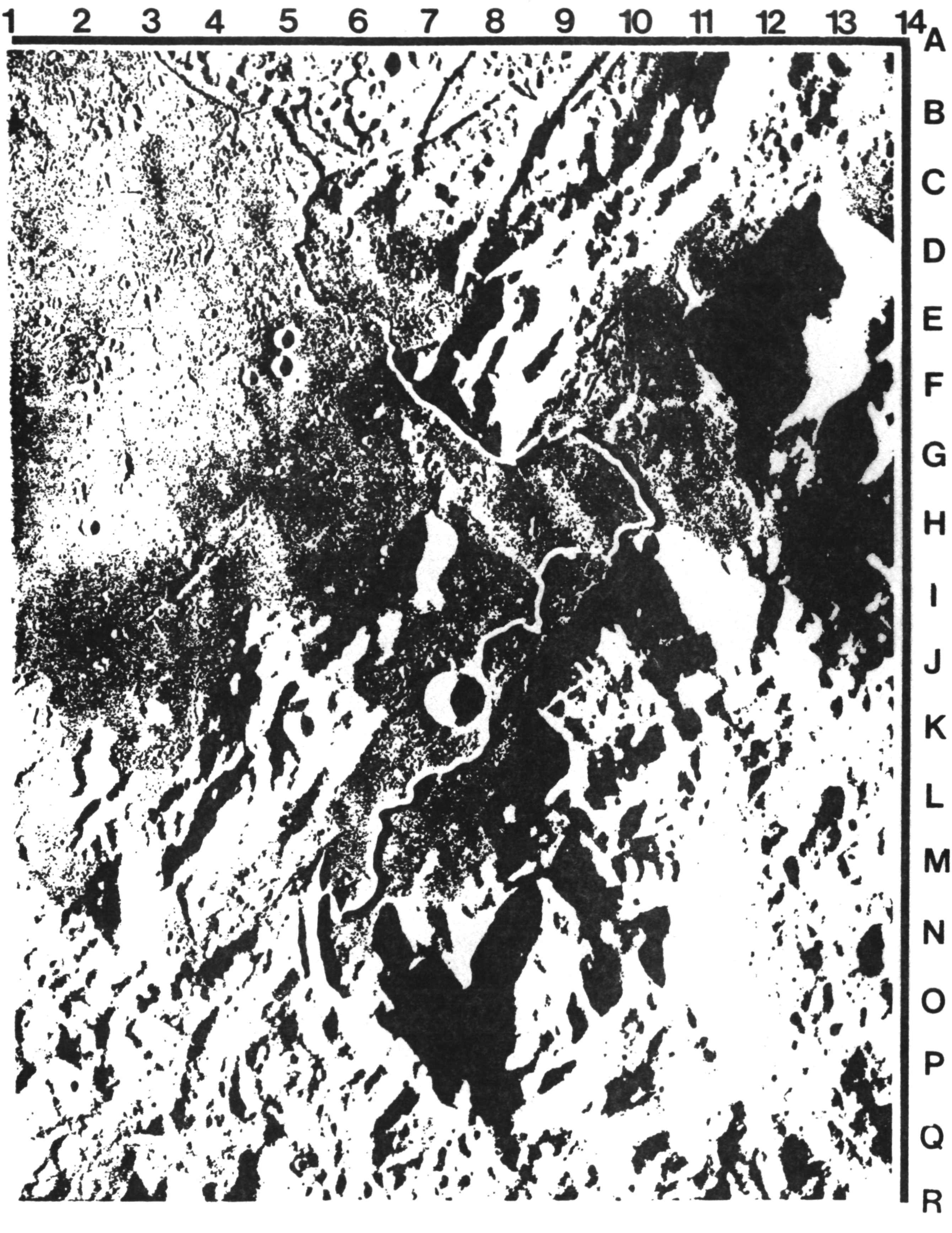

Fig. 5.4: Apollo metric mapping photograph AS15-0585. The picture was taken over the Apollo 15 landing site at H-11.

FIG. 2

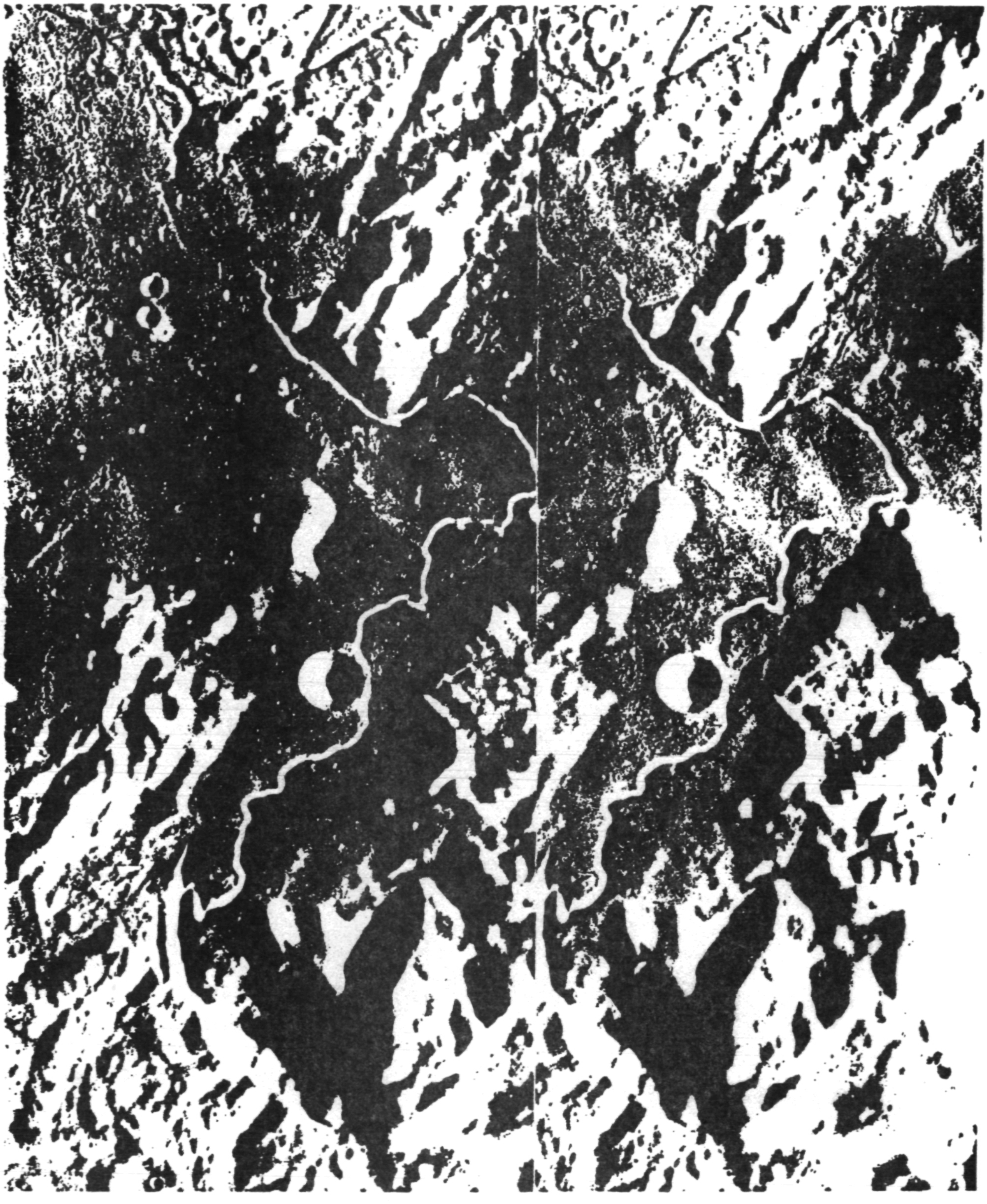

Fig. 5.6: Stereogram of the Apollo 15 landing site area. Left half is a portion of AS15-0586, right half, AS15-0585. Spacecraft motion is from right to left parallel to the bottom edges of the pictures. Rima Hadley, the sinuous trough, is 300 m deep. The prominent central crater, Hadley, is 5.7 km in diameter. Corresponding features in the left and right halves are 60 mm apart. North is to the top. The spacecraft was 103 km above the ground.

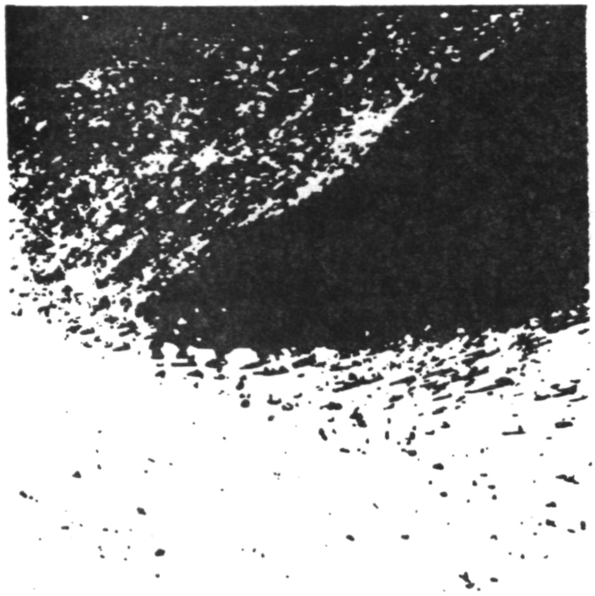

FIGURE 3.–Bottom of the rille, looking north from station 2. The largest block is 15 m across (AS15-84-11287).

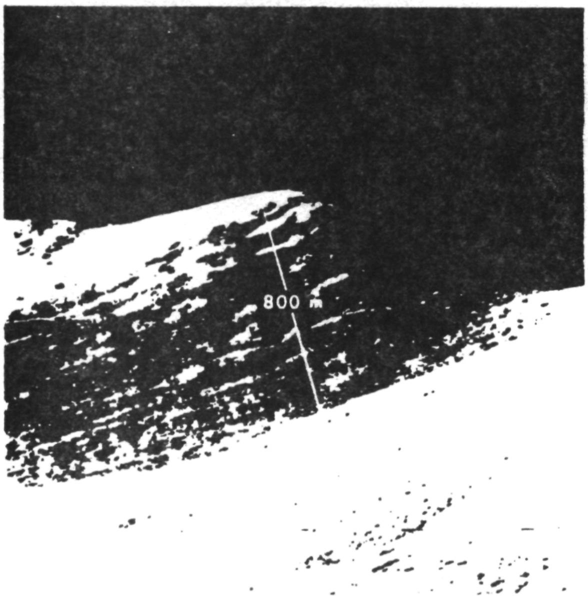

FIGURE 4.–Lunar-surface 500-mm photograph looking southeast toward Silver Spur, approximately 20 km away. View shows detail of massive ledges of the north-northeast lineament system (sloping gently left) and the possible fractures of the northwest lineament system (dark deeply shadowed depressions sloping steeply right). Slope of Hadley Delta is in the foreground (AS15-84-11250).

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EXTRACTION OF INFORMATION FROM MAJOR ELEMENT CHEMICAL ANALYSES OF LUNAR BASALTS

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When the history of igneous petrology is written in the year 2,100, students of the subject will note that the first hundered and twenty five years or so (1865 to 1990) marked a time when advances in analytical capabilities far exceeded advances in the ability of the petrologist to display and interpret the variability present in chemical analyses of rocks and minerals. One may argue that the quality of the data in todays publications exceeds that of any time in the past with respect to accuracy and precision. Does the fact, however, that the most common forms of dislaying petrochemical variability in the past - the binary and ternary scatterdiagrams imply that they have been shown to be superior to all other possible forms? I think not. Many authors have expressed the concern that focusing attention upon a subset of the available information is tanamount to ignoring a great deal of the total amount of available information. There is no doubt that this presents a problem for the petrologist to wrestle with but there remains a more fundamental foe. Namely, the form of the data itself.

Major element chemical analyses often form the framework within which one attempts to recognize similarities and differences among analyzed specimens and either to speculate upon the suitability of previously proposed genetic models or to devise a new genetic model to explain the observations. Although some authors have advocated multivariate models, there remains a reliance upon the binary and ternary scatter diagrams in spite of serious concerns voiced by Chayes (1) and others concerning all such analytical approaches when the data are presented as percentages or proportions. Given a set of M amounts (oxide weight percentages, for example) of the chemical constituents in a rock speciment, an increase in one must of necessity result in the reduction of at least one of the others as the sum of all M must remain a constant. A binary scatter diagram, for example, of MgO versus FeO may exhibit a strong negative relationship. How should the investigator interpret such a display? Is it "safe" to assume that one is "viewing" the results of crystal fractionation in which removal of early-formed Mg-rich phases produced a liquid in which Fe was enriched? Or, is it possible that the inverse variation is only a manifestation of the aforementioned constraint upon percentages and proportions in general? A third possibility obviously exists as the "correct" answer may in fact be that both mechanisms - petrogenetic and numeric - may be recorded by the observed variation. One may agrue that the problem can be cast in the form of a null hypothesis which states that the variables are "independent" (uncorrelated in this note) and that a standard test of independence can be evaluated; for example, testing the observed correlation coefficient against a null value of 0.0. Unfortunately, this is the crux of the problem.

Performing such a test (or worse yet, judging the strength of a variation on the basis of simplicity of observed variation) assumes that one knows how to recognize independence in percentages. As Chayes (1) and Aitchison (2,3) have demonstrated, however, such is not the case.

Aitchison (2,3) has proposed a statistical framework within which one may be able to answer questions such as those noted above. Preliminary studies (Butler and Woronow, in preparation) have been encouraging although there remain numerous questions as Aitchison style and notations are somewhat obscure to this geologist. When percentages are formed the ratios of pairs of the components are preserved whereas many of the familiar statistical and geometrical descriptors are likely to exhibit major changes. This ratio-preserving aspect forms the basis for much of Aitchison's proposals.

The set of 42 major element analyses of the "lunar reference samples" (4) was selected as part of a major investigation of Aitchison's proposals. A somewhat subjective decision was made to ignore those variables with mean values less than 0.35 weight percent which yields a set with seven "major variables" : SiO_2, TiO_2, Al_2O_3, FeO, MgO, CaO and Cr_2O_3.

An analysis of compositional variability within this set of data must be prefaced by determining if the covariance structure present in this matrix could be the sole result of percentages having been formed from independent components; expressed by Aitchison (4) as a hypothesis of complete subcompositional independence. The computed chi-squared test statistic of 115.9 (with 14 degrees of freedom) greatly exceeds the tabulated chi-squared value of 23.7 at the 95% confidence level. Thus the null hyothesis is rejected and, in the opinion of the author, one can safely proceed with an analysis of the data set. Failure to reject such a null hypothesis should call a hault to such extensions as one would be assigning petrogenetic significance to variability most likely induced by forming percentages.

Following Aitchison's (3) suggestions, the set of 6 non-zero eigenvalues and associated eigenvectors were extracted from the variance-covariance matrix of the log-row-centered form of the data set. In effect, each component in a sample is normalized to the geometric mean of the sample.

A plot (Figure 1) of the first versus the second principal component scores (I and II) displays more than 96% of the total variability of this data set. No single pair of components in the set of oxide weight percentages or log-row-centered variates accounts for more than some 70% of the total variability of the array. The correlation coefficient between scores I and II is constrained to be zero yet "clusters" of similar specimens are evident. An analysis of the correlations among scores I and II and the raw data set (including the computed magnesium number) indicates that the first score is a measure of TiO_2 and Cr_2O_3

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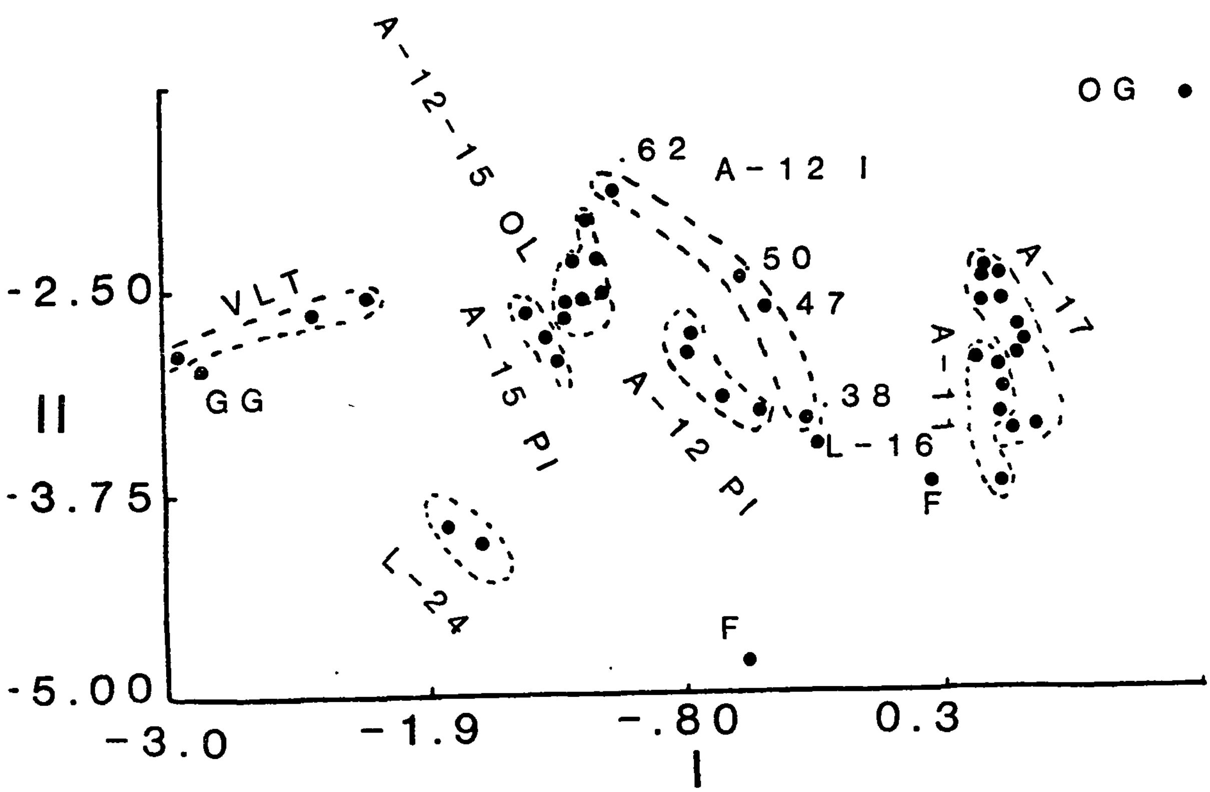
variability whereas the second score correlated with Mg number and Al_2O_3 (see Figure 1). For example, within each outlined cluster there is a systematic variation of Mg number (given just for the set of Apollo 12 ilmenite basalts).

The potential utility of such a plot should be evident. First, it is based upon a data set in which one "knows" that the petrologic information content exceeds that expected from having formed percentages from independent variables. Second, very little information is not contained within the plane defined by the first two principal components. Although it may be comforting to note that the familiar groups of lunar samples are recognized in Figure 1, this in and of itself is not a justification for the process.

References : (1) Chayes, F., (1971) Ratio Correlation, University of Chicago Press, Chicago, Ill., 99p. (2) Aitchison, J. (1981), Math. Geol., 13, 175. (3) Aitchison, J., (1984), Math. Geol., 16, 617. (4) Basaltic Volcanism Study Project, (1981), Basaltic Volcanism on Terrestrial Planets, Pergamon Press, Inc, New York, 236.

Figure 1 . A plot of the first two principal components (I and II) from the set of 42 Lunar Reference Samples (4). GG and OG refer to Apollo 15 green glass and Apollo 17 orange glass respectively. VLT refers to the very low titanium basalts and the prefix L denotes Luna basalts. F refers to the feldspathic-rich basalts, PI to pigeonite-bearing basalts, OL to olivene basalts and IL to illmenite-rich basalts.



APOLLO 15 MARE VOLCANISM: CONSTRAINTS AND PROBLEMS.

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Introduction

The Apollo 15 landing site contains mare volcanics in the form of crystalline basalts (open symbols in Figure 1) and pristine glasses (solid symbols), which form the framework for all models dealing with the mantle beneath that site. This abstract summarizes some of the major issues bearing on the petrology of the mare source-regions beneath that portion of Mare Imbrium.

Magmas at Apollo 15

Petrologists who study the Earth's upper mantle rely on (a) basaltic magmas and (b) ultramafic xenoliths. While that combination of samples has proven successful in furnishing first-order information about the chemistry of the terrestrial upper mantle, this dual approach has not been possible on the Moon due to the absence of ultramafic xenoliths. As a result, lunar petrologists have had to depend only on mantle-derived magmas (i.e. LIQUIDS). This has involved searching for volcanic samples with vitreous or aphanitic textures without accumulated mineral-phases (e.g. 15016; 15597; pristine glasses). Six major varieties of magma, plus four sub-varieties, have been identified by investigators since 1972 (Table). These magmas include: (a) quartz-normative basalt 15597; (b) olivine-normative basalt 15016; (c) five varieties of pristine green glass; (d) pristine yellow glass; (e) pristine orange glass, which is chemically indistinguishable from that found at Apollo 17; and (f) pristine red glass. These magmas can not have been derived from one another by crystal/liquid fractionation and hence represent 10 separate volcanic events (e.g. Chappell and Green, 1973; Ma et al., 1978; Walker et al., 1977).

The Apollo 15 magmas are compositionally diverse. For example, the range in Ti-abundance among these magmas is nearly as large as that observed for the entire collection of mare samples returned by all Apollo missions. Although this compositional variety in magmatic samples from one landing site probably has important implications for the chemical diversity in the lunar mantle, caution must be exercised since the eruptive sites of these magmas are not known. Consequently, local provenance is not assured for all ten magmas.

Primary versus Differentiated

Following the identification of samples that represent magmatic compositions, petrologists ascertain whether each magma was primary or differentiated. A magma is primary if it ascended from its source-region without undergoing changes in its original chemistry. A differentiated magma, however, underwent assimilation of wall-rock and/or crystal/liquid fractionation, such that its chemistry has been altered subsequent to leaving the source-region. Primary magmas possess vital petrologic information about their source-regions. However, primary magmas are rare. For example, fewer than 1% of the magmas erupted onto the Earth's surface are primary (Walker et al., 1979; p. 2009).

To determine whether a magma is primary, petrologists focus on the abundances of elements that are most sensitive to differentiation processes (e.g. Mg, Ni). While this approach in tandem with studies of ultramafic xenoliths has led to a consensus on the chemical nature of primary MORB's (mid-ocean ridge basalts) on Earth (e.g. Elthon and Scarfe, 1984; Green et al., 1979; Stolper, 1980), the absence of ultramafic xenoliths among lunar samples has made the task of identifying primary lunar magmas more difficult (Bence et al., 1980).

The Apollo 15 magmas are plotted in Figure 1a against an element that is sensitive to differentiation (Mg). Note that the basalts, 15016 and 15597, have lower Mg-abundances than the pristine glasses. A similar relationship also exists at Apollo 11, 14, and 17, and suggests that the magmas represented by the crystalline basalts appear to be differentiated compared to the pristine glasses (e.g. differentiation drives magmatic compositions to the left in Figure 1a). The pristine glasses are the best candidates for primary magmas yet identified (e.g. Binder, 1982, 1985a,b; Delano and Livi, 1981; Delano, 1985; Green and Ringwood, 1973; Marvin and Walker, 1978). However, while the quartz-normative basalt 15597 can be confidently concluded not to be a primary magma (see next section), the olivine-normative basalt 15016 can not be completely excluded from consideration.

Depths of Mantle Source-Regions

To constrain the depths of source-regions, petrologists must (a) identify primary magmas and (b) assume that two-or-more minerals were present in the residue during partial melting. While it is generally agreed among terrestrial petrologists that olivine + pyroxene(s) were residual phases in the source-regions of MORB's (e.g. Elthon and Scarfe, 1984; Green et al., 1979; Stolper, 1980), this consensus has emerged only after years of investigations on MORB samples and ultramafic xenoliths. Unfortunate for lunar petrologists, the absence of mantle-derived xenoliths has severely restricted efforts to evaluate whether or not the "2+-phase assumption" is valid in the case of primary mare magmas. Consequently, the depth of the mare source-regions remains a contentious issue (e.g. Binder, 1982, 1985a,b; Delano, 1980, 1985).

IF the "2+-phase assumption" is correct, Figure 1b shows the experimentally determined depths of the source-regions for the Apollo 15 magmas. First, note that the depth indicated by quartz-normative basalt 15597 is only about 50 kilometers (i.e. within the anorthositic highlands crust). This result, in concert with this magma's low Mg-abundance (Figure 1a) prompted Walker et al. (1977) to conclude that the quartz-normative magma is not primary, and hence provides few direct constraints on the petrologic nature of the lunar mantle. Second, the experimental results derived from the pristine glasses (solid symbols in Figure 1b) suggest that these magmas were all derived from the limited depth-interval of 350 km to 450 km (e.g. Delano, 1980; Green et al., 1975; Grove and Lindsley, 1978; Kesson, 1975; Stolper, 1974). Since these Apollo 15 magmas have Ti-abundances that vary by a factor of 30, this implies that the lunar mantle is heterogeneous (e.g. Bence et al., 1980). Finally, Stolper et al. (1981), noting that the pressures in the source-regions of MORBs (25-35 kbars) and mare magmas (20-25 kbars) were similar, speculated that it may be related to melt compressibility and the resulting buoyant force. If that comparison is significant, it suggests a physical basis by which the depths experimentally inferred for the mare sources (Figure 1b) using the "2+-phase assumption" might be meaningful.

If the "2+-phase assumption" is not correct for the primary mare magmas, as argued by Binder (1982, 1985a,b), then the experimentally derived depths shown in Figure 1b have no significance other than to be maxima. Binder has proposed that the mare source-regions were located at depths of about 200 km.

Mg/(Mg + Fe) ratio of the Source-Region

The Mg/(Mg + Fe) ratio in the silicate residuum of the source-regions can be determined using the chemistry of primary magmas. Based upon the compositional- and pressure-dependence of the Fe- and Mg-distribution coefficient (K_D) between olivine and liquid, the Mg/(Mg + Fe) ratios of the residuum have been determined for the Apollo 15 mare magmas (e.g. Delano, 1980; Green et al., 1975; Grover et al., 1980; Longhi et al., 1978). Differentiation of a magma would drive the calculated points in Figure 1c to the left toward lower values of the ratio. Note that the residual silicate(s) in the source-regions of the Apollo 15 pristine glasses have a range of only 10% (i.e. from 0.77 to 0.85), even though the Ti-abundance among these magmas differs by more than a factor of 30. This suppressed variation of the Mg/(Mg + Fe) ratio of the lunar mantle has been noted at other Apollo landing sites (e.g. Green et al., 1975; Walker et al., 1975). Since this parameter involves few assumptions, it is a reliable indicator of an important characteristic of the lunar mantle. In recognition of its importance, various models for the magma ocean have been proposed to account for it (e.g. Binder, 1982, 1985a,b; Longhi, 1981; Ringwood and Kesson, 1976).

Remaining Questions

(a) Were any ultramafic xenoliths carried to the lunar surface by mare volcanism?
(b) What process(es) suppressed variation of the Mg/(Mg + Fe) ratio in the differentiated lunar mantle?
(c) How deep were the mare source-regions?
(d) Where are eruptive sites of the chemically diverse magmas at Apollo 15?
(e) Why are mare magmas about 2x richer in FeO than terrestrial MORB's?
(f) How thick was the magma ocean?
(g) Where did the volatiles associated with the basalts and pristine glasses come from?
(h) Are there pieces of the Eratosthenian-age basalts from Mare Imbrium (e.g. Boyce et al., 1974) in the Apollo 15 sample collection?
(i) What processes caused the unique fractionation trends in the Apollo 15 pristine green glasses (Basu et al., 1979; Delano, 1979; Delano and Lindsley, 1982; Grove, 1981; Ma et al., 1981)?

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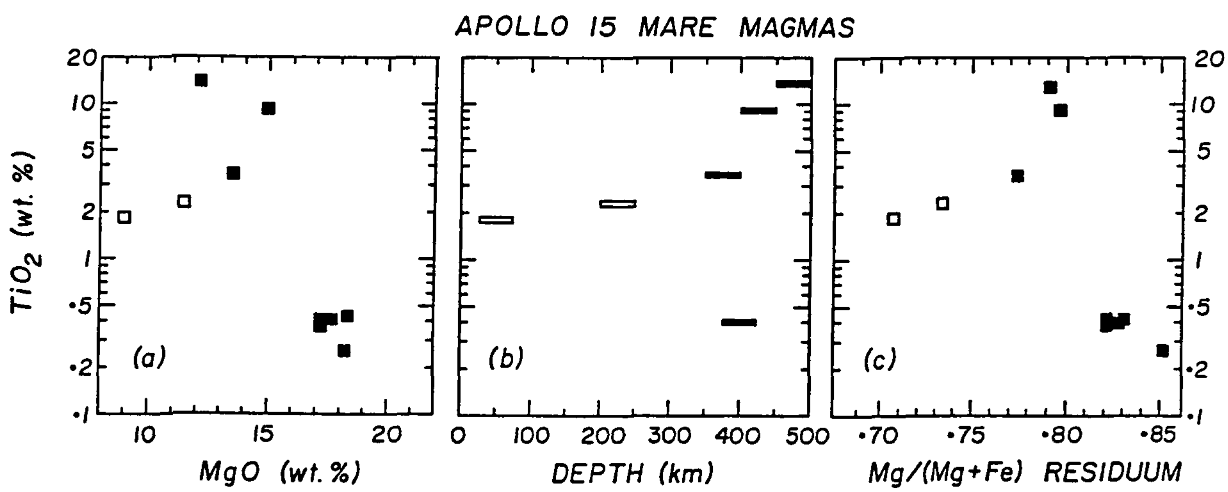
TABLE: Major-element compositions of Apollo 15 mare magmas.

	BASALTS		PRISTINE GLASSES							
	1	2	3	4	5	6	7	8	9	10
SiO_2	44.1	48.0	48.0	45.5	46.0	45.1	45.2	42.9	37.9	35.6
TiO_2	2.29	1.84	0.26	0.38	0.40	0.41	0.43	3.48	9.12	13.8
Al_2O_3	8.41	9.36	7.74	7.75	7.92	7.43	7.44	8.30	5.63	7.15
Cr_2O_3	0.66	0.49	0.57	0.56	0.55	0.55	0.54	0.59	0.65	0.77
FeO	22.8	20.2	16.5	19.7	19.1	20.3	19.8	22.1	23.7	21.9
MnO	0.31	0.28	0.19	0.22	n.a.	0.22	0.22	0.27	n.a.	0.25
MgO	11.4	8.96	18.2	17.2	17.2	17.6	18.3	13.5	14.9	12.1
CaO	9.30	10.1	8.57	8.65	8.75	8.43	8.15	8.50	7.41	7.89
Na_2O	0.27	0.32	n.d.	n.d.	n.d.	n.d.	n.d.	0.45	0.36	0.49
K_2O	0.04	0.06	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.12

[1] Olivine-normative basalt 15016 (Cuttitta et al., 1973; Rhodes and Hubbard, 1973).
[2] Quartz normative basalt 15597 (Chappell and Green, 1973; Nava, 1974).
[3-7] Pristine green glasses (Groups C,A,B,C,D; Delano, 1979).
[8] Pristine yellow glass (Butler, 1978; Delano and Livi, 1981).
[9] Pristine orange glass that is indistinguishable from 74220 (Delano and Livi, 1981)
[10] Pristine red glass (Delano, 1980)

FIGURE 1



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CHARACTERIZATION OF THE APOLLO 15 FELDSPATHIC BASALT SUITE.

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<u>INTRODUCTION</u>. One of the unexpected and highly fortunate outcomes of the APOLLO 15 mission was the discovery of a widespread suite of plagioclase-rich basaltic rocks of probable pre-Mare age. Such rocks are most commonly referred to as "KREEP" basalt [1-5], although a variety of other names have also appeared in the literature, including "highland" basalt [6], "medium-K Fra-Mauro" basalt (MKFM or IKFM) [7,8], and "alkalic, high-alumina" basalt [9]. In order to avoid ambiguity arising from the association of a specific rock type with chemically defined components, the descriptive term APOLLO 15 "feldspathic basalt suite" (FBS) will be used here (cf., [10-12]). Nevertheless, the implicit association of the APOLLO 15 FBS with KREEP suggests that these rocks could provide key information relevant to the petrogenesis of lunar materials enriched in incompatible trace elements. This report summarizes information on the occurrence, chemistry and petrology of this most enigmatic of lunar rock types. The interested reader should refer to the earlier reviews by Irving [13,14], Ryder & Spudis [15], and Meyer [40] for additional summaries on this subject.

<u>OCCURRENCE</u>. Materials with the chemical characteristics of the FBS have been identified at all APOLLO 15 sampling stations, both through bulk soil analyses [16; see also Korotev, this volume], and through compositional clusterings of analyses on glass particles of presumed impact origin [17]. Moreover, tiny rock and mineral fragments -- almost certainly derived from the FBS -- are abundant in APOLLO 15 surface and core soils [18-20]. These observations indicate that the FBS constitutes an important lithology in the vicinity of the APOLLO 15 landing site, where it presumably underlies a relatively thin cover of mare basalt, and may even outcrop as the Appenine Bench formation [21-22].

Despite the evidence that the FBS is abundant at APOLLO 15, it is not recognized among "hand-specimens", with the largest examples being represented by rake samples (e.g., 15382 & 15386) having masses of only a few grams. However, feldspathic basalts comprise up to 20% of certain vitric soil breccias where they are found as clasts ranging up to several cm in size (e.g., 15205 & 15465). In a great number of cases, such clasts preserve the texture, mineralogy, and chemistry of "pristine" igneous rocks unmodified by thermal (i.e., impact-induced) metamorphism. These clasts are therefore good candidates for characterizing internal petrological and chemical variations among the FBS. Accordingly, much of our current understanding about the diversity of the FBS has come from studies of such breccia clasts.

<u>CHEMISTRY</u>. One of the first bodies of data bearing on the very existence of the Apollo 15 FBS was provided by the results of the Soil Survey [17], where it was noted that major element analyses of a large proportion of Apollo 15 soil glass fragments clustered near a basaltic composition characterized by high concentrations of alumina and alkalis. Because of their broad resemblance to materials identified previously at Apollo 14, such glasses were termed "Fra Mauro" basalt, and low-, moderate-, and high-K varieties were distinguished. Subsequent work by other investigators on glass

fragments in soils and soil breccias confirmed and extended the initial results of the Soil Survey, demonstrating that this basaltic material was remarkably abundant among the Apollo 15 samples.

Representative average compositions of these glasses are listed in Table 1. In addition to the high Al, Na and K mentioned above, the glasses are also relatively magnesian (mg~0.6), and, where data are available, have high concentrations of P and Cr as well. These chemical features distinguish the feldspathic basalt glasses from typical mare and highland material, which have lower mg and CaO/Al_2O_3 respectively. Moreover, because of their high contents of K and P, many workers concluded that they are derived from KREEP-like sources.

If these glass compositions faithfully reflect that of their target material, then they would seem to establish the existence of a rock type(s) different from either typical mare or highland material. Mineral norms calculated from these glass compositions indicate that this material should be rich in plagioclase and low-Ca pyroxene, contain small quantities of high-Ca pyroxene, ilmenite and silica, and be essentially devoid of olivine; as it turns out, these are precisely the mineralogical characteristics of "crystalline" FBS samples (see below).

Bulk analyses on selected FBS fragments, carried out by a variety of methods, are shown in Table 2. The close correspondence between these data and the glass analyses in Table 1 provides encouraging support for the contention that the latter represent rock compositions. In particular, the comparable enrichments in K, Na and P argue against major selective loss of these elements by volatilization during impact melting. Other significant features of the major element composition of the FBS include "modest" SiO_2-contents (near 50 wt %) and "low" concentrations of TiO_2 (near 2 wt %).

Trace element analyses on FBS soil fragments (e.g., [19]) reveal typically high concentrations of Ba (~600-1000 ppm), Zr (~600-1100 ppm), Hf (~25-35 ppm), Th (~10-15 ppm), and the REE. The latter occur in concentrations near 200-300X chondritic abundances, whereas pattern shapes show slight LREE enrichment, and profound negative Eu-anomalies (Fig. 1). Collectively, these trace element characteristics demonstrate a close connection between some FBS samples and a KREEP component, although as Drake et al. [11] caution, a range of trace element abundances appears to exist; consequently, there may be a continuum from KREEP-rich to KREEP-poor feldspathic basalts. This problem merits closer attention in the future.

TEXTURES & MINERALOGY. A variety of textures characterize the FBS, but intersertal/intergranular to subophitic types are most common. In these, abundant early-formed plagioclase comprises a semi-continuous network of interlocking lath-shaped grains with pyroxene filling the interstices. Olivine (Fo 70-75) is exceedingly rare, and only three such occurrences are known to the writer; this rarity is consistent with the quartz-normative compositions of the FBS. Ilmenite has an acicular habit, and appears to have commenced crystallizing after pyroxene and plagioclase, as it penetrates both of these phases, and is commonly associated with late-stage silica (mostly cristobalite) and a glassy mesostasis. A low Mg-content of the ilmenite ($\lesssim$1 wt %) is consistent with late formation. Tiny needles of

Ca-phosphate may occur in mesostasis areas; Fe-metal and/or troilite also occur with mesostasis as tiny late crystallizing blebs. A limited amount of data exists which indicates a uniformly low Ni-content of this metal phase.

Grain size varies continuously from very fine to coarse. Most FBS fragments are texturally homogenous at the thin section scale, although plagioclase-porphyritic varieties have been noted by a few investigators. There are no reports of possible exotic xenocrysts.

Plagioclase crystals are strongly zoned, with compositions ranging from An 90 to An 70 (Fig. 2). In general, such compositions are more potassic and sodic than those found in other lunar rock types. Pyroxene compositions are extraordinarily variable (Fig. 3), and range across most of the quadrilateral. However, the nature of compositional zoning in pyroxene can vary considerably, as shown by data for three separate FBS fragments from sample 15205 (Fig. 4). Of particular interest is the apparent existence of a well-defined "two-pyroxene" association in the coarsest grained rocks (Fig. 4c).

A diagnostic mineralogical feature of the FBS is the ubiquitous presence of orthopyroxene, which ranges up to En 84 in composition. In some fragments, orthopyroxene exhibits unusual textures and compostions. Rounded and embayed cores of variable Al-content (1-3 wt %) are mantled by discontinuous rims of pigeonite and/or augite, as documented by the data in Fig. 5. It is conceivable that such cores represent the partially resorbed remnants of grains which crystallized at depth, prior to eruption of FBS magma (cf., [41]). Understanding the origin and petrogenetic significance of this type of orthopyroxene also merits closer attention.

AGE & ISOTOPIC CONSTRAINTS. Crystallization ages of ~3900 Ma have been determined for three FBS samples (15382, 15386 and 15434) from Rb-Sr mineral isochrons [31,32], whereas a Sm-Nd age of ~3850 Ma has been determined for sample 15386 [33]. These dates appear to establish a pre-Mare age of formation for at least some of the Apollo 15 FBS.

However, initial 87Sr/86Sr values are relatively high (0.7002-0.7005) compared to other lunar igneous rocks, suggesting derivation from a Rb-enriched source region. In addition, negative E-Nd values [33,34] indicate derivation from a light REE-enriched source. Furthermore, Rb-Sr T(BABI) [31,32] and Sm-Nd T(ICE) [34] model ages are both near 4300 Ma, suggesting that the source regions of these FBS samples were established very early in lunar history.

ORIGIN. Mineral-chemical and textural relationships establish beyond any doubt that the FBS are volcanic rocks which crystallized from melts. Variations in bulk composition, although not known as well as they might be, suggest the existence of a differentiated rock series whose major features are controlled by low pressure fractionation of plagioclase and Ca-poor pyroxene; this conclusion is supported by the tendency of analyses to cluster along the Plag-Opx boundary curve in the system Forsterite-Anorthite-Silica (Fig. 6).

Irrespective of these features, a debate has raged among lunar scientists as to whether the magma(s) parental to the FBS formed by partial melting in the lunar interior, or from melts generated during impact events. This divergence of opinion represents the most compelling, and as yet unanswered problem posed by the FBS. The isotopic data summarized above could be fully satisfied by a model in which the protolith of the FBS, having formed originally at 4.3 Ga, was remelted by impacts at 3.9 Ga. However, the apparent lack of siderophile element contamination [e.g., 4] argues against such an impact origin for the FBS.

Another puzzling aspect of the FBS concerns their relatively primitive major element compositions (viz., high mg), which suggsts relatively high degrees of partial melting, and their high concentrations of incompatible lithophile trace elements, which suggests small degrees of partial melting. Various models have been developed to explain this dichotomy [35,36], but no satisfactory resolution has emerged.

Similarly, the FBS have the highest Zr/Ti of all lunar rocks types [37], which would seem to require extensive ilmenite fractionation sometime in their evolution. Since ilmenite is nowhere near a liquidus phase in the FBS, a fact established both petrographically (see above) and through experiment [38], it is necessary to invoke scenarios in which this feature is a characteristic of the source region, much in the same way that negative-Eu anomalies in lunar mare basalts are attributed to plagioclase fractionation early in lunar history.

In summary, it does not seem possible to reconcile the various data on the FBS with a unique model for their formation. If the FBS are truely the products of endogenous lunar volcanism, then it becomes necessary to identify a heat source to promote melting. Perhaps the association of the FBS with KREEP-components, and the spatial association of KREEP-components with borders of the Imbrium basin [39] is more than fortuitous, as it seems entirely plausible that such a giant event would have triggered volcanic activity through pressure-release melting, as postulated by a number of investigators.

Table 1: Average Chemical Compositions of Apollo 15 Glasses Corresponding to the Felsdpathic Basalt Suite

Wt %	1.	2.	3.	4.	5.	6.	7.	8.
SiO2	49.58	48.68	50.1	49.9	48 91	48.47	50 49	50.45
TiO2	1.41	1 6	1 5	1.28	1 14	1.31	1.76	1.77
Al2O3	17 60	16 89	16 3	16.4	17 87	17.35	16.18	16 28
Cr2O3	0 17	0.26	*	0 27	0 23	*	0 16	0.26
MgO	8.94	8.79	8 9	9.2	9.42	10 45	8.05	8.28
FeO	9.52	9.13	9 8	9 9	9 27	10 15	10.12	9.62
MnO	*	*	*	0 13	*	0 12	*	0.14
CaO	10 79	10.23	10 8	10.1	10 77	10.93	10.43	10.47
Na2O	0 74	0 70	0.7	0 62	0 35	0.77	0 80	0 77
K2O	0.47	0.48	0 5	0 63	1.70	0.51	0 52	0.61
P2O5	*	*	*	0.29	*	*	0 66	0.52
CaO/Al2O3	0.613	0.606	0.663	0.616	0.603	0.630	0 645	0 643
mg	0 626	0 632	0.618	0.624	0.644	0 647	0.586	0.605

(1) Moderate K "Fra Mauro" basalt glass in A15 soils [26]. (2) Group III glass in breccia 15006 [23]. (3) Group V glass from various soils [27]. (4) Group III glass from various soils [28]. (5) High-K, "KREEP(?)" glass in breccia 15465 [6]. (6) Low-Fe, high-K basaltic "KREEP" glass from various soils [29]. (7) Moderate-K "Fra Mauro" basalt glass in breccias 15028 & 15059 [30]. (8) Alkalic, high-alumina basalt glass in breccia 15205 [12].

Table 2: Compositions of Apollo 15 Feldspathic Basalts

Wt %	1.	2.	3.	4.	5.	6.	7.	8.	9.
SiO2	51.86	49 70	51 01	*	52.53	51 89	52.4	*	50.83
TiO2	2.12	1 10	1.22	2.30	1.29	1.77	1.78	2 17	2.23
Al2O3	16.43	18 51	19.1	15.60	18.44	17.68	17.8	14.9	14.77
Cr2O3	0.35	0.44	0.19	0.29	*	*	0.21	*	*
MgO	7.52	7.35	6.65	8.19	6.75	7.01	7.1	7.4	8.17
FeO	10.61	8.57	6.50	10.17	8.27	9.42	8.6	9.2	10 55
MnO	0.18	*	0.09	0.14	*	*	0.10	*	0.16
CaO	10 16	11.38	11.09	9 31	10.29	10.30	9.9	7.1	9 71
Na2O	0.66	0.85	0 98	0.88	*	*	0 96	0.85	0 73
K2O	0 62	0.74	0 69	0.60	0.50	0.46	0.57	*	0 67
P2O5	0.60	*	0.38	*	*	*	0.55	*	0.70
CaO/Al2O3	0.618	0.815	0.581	0.597	0.558	0.583	0.556	0.477	0.657
mg	0.558	0.605	0 645	0.589	0.593	0.570	0.595	0 589	0.580

(1) Average of 4 "KREEP" basalt soil fragments; analysis by microprobe on fused glass [3] (2) Average "ophitic" basalt in breccia 15086; broad-beam microprobe analysis [23]. (3) Average of 9 "KREEP" basalt soil fragments; broad-beam microprobe analysis [18]. (4) Average of 7 "KREEP" basalt soil fragments; analysis by INAA [19]. (5), (6) "KREEP" basalt fragments 15434 & 15382; broad-beam microprobe analysis [5]. (7) "KREEP" basalt fragment 15382; broad-beam microprobe analysis [4]. (8) "KREEP" basalt 15382; analysis by INAA [24]. (9) "KREEP" basalt 15386; analysis by XRF [25].

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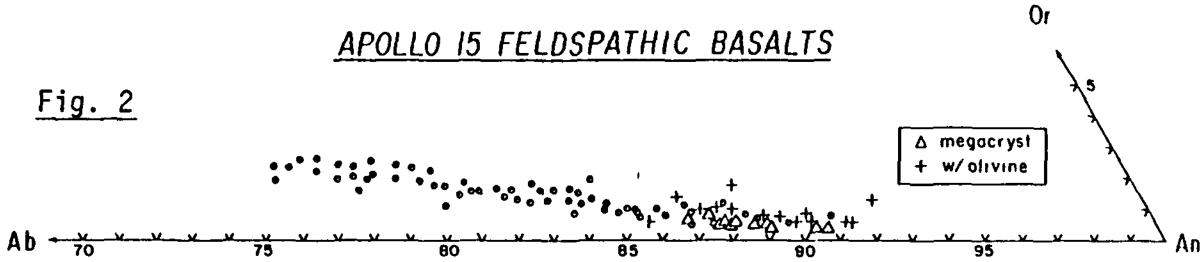
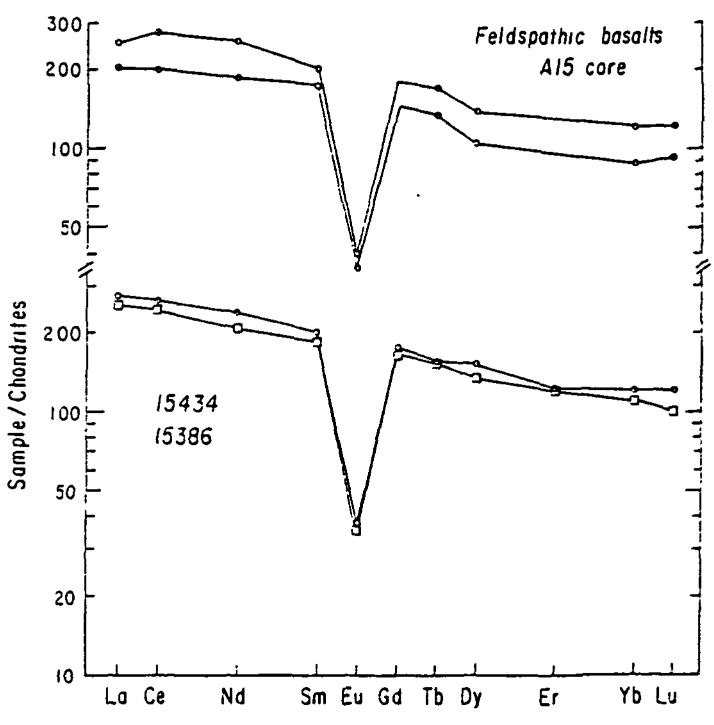


Fig. 2



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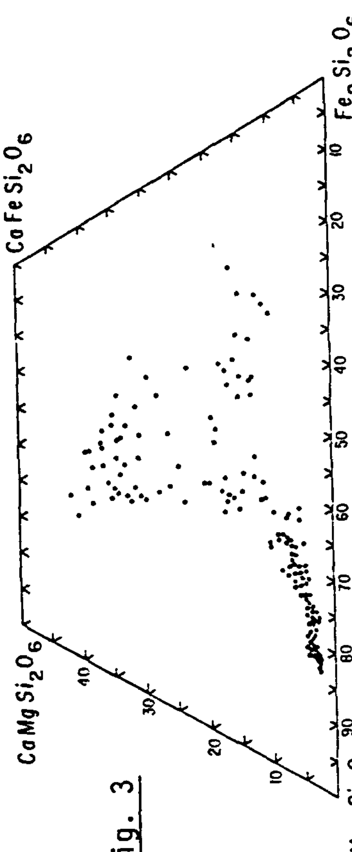

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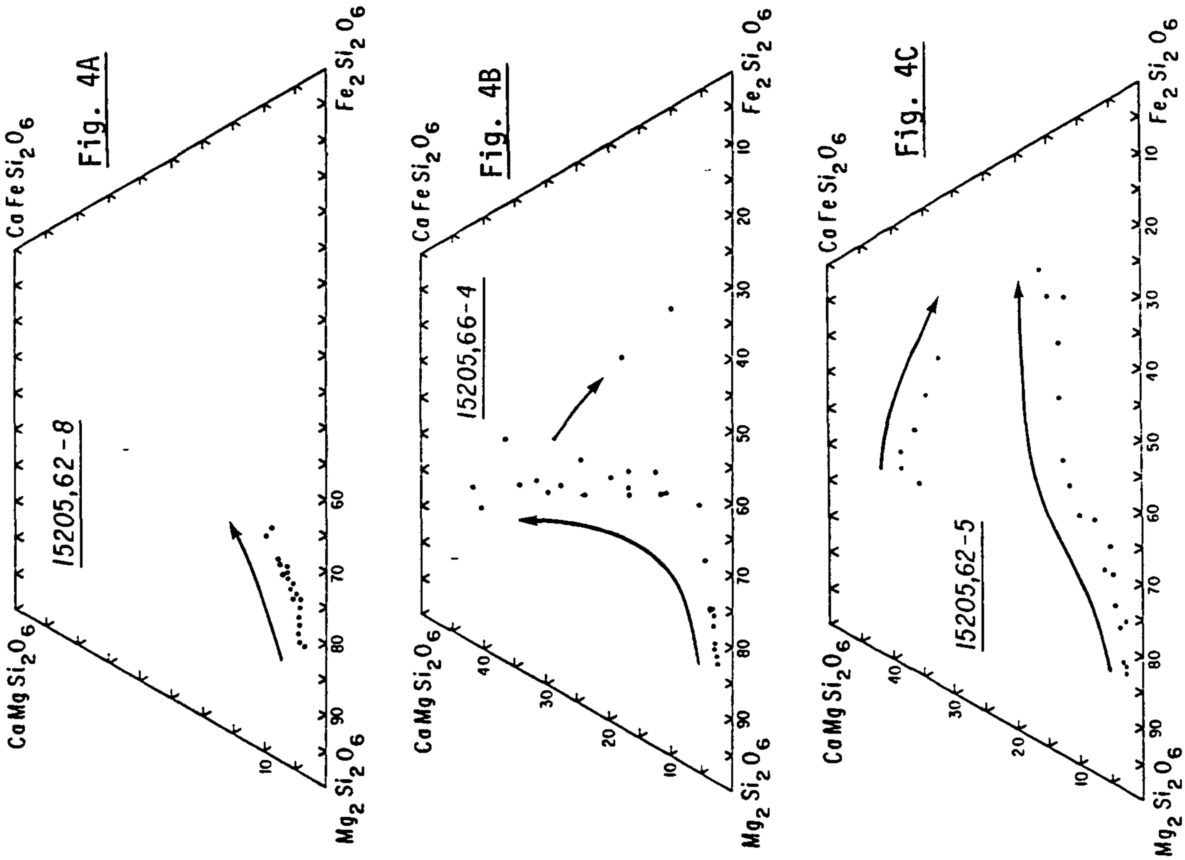

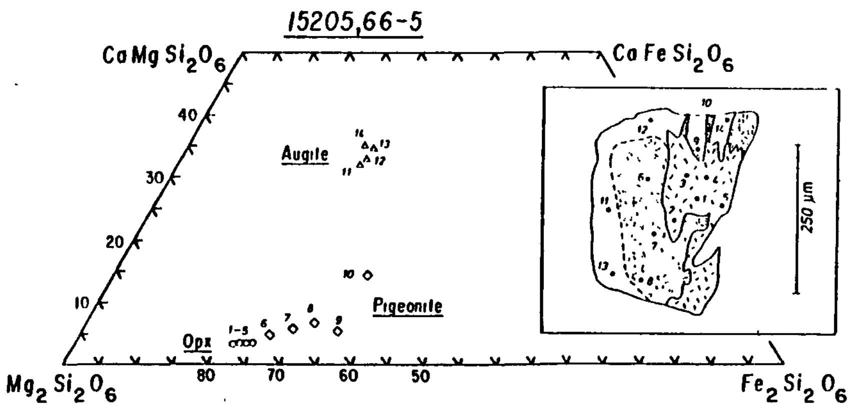

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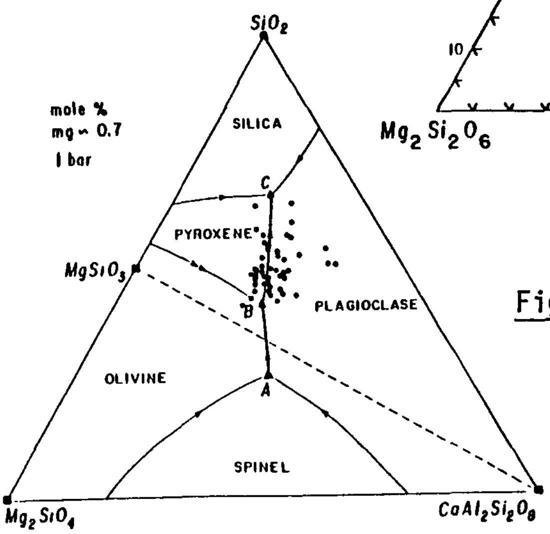

Fig. 6 (adapted from 14).

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HADLEY RILLE, LAVA TUBES AND MARE VOLCANISM AT THE APOLLO 15 SITE. Ronald Greeley (1) and Paul D. Spudis (2). 1. Department of Geology, Arizona State University, Tempe, Arizona 85287. 2. U.S. Geological Survey, Flagstaff, Arizona 86001.

INTRODUCTION. Prior to the Apollo missions, the origin of sinuous rilles--including the Hadley Rille--was a contentious topic. Although most workers agreed that a fluid of some sort was involved in rille origin, the nature of the fluid and of the process(es) involved in rille formation were debated. Hypotheses included origins related to volcanic ash flows (1), water, including periglacial and fluvial processes (2), fluidization of regolith resulting from outgassing (3), and to processes associated with basaltic lava flows (4). Based on comparisons with terrestrial analogs, it was proposed that the Hadley Rille (and similar lunar sinuous rilles) was a lava channel, parts of which were roofed to form lava tube segments (5). This interpretation was based on observations that Hadley and other lunar sinuous rilles (6): (a) appear to originate in irregularly-shaped depressions (inferred to be vents), (b) trend generally down slope, (c) have discontinuous channels and cut-off branches, (d) are fairly uniform in width, or narrow toward the terminous, (e) are restricted to mare surfaces and appear to be controlled by pre-mare topography, and (f) may form topographic highs along their axes. Moreover, lava tubes and channels are common in certain types of basaltic lavas; thus with determination of basaltic compositions for the mare lavas, the lack of extensive ash flows, and the lack of evidence for water, the hypothesis for rille origin narrowed to the now-generally-accepted lava channel/tubes origin.

GEOLOGY OF LAVA TUBES AND CHANNELS. Results from the Apollo 15 mission raised several key questions regarding the general geology and volcanic history for the site, and the role of the rille in the emplacement of lavas within the Hadley valley (7). Among these are questions related to: the sequence and style of emplacement of the mare lavas; thickness(es) of the flow unit(s) and total flow accumulation; possible ponding of lavas in the Hadley valley; sources of glasses and other volcanic materials near the landing site; and explanations for the topography along the rille. Consideration of the general geology of terrestrial lava tubes and channels (8) may shed light on some of these questions:

1. Lava tubes/channels typically form in flows of basaltic composition (although they could form in other flows of comparable rheological properties), erupted at moderate rates of effusion (lower than flood eruptions); this style of eruption ("Hawaiian") tends to produce thin ($<$ 5m), flows that are produced by long-duration eruptive periods. However, the effusion of lava is sporadic, not continuous, and this results in surges of lava and the formation of multiple flow units.

In general, the longer a given eruption sequence is active, the better established and larger the feeding tube/channel system. Moreover, previous tube-channel systems are frequently reactivated by later flows, even after long periods of quiescence. Thus, one would expect to see multiple, thin flow units in the walls of Hadley Rille. Although the size of Hadley Rille exceeds the largest of terrestrial tubes/channels by an order of magnitude, one might infer that it was the consequence of a very long-duration eruptive sequence, perhaps more than 100 years.

2. Flows fed through tubes and channels are emplaced by secondary (distributary) tubes and channels, as well as by overflow from open channels. Because lunar lavas are so low in viscosity (9), they would be expected to spread out in thin sheets from the rille as surges and flow units, leaving little in the way of flow fronts. The roofs of lava tubes, including distributary tubes, often rupture and produce local flows and other volcanic material. There is often the appearance of local vents that may, in fact, be "rootless". Thus, samples obtained in the vicinity of the Apollo 15 landing site may resemble near-vent products, but may have been derived from the cleft-shaped source-vent for the rille.

3. The formation of a tube roof, or of a crust on channelized flow, retards heat loss from the active lava, allowing greater flow lengths, and also retards loss of volatiles (in some respects, lava tubes are extensions of the vent conduit). Thus, some flow units emplaced via tubes/channels are vesicular at long distances from their source vents. On the other hand, fountain-fed flows may also collect and be emplaced via previously-formed tubes and channels; during fountaining, degassing often occurs. Thus, some of the flow units may also be nonvescicular.

4. Lava tube flows may erode by thermal (i.e. partial melting) and mechanical processes, as has been documented in terrestrial flows (10, 11, 12); in one case, a tube entrenched into pre-flow materials to a depth 4x the thickness of the flow (13). In addition, numerical models (14,15,16) suggest that extensive thermal erosion may occur in the development of lunar sinuous rilles. Thus, Hadley Rille may be entrenched substantially below the flow contact with valley floor. Thermal erosion (melting) could, in principle, alter lava compositions by assimilation during the lava flow emplacement via the tubes/channels.

5. Lava tubes/channels are primarily constructional features in that they emplace lava flows, both laterally and at the flow front. Accretion of lava along the sides of open channels, and via distributary tubes and channels raise the topography along its axis. However, the position of the tube may shift as it migrates (meanders) during active flow, and the axis does not always coincide with the topographically highest part of the flow. With drainage of the tube/channel and collapse of the roof segments, one side of the structure may be higher than the other side. In addition, the final "trench" may expose flow units of different textures and possibly different compositions, and the trench may cut into pre-flow rocks.

HADLEY RILLE AND APOLLO 15. Hadley Rille trends northwest and then east over 120 km in a valley between the Apennine scarp of the Imbrium basin and large terra slump blocks from the front. The rille is almost completely confined within mare material, although the source crater stradles the mare-highlands boundary (5,17). At the Apollo 15 site, the east (near) rim of the rille is about 30 to 40 m higher than its corresponding farside. In this locality, the rille is about 300 m deep and 1500 m wide. Apollo 15 photographs and observations show that the rille walls expose at least three different mare units. The lowermost layered unit (~8 m thick) is overlain by talus and debris (~5 m). This sequence is overlain by a massive, poorly-jointed unit, about 17 m thick. On top of the massive unit is a thin (1-2 m) dark unit, on which regolith is developed (7). These exposures give direct evidence for at least 30 to 40 m thickness of basalt in the landing site area. On the basis of geologic reconstruction of returned mare samples, it appears that Apollo 15 olivine-normative and quartz-normative basalts are representative of the upper dark unit and middle massive units, respectively (18,19).

On one of the traverses, Scott noted a dark band and topographic bench along the base of Mt. Hadley. This bench, clearly seen on orbital pan photographs, has been taken as evidence that the mare lavas in the site vicinity were ponded in this area to a thickness on the order of 90 m (7). If this interpretation is correct, the rille may have served to drain this ponded lava. Of the two Apollo 15 basalt groups, the olivine-normative basalts show an olivine fractionation trend (20). Moreover, "peridotitic" basalts, originally interpreted as from a separate lava flow (21) but in fact, possibly related to the olivine-normative group by olivine crystal accumulation, are found in Spur crater ejecta, 60 m above the current mean mare topographic level. This may be consistent with ponding of the olivine-normative basalts in the site area; if the rille served as a conduit to drain the lavas, the 1-2 m thickness of olivine basalt observed at Sta. 9A is not a simiple flow unit, but a veneer of lava left by the draining lava lake. The present exposure of this unit within the rille wall would then be due to post-draining collapse of the rille walls inward (7).

A question of crucial importance to Apollo 15 site geology is the total thickness of basalt at the site. The actual LM site lies atop a low (5 m), broad ridge; at this location, only one (quartz-normative) mare basalt (15058) was collected. The remaining samples are regolith breccias (that contain comminuted mare basalt debris). Petrography of soils at this site indicate up to 50% non-mare material (22). Although this could be due to post-mare ray material (18), it is also possible that mare basalts in this area are very thin (23). This is not precluded by the observations of basalt in the rille walls; the LM site is ~2 km from Sta. 9A and if 60 m of basalt pinched out to zero at the LM site, it would imply an average pre-flow slope of less than 2°.

It is possible the exposed portion of basalt seen in the walls of Hadley Rille represent the entire thickness of basalt at the site. In this case, rille formation must have included downcutting and erosion of some type (14). Both thermal and mechanical erosion during rille formation may have occured, but it is difficult to say which was dominant. Significant erosion by complete melting is unlikely because extruded mare lavas would not be superheated, as evidenced by phenocrysts in Apollo 15 mare basalts. However, some assimilation could produce partial melting of sub-mare, brecciated basement and this in turn would exacerbate mechnical erosion, which was probably already occurring during the high volume effusion of low-viscosity mare lavas (9). There is no evidence for a "delta" of eroded basement debris at the rille terminus, but this material could be covered by the late-draining lava pond, described above.

CONCLUSIONS. Hadley Rille appears to be a collapsed lava tube/channel, whose formational history may be more intimately related to the mare units sampled at Apollo 15 than had been previously thought. More work is needed relating samples and observations from Apollo 15 to the rille and its geologic evolution. As the only sinuous rille visited during the Apollo missions, Hadley Rille presents us with a data resource that is directly applicable to the deciphering of processes involved in lunar mare volcanism.

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THE GEOLOGIC HISTORY OF QUARTZ-NORMATIVE AND OLIVINE-NORMATIVE BASALTS IN THE VICINITY OF HADLEY RILLE (APOLLO 15); T.L. Grove, Dept. of Earth, Atmospheric, and Planetary Sciences, Mass. Institute of Technology, Cambridge, MA 02139.

This overview will be restricted to a discussion of the geologic history of the quartz normative (QNB) and olivine normative (ONB) basalt types at Hadley Rille A model for the geology of the mare basalts has been constructed from a combination of field observations, sample chemistry, sample petrology and personal bias from terrestrial experience. This model is speculative and proposes that the QNBs are the only mare lava type that is present as outcrop in the area traversed by the astronauts during the Apollo 15 mission. The returned QNB samples formed during a single eruptive phase of the Hadley Rille lava tube system. The ONB lavas are an exotic component transported to the site by a cratering event, perhaps by the event that formed Aristillus or Autolycus craters, or the ONBs are samples excavated from older mare bedrock that was partly covered by the QNB lavas. This model differs from the conventional one, which interprets the ONB lavas as a younger flow that overlies the QNB lavas. Several investigators have proposed that Hadley Rille is a giant collapsed lava tube (1,2,3). Like terrestrial lava tubes the Hadley Rille follows older fault controlled topography. At bends in the rille the outside has less curvature than the inside, the rille is deepest where it is widest, and the rock benches and talus deposits in the rille are similar to those found in terrestrial collapsed lava tubes.

Chemical and isotopic variability of mare lavas at Apollo 15. Two distinct compositional types were identified in the Apollo 15 mare basalt collection (excluding the older KREEP basalts). Major and trace element analyses (4,5) indicated that the QNBs showed limited within group compositional variations which could be explained by a small amount of near surface fractionation of olivine, spinel and/or pyroxene (<7%). The ONB group showed within group compositional variability caused by olivine fractionation (<15%). The two basalt types are not related to one another by any simple fractional crystallization process. The ONBs have higher FeO, TiO_2 and lower large ion lithophile element concentrations compared to the QNBs. Combined assimilation of anorthositic lunar crust and fractionation of an ONB-like parent can not produce the QNB compositional trend, because ONB lavas have higher normative plagioclase than the QNB lavas. The Rb-Sr ages and the initial $^{87}Sr/^{86}Sr$ of the ONB and QNBs overlap, and range from 3.28 to 3.44 AE and 0.69923±6 to 0.69937±4 (6).

Geology of mare lavas at Apollo 15.

QNB lavas. The dominant rock type sampled on the mare surface at Hadley Rille is QNB lava (7,8). The QNBs were sampled from the highest bedrock outcrop at the edge of the rille (sta. 9A). The textural characteristics of the samples obtained from the outcrop at sta. 9A indicate that this outcrop is the top of a lava flow (9). A large vesicular block at Dune Crater (sta. 4) is also a block of the QNB flow top. The thermal histories inferred for the QNB flow top vitrophyres are two stage, characterized by initial slow cooling followed by rapid cooling. The overbank deposits of a lava tube would be expected to experience similar thermal histories. At Elbow Crater (sta. 1) coarse-grained samples of QNB lava were excavated. These station 1 QNB microgabbros are samples of the slowly cooled interior of the QNB flow complex. Among the station 1 samples, 15065 and 15085 experienced the slowest cooling histories (9,10) and crystallized in the center of (a) lava flow(s) >20 m in thickness. The layered outcrops in Hadley Rille were interpreted (8) as flows with thicknesses of 10 to 20 meters. LSPET (8) describes these flows as light colored, massive units which contain prominent vertical joints and horizontal partings. An upper dark unit overlies the massive outcrops, and some layering resembles pahoehoe draining from beneath cooled crust.

The estimated physical properties of the QNB magma (9) and the restricted chemical variability of the QNB samples favor this lava as the occupant of Hadley Rille. Near liquidus viscosity is low (<100 poise) and the density contrast between pyroxene and liquid is slight (+.10 gm/cm^3). In this physical state the QNB lavas could flow in the tube system and undergo little change in bulk chemistry through differentiation by pyroxene settling. Presumably all liquidus olivine originally present in the QNB had settled out of the magma during an earlier upstream differentiation episode.

Terrestrial experience with collapsed lava tube systems at Medicine Lake Highland, California has shown that processes operating in a single lava tube system can create a complex range of cooling histories which results in substantial textural diversity in chilled lava samples. The QNB textural variations fall within the range sampled from a single flow in the 50 km long Giant Crater-Chimney Crater flow at Medicine Lake.

ONB lavas. The ONB lavas were sampled at all the mare sites, and this basalt component constitutes a substantial part of the soil at station 9A, and at the lunar module (11). The hand samples were commonly found to be isolated fragments; 15016 (sta. 3) was described as having been on the mare surface for a long time, while the sta. 9A samples (15535, 15536) were described as fresh crater ejecta. The textures of these ONB lavas are porphyritic to gabbroic, but no vitrophyric ONB samples have been identified from rake or hand samples (12). A textural characteristic of the gabbroic samples is that plagioclase poikilitically encloses sub-rounded olivine and pyroxene grains. The porphyritic samples contain radiate plagioclase and pyroxene intergrowths and olivine phenocrysts. An early and enduring interpretation of the ONB samples is that they represented a flow that had been degraded by meteorite impact (7,8). To explain the large proportions of ONB in the soil at stas. 9, 9A and LM, it was proposed that an ONB flow was stratigraphically above the QNB flows. This interpretation of an ONB-QNB flow contact is not consistent with textural characteristics of either basalt type. At Station 9A there are no ONB vitrophyres. Vitrophyres would be expected to form at the basal ONB chill margin. The vitrophyres at station 9A are QNBs, and these are fresh, and show no evidence of reheating by a later overlying flow. Terrestrial experience indicates that reheating of the proposed underlying QNB would be recorded by textural changes. The ONB samples with the plagioclase-poikilitic textures do show textural characteristics similar to those found in basalts heated by a later flow. Therefore, textures would suggest that the ONB flow was older. A simpler explanation is that the ONB lavas were transported mare ejecta from the Aristillus-Autolycus cratering event. The South Cluster and the bright ray that trends northwest across the Hadley Rille site were formed by this cratering event which impacted Mare Imbrium to the southeast. An alternative is that the ONB lavas are older bedrock that make up the NW trending ridge (Fig. 5-41, ref. 8) buried beneath younger QNB lava tube deposits.

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REMOTE SENSING OF THE HADLEY-APENNINE REGION; B.R. Hawke, Planetary Geosciences Division, Hawaii Institute of Geophysics, University of Hawaii, Honolulu, HI 96822.

INTRODUCTION: A wide variety of remote sensing data was collected for the Hadley-Apennine region before, during, and after the Apollo 15 mission. The data sets have been analyzed and interpreted in light of the results of Apollo 15 sample studies. These investigations have allowed us to extrapolate the findings at the site itself to a much larger portion of the lunar surface as well as to place the Apollo 15 samples in their proper regional context. The purposes of the paper are to review and summarize the more significant remote sensing results and to identify areas in which additional work would be productive.

EARTH-BASED RADAR AND INFRARED MEASUREMENTS: Zisk et al. [1] presented the results of radar (3.8 and 70 cm) and thermal studies of the Hadley-Apennine region. Although preliminary radar and thermal data interpretations had been included in various mission planning and site selection documents [e.g., 2,3,4], the Zisk et al. paper was the first (and only) formal presentation of a synthesis of the radar and thermal data sets. The workers divided the region into three major, morphologically distinct units. The first, the Apennine Crest (the Apennine Mt. or main Imbrium ring), exhibited a series of very bright radar returns at both 3.8 and 70 cm that coincided with the earth-facing slopes of the major mountain peaks. The 3.8 cm polarized returns were found to be up to 40 times greater than the average return, with corresponding depolarized returns of more than 10 times the average. When slope effects were taken into account, the resulting set of values was found to be from 1/7 to 1/2 of the observed echoes. Zisk et al. noted that a reasonable interpretation of all the measurements is that the Apennine Crest has a smooth, dense surface, with a dielectric constant of ~4.0 and with no more than an average number of surface and near-surface rocks larger than 1 cm.

The second unit, the Apennine Backslope, was found to contain two strips generally parallel to the crest which exhibited different appearances on the radar maps but not on the infrared. Zisk et al. noted the inner zone (within about 100 km of the crest) showed a moderately enhanced response at both 3.8 and 70 cm radar wavelengths and an average response in the infrared, in agreement with its appearance in high-sun and other photographs as a "typical" highland region. The outer zone (starting about 100 km southeast of the crest) exhibited lower radar values (0.7 times the average at 3.8 cm and average at 70 cm), but the thermal values were found to be the same as those for the inner zone. It was suggested that the regolith in this outer zone was more fine-grained than that nearer the crest and contained only an average number of rocks in the centimeter to meter range with few rocks exposed at the surface. They further suggested that this condition could be the result of a post-Imbrium surface deposit of fine-grained material. More recent work [e.g., 5,6,7,8,9] concerning lunar dark mantle deposits suggests that this outer zone is partly mantled with varying amounts of pyroclastic debris.

In Palus Putredinis, the radar albedo was noted to be locally enhanced by as much as a factor of 3. Several bright, diffuse radar patches proved to be correlated with small (<1 km) craters surrounded by a radar halo that extends up to 10 crater diameters from the center. This is in strong contrast to the backslope, where radar halos around small craters generally extend no more than 3 diameters. Zisk et al. concluded that craters in the Apennine Backslope have fewer radar wavelength-size blocks at distances from 3 to 10 crater diameters than do craters of similar size on the mare. This was attributed to the less cohesive nature of backslope material. It was noted that the southeastern part of Palus Putredinis has a very low radar albedo whereas north of 27°N, the mare surface exhibits enhanced 3.8 cm radar (and possibly enhanced infrared) values. Several explanations were offered: 1) different flows or flow ages, 2) a thin layer of low albedo fine debris, or 3) a layer of Aristillus/Autolycus ray material. Subsequent remote sensing studies have not resolved this problem [9,10,11] although a small pyroclastic deposit was identified in the southern portion of Palus Putredinis [9].

Zisk et al. [1] pointed out three outstanding examples of large radar and infrared enhancements associated with craters in the region. Aratus (D=11 km) and Hadley A (Joy; D=6 km) are extremely enhanced in both the 3.8 and 70 cm radar images as well as in the thermal data. Both exhibit very high albedos in full-moon photographs and albedo maps, and also appear very fresh, blocky, and sharp in high-resolution Lunar Orbiter and Apollo photographs [1,12]. These observations were interpreted as indicating that an extensive field of decimeter- and meter-size rocks surrounds each of these craters and extends out to about 10 km and that Aratus and Hadley A are very young (Copernican).

Conon crater (D=22km) is very bright on the 70 cm radar map but only moderately enhanced on the infrared map. On the 3.8 cm map, as well as full-moon photographs, the wall and raised rim are quite bright, but there are only slight enhancements associated with the floor and more distal ejecta deposits. Conan was interpreted as an older, Eratosthenian-aged crater, in which the original population of surface rocks has been depleted everywhere except on the wall and rim but an excess of meter-size rocks remains a few meters beneath the surface.

MULTISPECTRAL MAPPING: Both color-difference photographs and multispectral ratio images have been used to define and map the distribution of spectral units in the Apollo 15 region as well as to make inferences concerning unit compositions. Soderblom and Lebofsky [13] utilized the multispectral photography of Whitaker [14] to define two mare units in the region. They noted that low-albedo deposits of undetermined age were superimposed on older "red" mare materials in the region west of the landing site. These deposits appear as "blue" mare units in the multispectral photography of Whitaker [14]. Soderblom and Lebofsky [13] suggested that the Apennine Bench Formation should have a crystallization age of near 4 b.y. and that the next youngest unit, the older "red" mare basalt should have a crystallization age near 3.5 b.y.

Malin [15] also used color-difference photographs to locate and investigate spectral anomalies on the lunar surface. He noted that the rim deposits of the craters Plato and Archimedes are extremely right in the IR-UV prints and suggested that the "red" material may represent either Imbrium ejecta or bedrock from beneath the ejecta blanket.

Wood and Head [16] also pointed out that Plato and Archimedes exhibited extremely red rim deposits and noted that both lie just within the trace of the second ring which appears to correspond to the Imbrium crater rim. They suggested that pre-Imbrian material was excavated. It was noted that the Iridum crater is in a similar position with respect to the rim but is not as distinctly red as Plato and Archimedes. This observation was attributed to inhomogeneities in sub-basin materials.

Multispectral and geologic studies of the Apollo 15-Apennine region were conducted by Hawke et al. [9] in order to identify and to map the extent of dark mantling units. These deposits display a low albedo, appear to mantle and subdue subjacent terrain, are spectrally distinct on multispectral maps (high in the near infrared but low in the ultraviolet) and generally exhibit a weak depolarized 3.8 cm radar echo. Concentrations of dark mantle material are commonly associated with vents located along marginal fractures and faults near the base of the Apennines. Hawke _et al_. [9] concluded that these dark mantle deposits were almost certainly of pyroclastic origin and that explosive volcanism was a more important and widespread process in the Hadley-Apennine region than had been previously thought. In addition, it was noted that the spectral properties of the pyroclastic deposits are incompatible with those of fresh Apollo 15 green glasses but they are consistent with the properties of Apollo 15 brown or yellow glass. However, it should be pointed out that the spectral characteristics of "mature" green glass deposits are unknown.

SPECTRAL REFLECTANCE STUDIES: McCord _et al_. [17] presented spectrophotometry (0.3 to 1.1 µm) of the visited and proposed Apollo landing sites. Four spectra were presented for features in the Hadley-Apennine region. It was determined that the two mare spectra were very similar to those obtained for the Apollo 12 landing site. The two Hadley-Apennine mare spectra differ in only one respect: the spectrum obtained for the mare west of the landing site indicated a lower titanium abundance than that of the mare southwest of the site. These workers suggested that the Hadley Delta area contained material similar to that found at the Apollo 14 landing site. The spectrum of a high albedo steep slope in the Apennine Mountains south of Hadley Delta was interpreted to represent freshly exposed, highly crystalline material. No explanation for this difference between the reflectivities of Hadley Delta and the steep slope to the south was presented. However, I suggest that the difference is largely a maturity effect.

Hawke and Lucey [18,19] have recently presented the preliminary results of an analysis of thirty near-infrared reflectance spectra of features in the Hadley-Apennine region. Spectra were presented for six relatively fresh surfaces in the Apennine Mountains (Front), for eleven fresh crater deposits on the Imbrium backslope, and for a variety of highlands units within the Apennine ring (Imbrium interior). The latter included two fresh, small (D<5 km) craters on the Apennine Bench as well as the eastern wall deposits of Archimedes, Aristillus, Autolycus, and Timocharis craters.

Spectral analysis revealed the presence of several distinct spectral groups. Two major classes of spectra were identified and these correlated with location relative to Imbrium basin. Spectra for features inside of the Apennine ring (Imbrium interior) were found to exhibit both a longer "one micron" absorption band center as well as a greater band width than spectra for areas on the Apennine front and backslope. In general, the non-mare units on the Imbrium interior have more calcium-rich pyroxene assemblages than the exterior units. However, two interior spectra have been interpreted as indicating the presence of volcanic glass (south rim of Archimedes [20] or impact-generated glass (dark streak on Arestillus wall [21]). In some instances, the more calcium-rich composition of the pyroxene the interior units may be due to the presence of a mare basalt component. Mare basalt was clearly present in the pre-impact target site of the craters for which these spectra were acquired. In other cases, both geologic and spectral evidence indicates the near absence of mare material.

The other major class consists of spectra obtained for the Apennine Mts. and backslope (Imbrium exterior). These spectra exhibit many similar characteristics including "one micron" band centers which range between 0.92 and 0.93 microns, typical highlands continuum slopes, and a variety of "one micron" band strengths. Two subclasses were identified. The first subclass exhibits very deep bands (10-14%) while the second subclass has shallower band depths similar to those shown by spectra of typical fresh highland surfaces. Analysis of the spectra obtained for the Imbrium backslope and the Apennine

Mountains indicates that these terrains consist of Fe-bearing plagioclase feldspar and a mafic component dominated by low-Ca orthopyroxene. Norites and anorthositic norites are the dominant rock types. The spectrum of one crater on the backslope (Marco Polo F, D=4 km) appears to be dominated by an olivine absorption.

The material exposed in the Apennine Mountains and the Imbrium backslope should consist largely of crustal debris derived from several tens of kilometers beneath the surface. Hence, it appears that the deep (>10 km) lunar crust in the vicinity of the Imbrium target site was composed of low Ca-orthopyroxene and Fe-bearing plagioclase feldspar [18].

APOLLO ORBITAL GEOCHEMISTRY DATA: Initial analyses of the Apollo 15 gamma-ray and x-ray spectrometer data provided general answers to several first-order questions concerning the composition of the Hadley-Apennine region [e.g., 22,23]. For example, Metzger et al. [22] presented the preliminary results of the Apollo 15 gamma-ray spectrometer and demonstrated that the highlands immediately west of the Apollo 15 landing site was one of three regions of high radioactivity due to the existence of Th, U, and K in the surface layers. They suggested the presence a major component of KREEP in each of the three regions.

Later studies resulted in further improvement of the various data sets [e.g., 24,25,26]. By the late seventies, the final versions of both the gamma ray and x-ray data sets were available for analysis and interpretation [11,27,28,29,30]. The Th data presented by Metzger et al. [27] clearly indicated that the Archimedes region was more enriched in Th (4.6 ppm) than the Haemus Mt. region to the east (2.7 ppm). Additional insight was provided by the later Th deconvolution studies conducted by Metzger et al. [31]. These workers showed that the highest Th values (16-20 ppm) were associated with the rim and ejecta deposits of Archimedes crater (and possibly Autolycus and Aristillus craters). Th abundances typical of the Apollo 15 KREEP basalts (~11-12 ppm) were found associated with the Apennine Bench Formation. Distribution models for the southern Apennine Mts. suggested that Th is present in concentrations ranging from 7.3 to 8.2 ppm. The presence of a major component of medium-K Fra Mauro basalt in the southern Apennines was suggested [31]. It was determined that a major transition occurs in the vicinity of the Apollo 15 site. The Apennines north of the site exhibit a Th abundance (~3.0 ppm) which is less than half that of the southern Apennines. The Haemus region, which includes not only the Haemus Mountains but also the northern portion of the Imbrium backslopes, the Sulpicius Gallus Formation, and numerous small ponds of mare basalt, was found to have a Th abundance ranging between 2.9 and 3.3 ppm. Finally, it was determined that both Timocharis and Lambert craters excavated Th-rich material from beneath the mare basalts in Imbrium.

Hawke et al. [32] presented the most recent summary of the orbital gamma-ray data for the Imbrium region. They noted that the Haemus region has a very high Ti abundance (Ti=2.3%) relative to the lunar highlands. This high value was attributed to the presence of small mare patches and dark mantling material of probable pyroclastic origin. Examination of 0.40/0.56μm multispectral ratio images showed that the mare patches are likely to be surfaced with basalt abnormally rich in Ti. In addition, numerous workers have suggested that the dark mantling unit is composed of high-Ti pyroclastic glasses similar to those returned from the Apollo 17 site. The relatively high Th and K concentrations as well as the x-ray data presented by Clark and Hawke [11] suggested that the highlands material exposed in the region is dominated by low-K Fra Mauro basalt [32]. The Apennines region includes the Apennine Mts. and major portions of the Imbrium backslope. Material interpacted as Imbrium ejecta is the dominant surface unit but pre-Imbrium material may be present in the vicinity of the Apennines. The Apennine region Ti value (0.8%) is lower than that for the Haemus region whereas the Apennines K (0.21%) and Th (4.6 ppm) values are markedly higher. Hawke et al. [32] attributed this to the much lower abundance of mare basalt and pyroclastic material in the Apennine region as well as a change in the composition of the highlands material. Mixing model calculations based on the values presented by Hawke et al [32] and Clark and Hawke [11] suggest the southern Apennines are dominated by medium-K Fra Mauro basalt (30%) and anorthositic norite/gabbro (42%). Much lesser amounts of low-K Fra Mauro basalt (20%) and mare material (8%) are present.

The Archimedes region is dominated by the Apennine Bench Formation but also includes Archimedes crater deposits and some mare units. The region exhibits extremely high Th and K values. Mixing model and other geochemical studies by Hawke and Head [33], Spudis [35], and Hawke et al. [32] indicated that the region was dominated by medium-K Fra Mauro (KREEP) basalt. As noted above, Metzger et al. [31] have demonstrated that the Th values exhibited by the Apennine Bench Formation indicated the presence of KREEP basalt. The x-ray results presented by Clark and Hawke [11] also clearly indicated that the surface of the Apennine Bench was composed of KREEP. Finally, Spudis and Hawke [34] presented a final summary of all the available geochemical data for the Apennine Bench Formation and they concluded that there was no doubt that the Bench was composed of KREEP basalt similar to that returned from the Apollo 15 landing site.

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PETROLOGY AND GEOCHEMISTRY OF HIGHLANDS SAMPLES FROM THE APENNINE FRONT; Marilyn M. Lindstrom, Department of Earth and Planetary Sciences and McDonnell Center for Space Sciences, Washington University, St. Louis, Mo.

At the Apollo 15 site, the lunar highlands are represented by Hadley Delta massif. It is part of the Apennine Front, an arcuate mountain belt which forms the most prominent ring of the Imbrium basin. The site also falls within the rings of the older Serenitatis basin. Samples returned from the front were therefore expected to consist mainly of Imbrium ejecta and possibly to contain some Serenitatis materials. As is the case for other highlands landing sites, the samples collected at the base of the Apennine Front are dominated by breccias. True highlands igneous rocks are rare, but because of the proximity to Palus Putredinis, mare basalts are common. The distribution of large rocks at the three stations is: 15 regolith breccias; 3 green glass clods; 3 impact melt breccias; 1 basalt breccia; 1 anorthosite; 1 recrystallized anorthositic norite. The distribution of rock types among rake and coarse soil particles is similar, except that mare basalts are more common and the polymict breccias are not separated into distinct categories. Geologic interpretations of the highlands samples from the Apennine Front rely upon detailed petrologic and geochemical studies of breccia clasts and matrices, which provide data on the rock types and their associations.

Descriptions of Samples.

Although regolith breccias are the most common rock type at the front, they are complex mixtures of many components. This description of individual rocks begins with the simplest samples and builds to the most complex regolith breccias.

15415. Anorthosite (269 g), the Genesis Rock, was collected at the rim of Spur Crater(Sta 7), perched on a pedestal of regolith breccia 15435, one of the largest rock fragments in the vicinity. It consists of > 95% plagioclase (An97), accessory pyroxene (augite with Mg'72 > pigeonite with Mg'58) and trace ilmenite, silica, olivine and apatite. Its texture is cataclastic and granulitic, refecting a complex metamorphic history[1]. It is a typical ferroan anorthosite, as shown by mineral compositions in Fig 1. Concentrations of REE (Fig 2) and other incompatible elements are very low and typical of ferroan anorthosites[2]. Rake sample 15362 is very similar to 15415.

15418. Granulitic breccia (1140 g), from Sta. 7, is an anorthositic norite with mineral compositions similar to 15415, yet a more complex texture. It is a shock-melted, devitrified and recrystallized breccia in which the equilibrated poikilitic rock was later modified by at least two episodes of brecciation and recrystallization [3]. REE concentrations are low, with a relatively flat pattern [4].

15256. Basaltic breccia (201 g), from Sta. 6, has the mineralogy and chemistry of a mare basalt, but a clastic texture[5].

15405. KREEP breccia (513 g), from a large boulder at Sta. 6a, is an impact melt of KREEP basalt containing clasts of the basalt, and its differentiates quartz monzodiorite and granite[6]. Mineral compositions of basalt clasts show normal crystallization trends, but are plotted as ranges in Fig 1. REE concentrations are high, with patterns similar to those of KREEP breccias [7]. Both basalt and QMD clasts are free of siderophile element contamination from meteorites. The QMD clast has been dated at 4.37 BY, the matrix at 1.25 BY. Rake samples 15382 and 15386 are also KREEP basalts.

15445 and 15455. Black and white breccias (287 & 937 g), representing a large boulder at Sta 7, are impact melt breccias containing clasts of Mg-suite norites, anorthositic norites, troctolites and spinel troctolites[8]. These clasts are among the best examples of pristine mafic rocks returned from Moon. They are highly magnesian (Fig 1), have low REE concentrations (Fig 2) and are ancient (norite dated at 4.52BY) [7,9]. No clasts of ferroan anorthosite or anorthositic norite, KREEP, or mare basalt are found in either breccia. The melt rock matrix has basaltic composition (Al_2O_3 17%), with moderately high Mg′ (73) and REE concentrations (50 x chondritic), and has been dated at 3.9BY [7].

15425-7. Green glass clods (136, 224 & 116 g), from Sta. 7, are regolith breccias dominated by green glass spheres. Other clasts include yellow and red glasses, mare basalts, anorthositic and noritic fragments, and melt rocks. Although green glass is presumed to be a mare pyroclastic glass, it is found concentrated at Sta. 7 and not on the mare plain. The green glass and clods are rich in Fe, Mg and trace transition metals, and poor in REE [10].

Regolith breccias. (15 large samples, total 12,648 g) These brown glass matrix breccias are common at all three Apennine Front stations. They contain a diverse suite of clasts including anorthosites and other feldspathic rocks, KREEP basalts, mare basalts and green glass. Extreme variations in clast proportions are observed among the breccias, for example 15205 [11] is dominated by KREEP basalt, while 15459 [12] has little KREEP and is made up of feldspathic and mare components. Mineral compositions and REE patterns for clasts in the regolith breccias are shown in Figs 1b and 2b, for comparison with those of the simpler breccias. Although the KREEP and mare components of the regolith breccias are well characterized, the feldspathic components are not. Highly magnesian plutonic rocks like the clasts in the black and white breccias are rare in the regolith breccias. Ferroan anorthosites are found as clasts in several breccias, but are not abundant. The majority of feldspathic clasts are poikilitic norites or anorthositic norites whose textures have usually been interpreted as metamorphic [12,13], but which could also be the products of impact melting. Based on microprobe data, these clasts exhibit considerable range in composition (Al_2O_3 19-26%, Mg′ 60-80). Detailed compositional characterization has not been done. Some of the clasts appear to resemble 15418, but most are much more magnesian.

Discussion

The samples collected from the Apennine Front are a diverse suite of breccias which include all three major classes of pristine highland rocks as well as mare basalts and glasses. Relationships among samples may be evaluated using Fig 3, a plot of Sc vs. Sm for Apennine Front samples. The Sm axis shows variations in the KREEP component (with the reminder that pure KREEP is itself variable). The Sc axis reflects variations in both the amount and composition of mafic minerals. Thus anorthositic norite 15418 has higher Sc than ferroan anorthosites because it has a higher proportion of mafic minerals, and higher Sc than Mg-suite troctolites and norites because it has ferroan composition. Endogenous lunar rocks occupy the extremes of the diagram, while melt rocks, breccias and soils scatter in the interior. Matrices of the black and white breccias occupy a field distant from both KREEP and mare basalt. Some samples trend away from the main group in the direction of the Mg-suite clasts from the breccias; these may represent dilution of the matrices with clast material. Regolith breccias scatter along two trends, one toward KREEP, the other toward green glass. (Regolith breccias from mare stations trend toward mare basalts.) The fields for Apennine Front soils [14] are shown for comparison with regolith breccias. Sta. 2 soils are adjacent to the matrices of the black and white breccias. The Sta. 6 regolith breccias cluster around the soils, while most Sta. 7 regolith breccias form a trend parallel to their soils. The most KREEP-rich breccias are found at Sta. 2 and 7. Regolith breccias and soils are obviously mixtures of a variety of components, but geologic interpretations depend on the choice of components. The question is whether the pristine components mix independently or are associated in some common polymict one. The enigmatic LKFM may be such a component since it falls near the point where the trends diverge.

LKFM. Reid et al. [14] used the term low K Fra Mauro (LKFM) basalt for a cluster of glass compositions in Apollo 15 soils. It is similar to KREEP basalt glass but has much lower K and Na, lower Si, higher Al, Mg and Mg'. They concluded that LKFM was a major component of the Apennine Front because it is more abundant in soils near the front. The ensuing search for rocks of LKFM composition produced no endogenous lunar rocks, but some impact melts [17]. Taylor [16] equated LKFM with the matrix of the black and white breccias, a definition which survives today. Glasses of LKFM composition are found in soils from all highland sites[15], but these glasses vary in composition from site to site, as do the compositions of melt rocks which most closely match the glass compositions [17]. Inspection of the original glass data shows that the LKFM cluster is not a tight compositional group as would be expected for an endogenous or impact melt of a single composition. LKFM composition closely resembles that of the Apennine Front soils [14], and based on remote geochemical data [18] is widespread in the Apennines. These variations in compositions and similarities to average surface compositions suggest that LKFM is a common mixture of components at the Apennine Front and not an endogenous rock or impact melt representing a limited assemblage of components. Ryder and Spudis [19] discussed problems with the use of LKFM for geologic interpretations and dismissed it in favor of individual samples. At present LKFM is a loosely defined term which will be useful in future interpretations only if it can be defined as a specific geologic association.

Geologic interpretations of the samples are speculative because of the limited dataset, but they provide models to be tested when additional data are available. Ryder[8,20] concluded that the black and white breccias are Imbrium melt rocks because of their age (3.9BY) and deep-crustal clast assemblage. KREEP breccia 15405 was rejected as a product of a major basin-forming event because of its young age (1.25BY) and lack of deep-crustal components. Spudis [21] accepted the Imbrium origin of the black and white breccias and suggested that LKFM represented Serenitatis ejecta because of its closer similarity to Apollo 17 melt rocks. In this scenario the feldspathic rocks are pre-Serenitatis materials. He also suggested that KREEP basalts originated as lava flows from the Apennine Bench formation which may underlie the mare basalts, rather than being ray material from young craters Aristillus and Autolycus. If these models are correct, the regolith breccias and soils, which are made up largely of Apennine Front debris, should have black and white breccias and LKFM as major components and feldspathic rocks as only very minor components. Indeed, the compositions of regolith materials do resemble these proposed basin components, but they are not present as recognizable clast assemblages. It is strange that the predominant lithologies of the two basin formations are not preserved in recognizable form when the feldspathic, KREEP, and mare clasts are. The resolution of this dilemma awaits detailed petrographic and compositional studies of clasts from the regolith breccias and of rake and coarse soil particles. These studies will provide new data on the variety and distribution of rock types which are required before we understand the geology of the Apennine Front.

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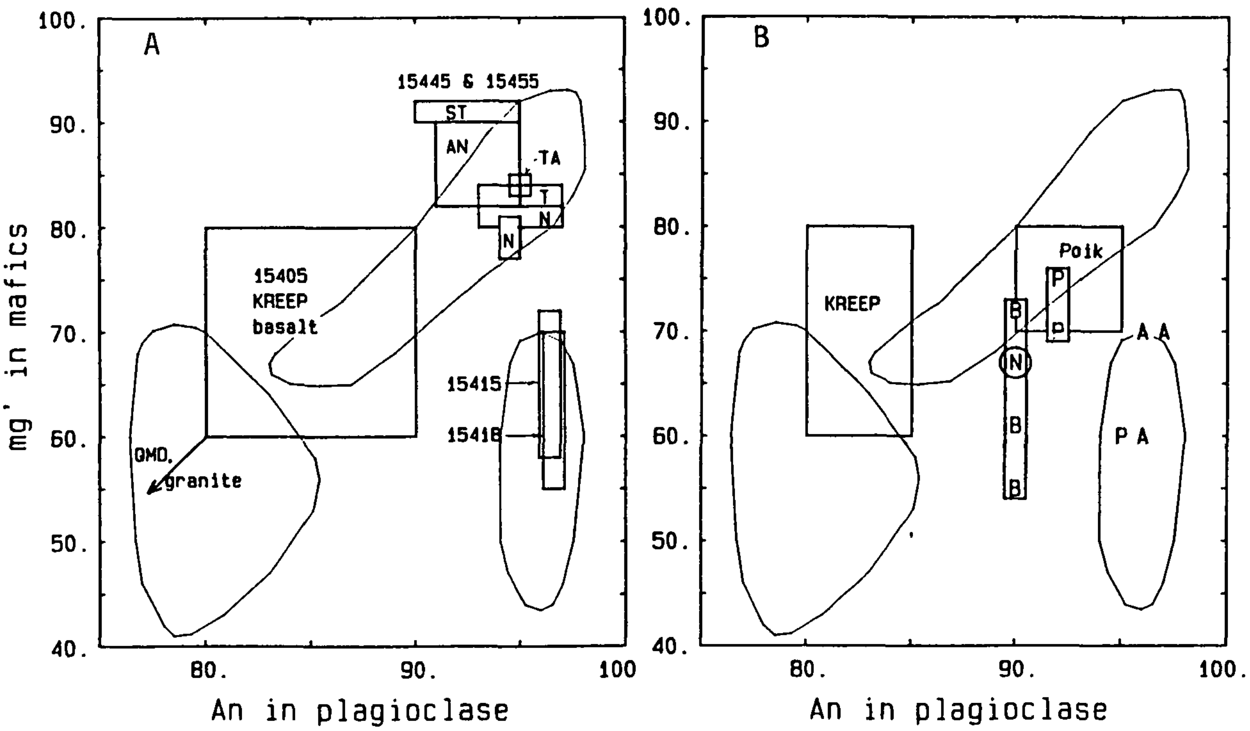
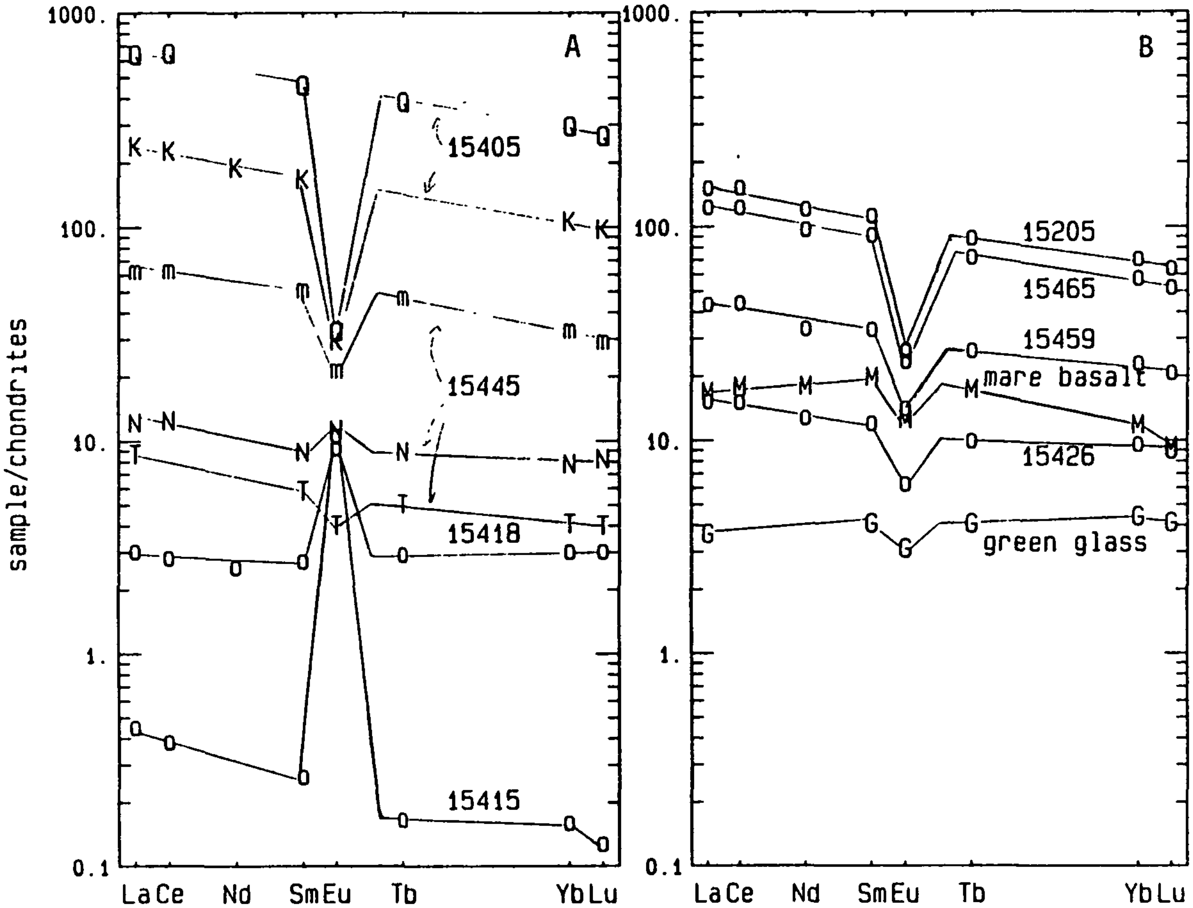
Fig 1. Mg′ in mafic minerals vs. An in plagioclase for Apennine Front samples. A. Feldspathic rocks and clasts in impact melt breccias. B. Regolith breccia clasts.





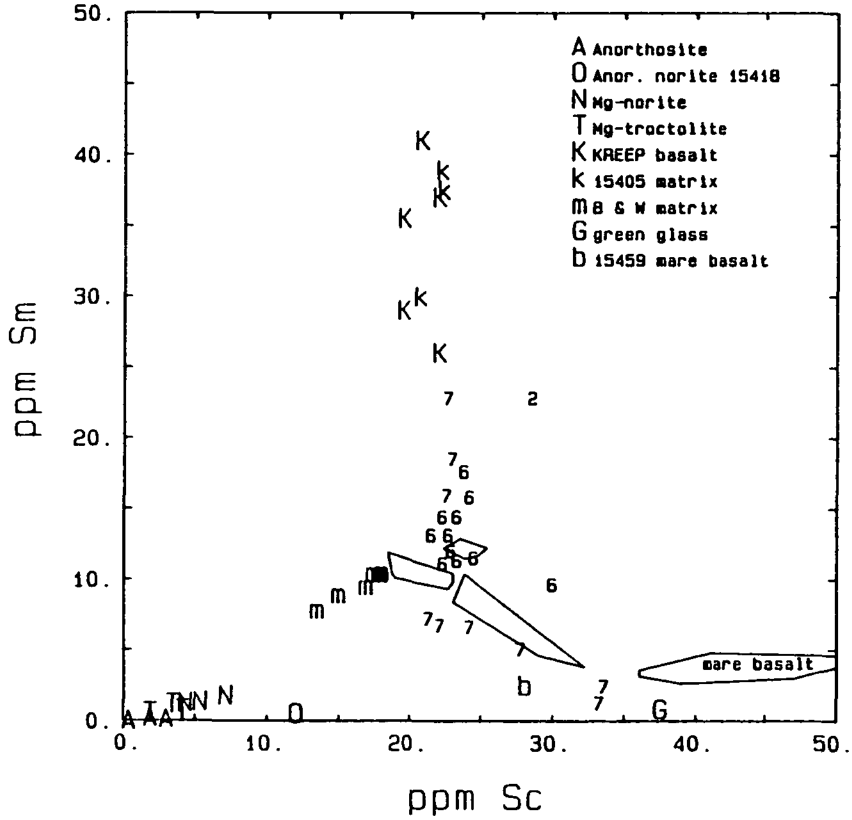


Fig 2. Chondrite-normalized REE plots for Apennine Front samples. A. Feldspathic rocks and impact melt breccias. B. Regolith breccia matrices and mare basalt and glass.

Fig 3. Sc vs. Sm in Apennine Front samples. Distinct rock types are listed in the legend. Regolith breccias are indicated by station numbers. Fields of soils from stations 2, 6, and 7 are shown.

CHEMICAL COMPONENTS OF THE APOLLO 15 REGOLITH; Randy L. Korotev

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The lunar regolith is a complex mixture of many components. A major goal of compositional studies of lunar regolith is to use the compositional data to identify and estimate the relative importance of the various chemical components of the regolith. This paper reviews the results and conclusions of four methods that have been applied to Apollo 15 regolith data and samples to determine the important chemical components: graphical techniques, analysis of individual soil particles, factor analysis, and multicomponent mixing models. This synthesis relies heavily on data and conclusions from the literature as well as new analyses on 28 regolith breccia samples, 28 soil samples, and 50 individual 1-2 mm particles from soil 15272 [Korotev, unpub.].

Graphical. Fig. 1 is a plot of the concentrations of Sm and Sc in soils and regolith breccias compared to those in some important rock types found at Apollo 15. The Sm vs. Sc plot, which is essentially equivalent to the plot of Sm vs. Cr [11] is useful because compared to many other two-element plots the overlap of fields for different rock types is minimal. Fig. 2 is a plot of Mg' (mole % Mg/(Mg+Fe)) as a function of alumina concentration for the soils. These plots reflect most of the compositional variation observed in the Apollo 15 regolith. Although the variation among stations is considerable, soils from a given station are more similar in composition to each other than they are to soils from other stations (Fig. 1). The greatest range is seen in the stn. 7 soils from Spur Crater.

Most of the variation in soil compositions results because the soils are predominantly binary mixtures containing different proportions of mare material and highland material from the Apennine Front (AF). This is similar to what is observed at Apollo 17 which is also at the interface between the mare and highlands [e.g., 10]. At one extreme are the soils from station 9a at Hadley Rille which are the most similar in composition to the mare basalts. Even these soils, however, are richer in incompatible trace elements (ITEs) and generally less mafic than the basalts, indicating the presence of some nonmare material in the soil. At the other extreme, the least mafic and most feldspathic soils are samples from the bottom (55-57 cm) of the 15007/8 drive tube at stn. 2 on the AF [Korotev, unpub. data]. These soils are less mafic than the stn. 2 surface soils and are presumably the most representative of the AF in being the least 'contaminated' by mare basalt. Most of the other soils are intermediate in composition between these two extremes. Important exceptions are some samples from stn. 7. In both Figs. 1, 2 and 3 samples of soil 15421 and regolith breccia 15426 plot closest to the point for pure green glass separated from 15426. Other stn. 7 soils and breccias plot between the green glass and the stn. 2 soils. Another perturbation to the dominant mare-highlands mixing trend is that soils from stn. 6 (AF), stn. 9 (Hadley Rille), and the LM area plot to the high-Sm side (Fig. 1) of the mare-AF mixing line, suggesting that a KREEP-like material is also a component of these soils.

Regolith breccias collected at a given station are usually similar in composition to the soils from the same station (Fig. 1b). Some breccias have more extreme compositions than the soils, however. Most of these breccias differ in having higher concentrations of Sm and other ITEs than any soil, with four samples approaching the levels in Apollo 15 KREEP basalt. These Sm-rich breccias are found at both mare and AF stations and cannot be lithified samples of the present, local soil as no returned soil contains such high ITE concentrations. Some may be exotic to the immediate Apollo 15 site. Alternatively, they may be samples of an old, buried, KREEP-enriched regolith.

Thus, in order to explain the trends on the variation diagrams of Figs. 1 and 2, a minimum of only four components is required. Three of these can be unambiguously associated with local materials represented by rock types which are regarded as primary (i.e., not polymict): Apollo 15 green glass (a rock type in the chemical sense), mare basalt, and KREEP basalt. The 4th component is a noritic component and is principly associated with the AF and the stn. 2 soils. The relationship of the AF component to local rock will be discussed in more detail later, but the similarity to the dark melt portions of breccias 15445 and 15455 is obvious from Figs. 1 and 2. The composition of these melts is often equated with, if not defined as, the 'LKFM composition' [9, 13].

Soil particles. Plotted in Fig. 3 are data for the 50 largest particles in a 225 mg allocation of station 6 (AF) soil 15272, the 1-2 mm grain-size fraction of 15270. About 21 of the particles are similar in composition to the < 1mm soils from stn. 6 and are probably small regolith breccias like the larger samples plotted in Fig. 1b. Three of the particles are mare basalts and two resemble soils from other stations (1 and 2). Eighteen are slightly to considerably more enriched in ITEs than the station 6 soils. Only six of the particles are less mafic (and presumably more anorthositic) than the stn. 6 soils. Two of these are troctolitic anorthosites and one has a composition somewhat similar to that of the melt portions of 15445 and 15455. No particles similar to anorthosite 15415 or anorthositic norite 15418 were found. These results and those of [8] for particles from the deep-drill core (stn. 8/LM) indicate that >1 mm particles of mare basalt are common in the soil from the mare but not from the AF and that >1 mm particles of KREEP-like material are common in both mare and AF soils. In fact, the mean concentration of Sm in 15272 (1-2 mm) is 30% greater than that in 15271 (< 1mm), indicating a significantly greater proportion of KREEP-like components in the 1-2 mm size fraction. These KREEP particles may be relatively recent ejecta from a local crater which sampled underlying KREEP basalt. Many appear to be dark and crystalline; some have glass coatings. Note that several of the regolith breccias with Sm concentrations greater than the soils in Figs. 1b and 3 are also richer in Sc than the 15272 particles plotting in the same area. This indicates that some of the non-soil-like, ITE-rich regolith breccias (namely, 15025, 15028, 15205, 15528, and 15565) have only a small component of AF material compared to the soils and, thus, are primarily KREEP - mare basalt mixtures. This is basically the conclusion reached for 15205 on petrologic grounds [4].

For the 15272 particles the AF component is carried primarily by the glassy breccias of bulk soil composition, but also in part by the few 'ANT suite' particles. There is little information in these particles about what more primary rock types accounts for the overall noritic composition of the AF soils. We can conclude, however, that unlike the KREEP component the Apennine Front soil component (AFSC) is fine grained and well mixed.

Factor Analysis. Two- and three-element variation diagrams are useful because they are conceptually simple and geometrical arguments can be used to show mixing relationships. A disadvantage is that conclusions based on one such diagram may be contradicted by another when different elements are used. Compositional trends using all available data can be used to imply end-member components with computer techniques of factor analysis or principle component analysis. Despite the potential utility of these techniques there are very few applications to lunar regolith studies. One of these is the study of Apollo 15 soil compositions by Duncan et al. [3] in which factor analysis was applied to major and trace element concentrations in Apollo 15 soils. This study concluded that most of the soils lie on a mixing line between mare basalt and LKFM, but that soils from stations 6, 9, and LM contained "more KREEP material than other soils". (The importance of the green glass in stn. 7 soils is not evident in this study because the stn. 7 soil composition used was that for the stn. 7 soils that resemble stn. 2 soils, not the 15421 extreme.)

An important conclusion from each of the techniques discussed above is that there is no requirement in the soil data for components of anorthosite or anorthositic norite ('gabbro') to explain the variation in the data. Although these rock types occur as particles in the soil and are highly visible in the large rocks (15415 and 15418), the variation in composition of Apollo 15 soils is not primarily the result of variation in anorthositic components.

Mixing Models. Once the likely components of the soils are identified the validity of the choice can be tested and the relative proportions of the various components estimated by using 'mixing models'. The validity of the results of mixing model calculations depends on the reasonableness of both the components selected and the compositions chosen to represent the components. It is sometimes implied that a 'good fit' proves that the set of components selected represents the reasonable and true components of the soil. This is not true. The models can only 'prove' that a particular set of components does not fit the soil composition. Good fits can be obtained from unreasonable components. It is important to keep in mind that components used to model a soil mixture and the compositions used to represent those components are assumed input parameters to the calculations; they are not model results or predictions.

The contentions made above are easily demonstrated by Table 1 and 2. Table 1 presents a summary of components used in nine different models which have been applied to Apollo 15 soils and breccias. No two models are the same in regard to either which components are assumed to be the important components or which compositions are used to represent the component. Each provided a sufficiently good fit to the data that the authors were confident enough to publish the results, however. It is impossible to rigorously compare the goodness of fit of the various models because different elements were used in each and because two models which may provide equally good fits in a mathematical sense may not be equivalently good in a geochemical sense (the latter is more subjective). Table 1 represents differences in model input assumptions.

Table 2 summarizes some model predictions for stn. 2 soils, i.e., those AF soils with the lowest fraction of mare basalt. (Models in Table 1 which are not in Table 2 did not include stn. 2 soils.) The differences in model predictions in Table 2 are a direct result of the differences in input assumptions of Table 1. Despite the differences in the various models, there is some concensus. Mare basalt and green glass are clearly important components. Many models include both olivine- and quartz-normative basalts. Considering the similarity in composition of these two basalt types compared with their mutual difference in composition to the other rock types used in the models, it is unlikely that the models can truly predict the prevalence of one over the other for any but the most basalt-rich soils. For these, model results indicate a decided predominance of olivine basalt over quartz basalt of 5-10 to 1. Each of the soil models also includes KREEP, either Apollo 15 type (La = 230-250 times chondritic) or Apollo 14 type (La = 300-330 times chondritic). Because of the relatively small proportion of KREEP required to obtain mass balance for the ITEs, the models are not too sensitive to which kind of KREEP is used. The only effect is that models using Apollo 14 KREEP (high-K) predict a slightly lower proportion of KREEP in the best-fit mixture than those using 15386 KREEP (intermediate-K).

The major differences among the models is what rocks are used to represent the AF component. All models include some type of LKFM component as norites of this approximate composition are most nearly similar to the composition of the AF soils. However, some of the models do and others do not also include anorthositic components, either anorthosite such as 15415 or anorthositic norite ('gabbro') such as 15418. As noted earlier, there is no indication in the compositional data that such components are necessary to explain any of the variation in the soil data. This is not to say that anorthosites, anorthositic norites, and anorthositic troctolites, etc. are not components of the soils. If they are important components they must occur as well-mixed subcomponents of the AFSC. A multielement model that we have tested which accounts for the composition of Apollo 15 soils as well as any model listed in Table 1 requires only four components: mare basalt, green glass, KREEP, and an AF component represented by the least mafic soils from the 15007 (stn. 2) drive tube. These are the only four components needed to account for the variation in the soil data. Because the first three components are local rock types, the problem of modeling Apollo 15 soils in terms of mixtures of local rock types is thus reduced to modeling the AF soils.

The Apennine Front Soil Component (AFSC). The AF component is often identified as LKFM or other noritic compositions such as the dark melt portions of 15445 and 15455. The latter and other noritic rocks of similar composition are not alone sufficient to account for the soil data. As seen in Fig. 2, the stn. 2 soils are considerably more ferroan (Mg' = 61) than the 15455-type melt and other Apollo 15 norites (Mg' > 70). The AF soils must contain at least two ferroan components with a sufficiently high concentration of Fe to reduce the bulk Mg/Fe ratio. One of these is mare basalt. The curved line in Fig. 2 is the mixing line between stn. 9a soils (richest in mare basalt) and the stn. 2 soils (poorest in mare basalt). The line assumes that these two extreme soils are essentially binary mixtures of a mare basalt component (some mixture of olivine- and quartz normative basalt and green glass) and the AF soil component, but that neither soil is the 'pure' end member. Hence, removing the mare basalt component from the stn. 2 soils should yield a composition for the AFSC plotting on the extension of the curve to the high-Al side of the stn. 2 soils. This curve does not intersect the field for any known Apollo 15 noritic material. The AFSC component must be a mixture which also contains a component(s) plotting below the curve, such as anorthositic norite 15418. (The effect of KREEP is minimal on this diagram.) If 25% mare basalt is removed from the stn. 2 soils, as is indicated by several of the mixing models in Table 2, the composition obtained corresponds to point "+" on the curve. The fact that this point lies between the points for 15445-type melt and 15418 is not a coincidence, but a necessary result. Nearly every model in Table 2 which has included a noritic component with the 15445 composition has also required a more anorthositic and ferroan component with the 15418 composition in order to obtain a good fit to the stn. 2 soil data. This is essentially the same problem encountered with trying to model Apollo 16 soils using local melt rocks as the principle carriers of the ITEs and 'mafic' elements. Some type of ferroan norite or anorthositic norite is required [6,7].

An anorthositic norite with the composition of 15418 may, in fact, be the important ferroan subcomponent of the AFSC. An alternative possibility is that the ferroan subcomponent is actually more mafic (noritic) than 15418 (a unique sample) and, consequently, that there is less mare basalt in the stn. 2 soils than the 25% predicted by the mixing models. Note on Fig. 3 that a mixture of 15418, 15445-type dark melt, and a small amount of KREEP also satisfies the geometrical mixing requirements for the stn. 2 soils on the Sm-Sc diagram. Quantitative, multielement modeling of the AFSC is hampered by a lack of data for likely subcomponents [11]. Most modeling has been done on the basis of single analyses of unique rock types.

Summary and Conclusions. *The variation in composition of Apollo 15 soils can be* explained by mixing of four chemical components, some of which may be mixtures themselves or be represented by more than one petrographic component. The chemical components are (1) mare basalt, (2) green glass, (3) KREEP, and (4) an Apennine Front soil component. The AFSC is a composition, defined here as stn. 2 soil minus any mare basalt resulting from mechanical mixing of local mare material. It is best represented the composition of the least mafic soils from the bottom of the 15007/8 double drive tube. The mass fraction of local mare material in these soils is unknown but it is less than that of the stn. 2 surface soils. The AFSC is surely a complex mixture of many subcomponents, but in terms of known Apollo 15 rock types, it appears to be primarily a mixture of a magnesian norite, some ferroan norite or anorthositic norite like sample 15418, and some type of KREEP norite or basalt (which does not have to be the same KREEP component as (3) above). Anorthosite and troctolite may also be minor components. The magnesian norite may be the dark melt rock associated with 15445 and 15455. However, like these melt rocks, even the analysis of 15306,23, a "probably" pristine norite of [16] resembles the composition associated with LKFM (Fig. 3). Considering the original definition of LKFM as the composition of certain glasses found in the soils [e.g., 9] it is probably misleading and counterproductive for the purpose of unravelling the geology of the Apollo 15 site to strictly identify 'LKFM' as the AFSC, 15445 melt, or any other rock type. LKFM has been used to refer to a wide variety of rock types and compositions (e.g., Table 1) and it is not clear which, if any, Apollo 15 rock type deserves the apellation LKFM (e.g., Fig. 3).

Table. 1. Apollo 15 Breccia and Soil Mixing Models
(Values in parentheses are chondrite normalized La conc. of component)

	Mare			Highland				Met.
	ONB	QNB	GG	A	AG	LKFM	KREEP	CC1
BRECCIAS								
Taylor et al. (1973)				X (4)	X (9)	X (100)		
Lindstrom et al (1977) KREEP-rich	X				X (1-15)	X (100)	X (250)	
SOILS								
Fruchter et al (1973)	X		X		15418 (4)	15455 (100)	15059 (230)	X
Carr & Meyer (1974) major elements only	X	X	X		X	X	X	
Duncan et al. (1975)	X	X	X		15418 (4)	X (100)	X (300)	X
Chou et al. (1975)	X	X	X	X (0.4)		15455 (100)	X (330)	X
Schonfeld (1975)	X	X	X		(X) (5)	(X) (100)	X (250)	X
Korotev et al. (1980) stn. 2 (AF) only	X	X				HOA (16)	X (330)	X
Walker & Papike (1981)	X		X	X (0 4)		62295 (60)	15386 (250)	

ONB· Olivine norm. basalt; QNB Quartz norm. basalt
GG· Green glass [15426]; A Anorthosite (35% Al2O3) [15415]
AG Anorth. gabbro = Anorth. norite = Highland basalt (26-28% Al2O3)
LKFM Low-K Fra Mauro (17-19% Al2O3) [15445, 15455 melt]
KREEP Intermed -K Fra Mauro = Med -K KREEP = Apollo 15 KREEP [15382/6] or High-K KREEP [Apollo 14 KREEP]
Met Meteoritic component

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Table 2. Mixing Model Predictions: Mean percent mare component (basalt and green glass) and LKFM in Apollo 15 Apennine Front (stn. 2) soils.

	mare	LKFM
Carr & Meyer (1974)	20	44
Schonfeld (1974)	(25)	(32)
Fruchter et al. (1973)	26	34
Duncan et al. (1975)	26	59
Korotev et al. (1980)	27	50
Walker & Papike (1981)	31	29

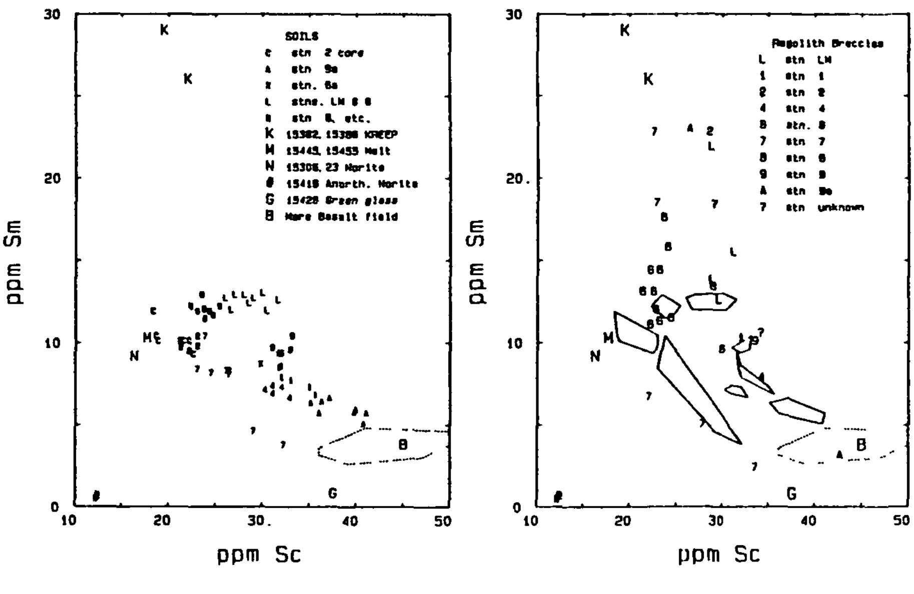
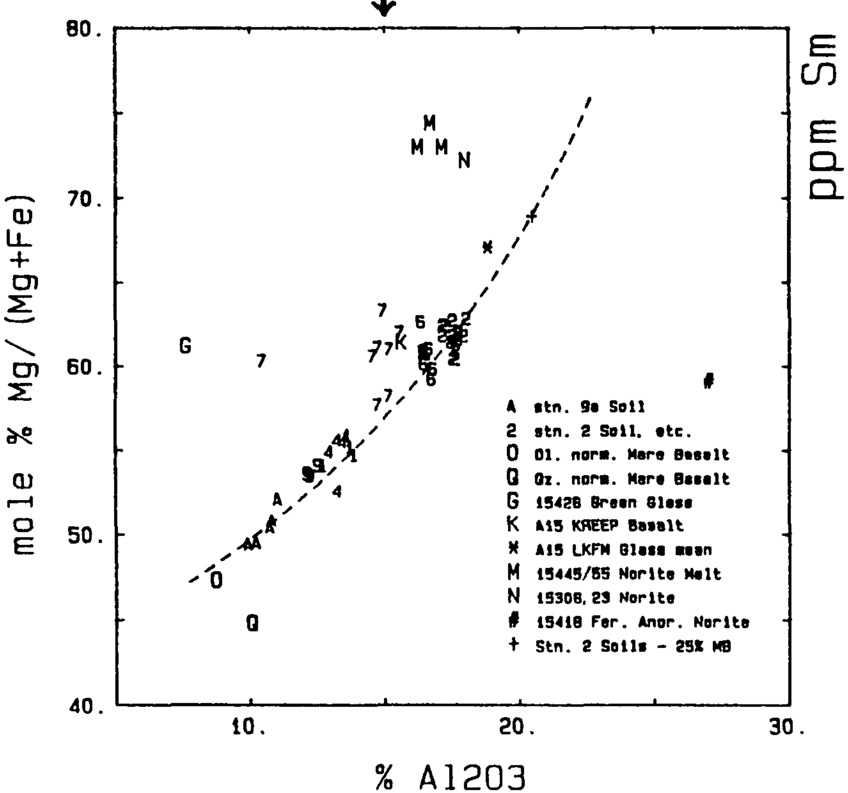
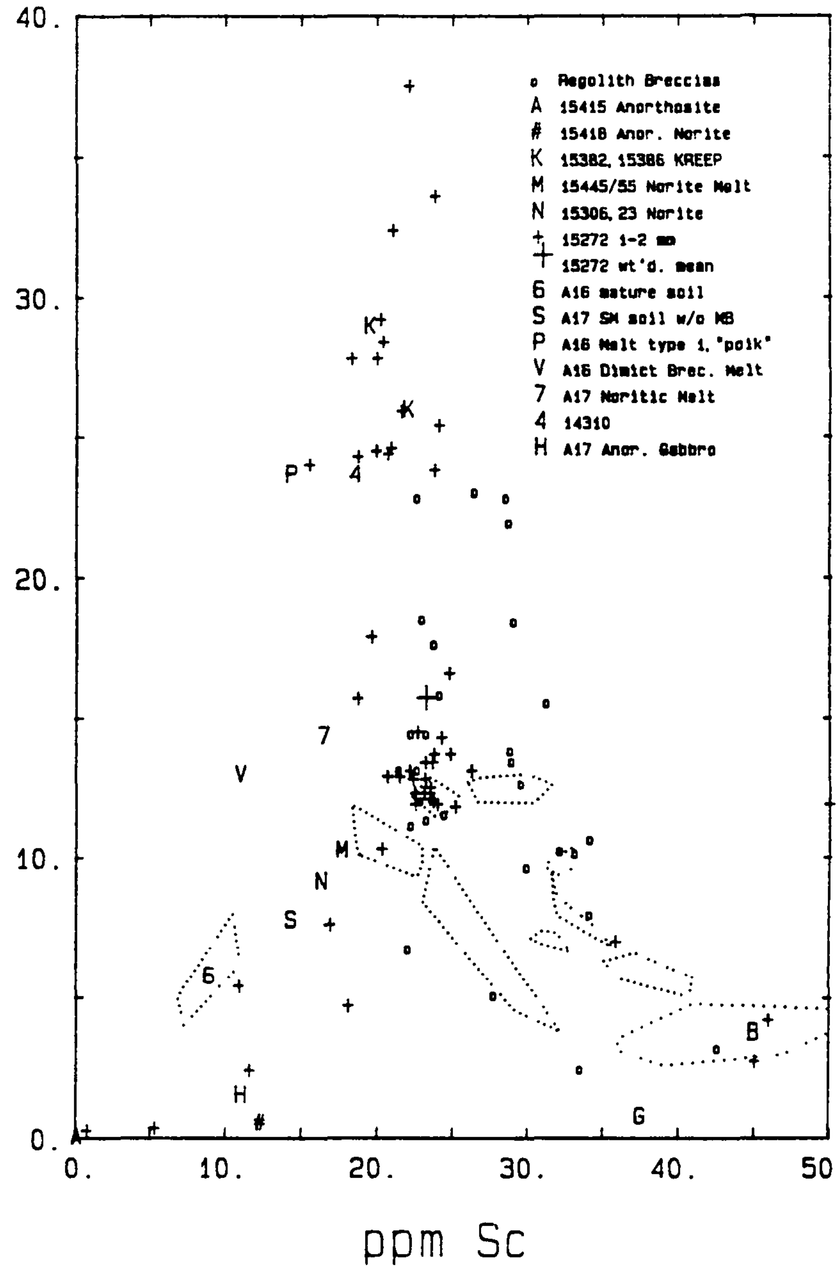


Figure 1. Sm and Sc concentrations in Apollo 15 soils (a) and regolith breccias (b) compared to some local rock types and keyed to station number. Data for Figs. 1, 2, and 3, are from many literature sources which will be referenced properly in a later publication and also from unpublished data of Korotev (soils and regolith breccias) and M. Lindstrom (15445, 15455 melt).

Figure 3. Like Fig. 1, but with data for some soil particles (Korotev, unpub.). Data for average compositions of some rocks and soils from other sites are included for reference. ⟶

Figure 2. Mg' versus alumina in Apollo 15 soils and some rock types. Numbers are station numbers of soils. The curved line is the mixing line through the stn. 9a and stn. 2 mean soil compositions. The + on the line represents the composition obtained by removing 25% mare basalt component with the same composition as that in the stn. 9a soils from the stn. 2 soils. LKFM glass composition from ref. [9].





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ULTRAMAFIC PARENT MAGMAS FOR MARE BASALTS? J. Longhi, Dept. G&G, Yale U., New Haven, CT 06511

The unaltered solidification products of basaltic magmas at the Apollo 15 site are present in two well-studied forms: fine-grained basalts and ultramafic glasses. The ultramafic glasses generally have higher Mg/Fe ratios than the fine-grained basalts and thus are judged to be more primitive (1). However, numerous workers, e.g. (2,3), have shown that the most common ultramafic glass at Apollo 15, the emerald green glass (4), cannot produce the observed basalt compositions by any reasonable combination of fractionation and melting processes. The present study extends these earlier studies to include the 25 chemical groups of ultramafic glasses recognized by (5), 8 of which have been collected at the Apollo 15 site. Consideration of simple $MgO-TiO_2-Al_2O_3$ systematics plus the results of calculations of fractional crystallization demonstrate that none parental magmas of the recognized groups of ultramafic glasses could have fractionated to produce the Apollo 15 basalts, nor conversely could any of the Apollo 15 ultramafic magmas have produced any of the low-Ti basalts collected at the other sites. The obvious question is whether this lack of correlation between ultramafic glasses and basalts is caused by limited sampling of a wide range of magma types or whether some more profound (and interesting) physical process operated to produce this lack of correlation.

Figs. 1 and 2 are plots of TiO_2 and Al_2O_3 versus MgO respectively in which the compositions of the low to intermediate Ti ultramafic glass groups recognized by (5) are plotted along with the compositions of fine-grained mare basalts from several landing sites (the compositions of coarser-grained basalts or micro-gabbros are omitted). The compositional variation produced by fractional crystallization of olivine in some of the molten parents of the ultramafic glasses has been calculated by the methods of (6) and is shown by dashed lines in the figures. The low-MgO ends of these curves represent the liquid composition at the first appearance of low-Ca pyroxene during fractional crystallization. The calculated lines of fractional crystallization are sub-parallel to the arrays of the various basalt groups indicating that olivine fractionation is probably the dominant control on compositional variation within the groups. Chromite is likely to have fractionated as well from the ultramafic magmas, but only in small amounts with barely discernable effects on the TiO_2 and Al_2O_3 trends. Separation of approximately 20 vol% of olivine from an ultramafic parent is required to produce the most magnesian ol-basalts; approximately 30 vol% to produce quartz-normative basalts.

Figure 1 illustrates an important point made previously by (7) that there are two major groups of low-Ti basalts collected at Apollo 15 -- ol-basalts (OB15) and pigeonite + olivine-phyric quartz-normative basalts (QNB15) -- and neither group could be parental to the other. At the Apollo 12 site there are two similar groups of low-Ti basalts (ol and quartz-normative) that can be related by fractional crystallization

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(8). So it seems reasonable to assume that at the Apollo 15 site there are pigeonite-phyric quartz-normative derivatives of the Apollo 15 olivine basalts and olivine-rich parents of the quartz-normative basalts (QNB15) that were not sampled. Taken together Figs. 1 and 2 also preclude deriving ultramafic parents to OB15 and QNB15 by different degrees of partial melting of the same olivine-rich source: Mg-Ti relationships suggest that the QNB15 parent should have been produced by ~1/3 more melting than the OB15 parent, whereas Mg-Al relationships suggest that an ultramafic parent to QNB15 would have formed from similar or somewhat lower degrees of partial melting than the OB15 parent.

The same $MgO-TiO_2-Al_2O_3$ systematics that preclude a similar parentage for OB15 and QNB15 also preclude deriving either of these two basalt groups from ultramafic liquids with compositions similar to any of the ultramafic glass groups recognized by (5). Figs. 1 and 2 suggest that the lack of correlation between low-Ti basalts and ultramafic glass compositions at Apollo 15 is a feature of samples of low-Ti mare basalts collected from other sites as well. The closest relationships appear to be between Apollo 17 VLT basalts and VLT17 glass, and between QNB15 and Apollo 14 green glass A (GA14), yet even in these cases lineages are distinct.

Another way of looking at the basalt/ultramafic glass problem is to note that of the 25 varieties of ultramafic glass identified by (5) only two (Y14 and Y15) have TiO_2 concentrations between 1 and 6 wt%, the range of concentrations for low-Ti basalts from Apollo 12, 14, 15, and Luna 16. Is it merely an accident of sampling that produced a paucity of low-Ti ultramafic glasses and an abundance of low-Ti basalts? If so, then more categories of yellow to green ultramafic glasses await to be recognized in the Apollo 12 and 15 soils. Perhaps the ultramafic parents of the low-Ti basalts were less prone to the fire-fountaining that produced the glass balls and hence crystallized extensively upon eruption. If so, then the calculations of fractional crystallization indicate that there may be significant amounts olivines present in the soils with distinctive composition: <u>Mg</u>~0.80-0.85 and CaO~0.3-0.4 wt%. If neither of these tests is positive, then we must entertain the possibility the low-Ti basalts did not have ultramafic parents near the Moon's surface.

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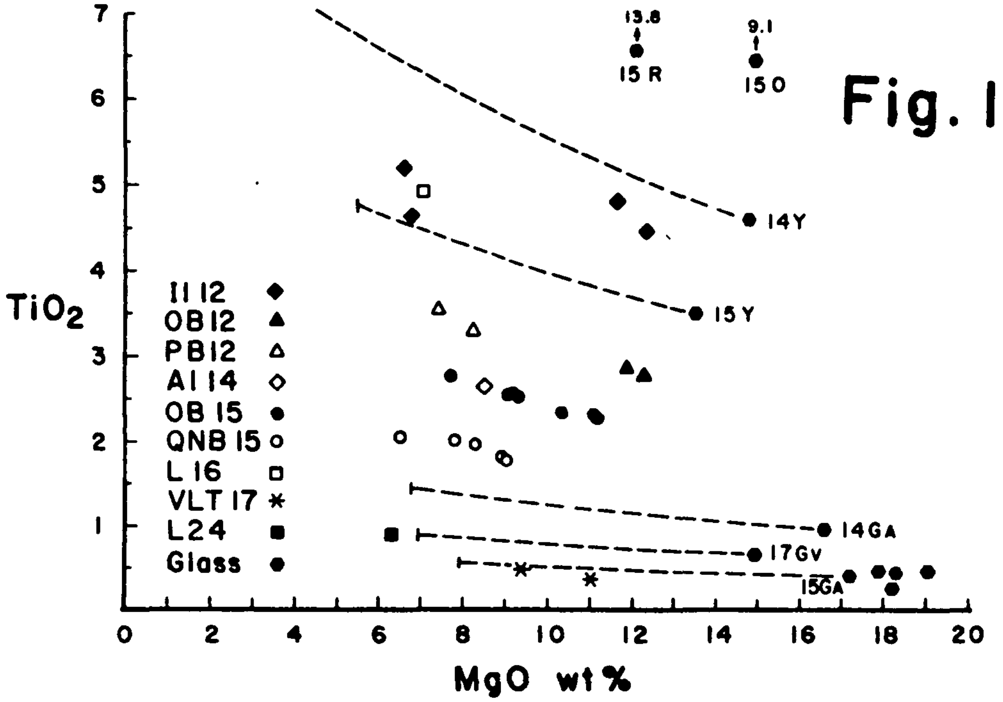
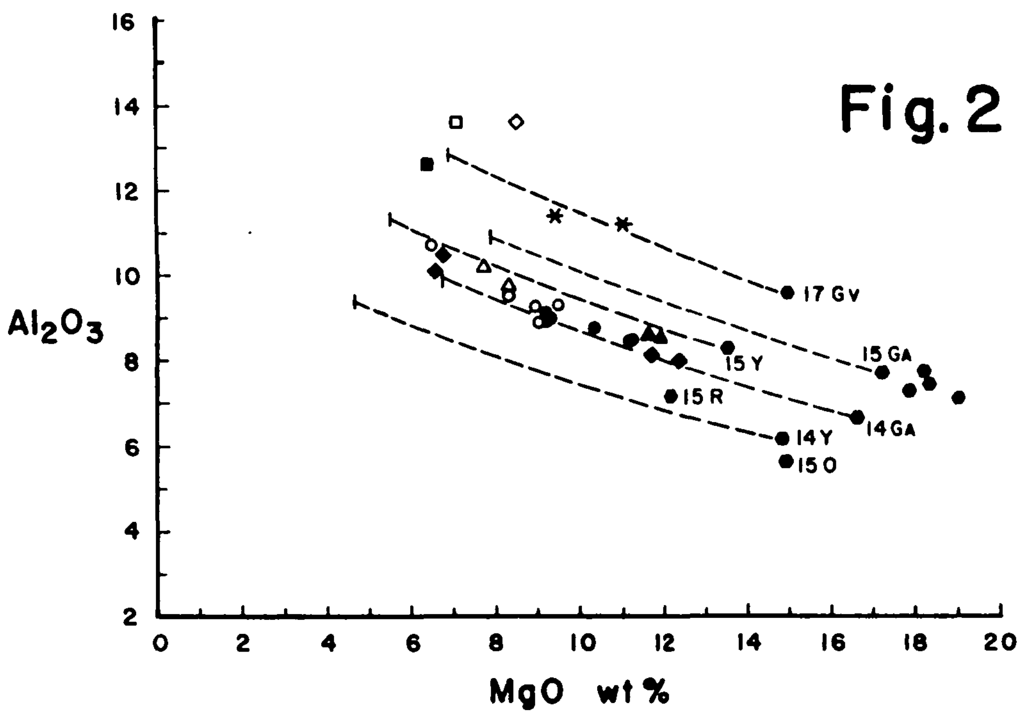


Fig. 1. TiO_2 vs MgO in wt% oxides. Abbreviations: Il = ilmenite basalt; OB = olivine basalt; PB = pigeonite basalt; Al = aluminous basalt; QNB = quartz-normative basalt; L = Luna; VLT = very-low-Ti basalt. Glasses: R = red; Y= yellow; O = orange; G = green. Glass data from (5); basalt compositions from (7, 8,9) Dashed lines are calculated paths of fractional crystallization of olivine(6).

Fig. 2. Al_2O_3 vs MgO in wt% oxides. Symbols as in Fig. 1.



SPECTRAL REFLECTANCE STUDY OF THE HADLEY-APENNINE (APOLLO 15) REGION. P.G. Lucey and B.R. Hawke, Plan. Geosci. Div., Hi. Inst. of Geophys., Univ. of Hawaii, Honolulu, HI 96822.

Introduction: Detailed information concerning the composition of surface material in the Hadley-Apennine region is necessary in order to understand the nature and origin of Imbrium basin-related units. Even though progress has been made in recent remote sensing studies (e.g., 1-6), many unanswered questions still remain. These include the compositions of Imbrium ejecta and pre-Imbrian material exposed both on the Imbrium backslope and in the Apennine Mts. (Apennine front), the variation in Imbrium ejecta composition as a function of distance from, and position around, the basin, and the nature of the material responsible for the thorium anomaly associated with the region. The purpose of this paper is to present results of an analysis of near-infrared spectral obtained for surface units in the Hadley-Apennine region.

Method: Twenty-three near-infrared spectra were recently obtained at the Mauna Kea Observatory 2.2-m telescope using the Planetary Geosciences Division indium antimonide spectrometer. Spectra were obtained for six relatively fresh surfaces in the Apennine Mts. (front), for five fresh crater deposits on the Imbrium backslope, and for a variety of highland units within the Apennine ring (Imbrium interior). The latter includes the following: 1) two fresh, small (D $<$ 5 km) craters on the Apennine Bench and 2) the eastern wall deposits of Archimedes, Aristillus, Autolycus, and Timocharis craters. Four spectral parameters were derived from each spectrum after the methods of Lucey *et al*. (1985): the 1 micron band depth, width, and center and the infrared continuum slope.

Result: Examination of scatter diagrams which plot the six combinations of the four spectral parameters reveals the presence of two major spectral classes. Figure 1 shows a plot of band depth versus band width and illustrates the separation between the two classes on the basis of these parameters. Class 1, in the upper left, is characterized by a large band depth (9-15%), and bands narrow with respect to the rest of the region (.15-.24$\Delta\lambda$). The spectra of Class 1 appear to be those of a mixture of low Ca pyroxene and feldspar. The plagioclase to pyroxene ratio of the areas determined from the spectra indicate these locations are anorthositic norite to norite. Class 2 is in the lower right of Figure 1. On the plot of band width vs band center (Figure 2), Class 2 members form a linear trend rather than a cluster. The trend is not consistent with maturing of an end member. Plots of the parameters sensitive to maturity, band depth and continuum slope, show that the trend does not exhibit an increase in continuum slope with decrease in band depth, systematics typical of the maturing process. The trend displayed by spectral Class 2 shows a correlation with location. Areas interior to the Apennine ring have both a longer band center and wider bands than those points on or beyond the Apennine front. The spectra of locations on the Apennine Bench Formation seem to represent a spectral end-member with the widest bands and longest band centers. Spectra of the walls of large craters interior to the Apennine ring show values intermediate between those of the Apennine Bench and Apennine exterior locations.

The Class 2 spectra and trend may be interpreted in several ways. One interpretation is that the spectra represent mixtures of low Ca pyroxene and olivine (with unknown amounts of feldspar) and the trend is caused by a decrease in olivine content with distance from the basin center. These spectra are consistent with mixtures of olivine and pyroxene where the ol:pxn ratio varies from about 40:60 to 70:30 (Singer, 1981). However, two of the Class 2 spectra were collected for small craters (D=2 and 3 km) on the Apennine Bench. This mafic mineralogy is not consistent with the KREEP basalt composition of the Apennine Bench Formation as determined by the orbital geochemistry experiments (Spudis and Hawke, 1985; Clark and Hawke, 1981). Two alternatives present themselves. The small craters in the Apennine Bench Formation for which spectra have been obtained penetrated a thin (<200m) layer of KREEP basalt to excavate sub-Bench material which is more mafic than KREEP basalt. Alternatively, the spectral characteristics of the trend may be caused by variation in the amount of a glass which has a broad Fe^{2+} absorption feature, centered at 1.00μm.

Conclusions:

1) Spectra for features in the Hadley-Apennine region can be placed in two general classes.

2) Class 1 spectra are for some of the craters and massifs in the Apennine Mountains and backslope. Analyses of these spectra indicate that these terrains are composed of feldspar-rich rocks dominated by low-Ca orthopyroxene. Norites and anorthositic norites are suggested.

3) Class 2 spectra were collected for highlands features inside the Apennine ring (Imbrium interior) and for locations on the Apennine ring and on the Apennine backslope. These spectra have shallower, wider bands centered at longer wavelengths than those of Class 1. Class 2 spectra are consistent with the presence of relatively large amounts of olivine in the locations observed. However, at least two of the spectra are for units thought to contain abundant impact or volcanic glass. In addition, the orbital geochemistry data constrains the amount of mafic material in the region. Additional work is necessary to satisfactorily interpret the Class 2 spectra.

4) The material exposed in the Apennine Mts. and backslope should be dominated by Imbrium ejecta derived from several kilometers to tens of kilometers beneath the surface. The presence of two spectral classes in this region suggests that at least two distinct compositions were excavated by Imbrium basin.

5) Class 2 spectra show a compositional trend from interior to exterior of Imbrium which may be the result of decreasing abundance of olivine with distance from the basin center. The trend may be a reflection of a change in composition with depth in the Imbrium target site.

6) The spectrum of one crater on the backslope (Marco Polo F, D = 4 km) appears to be dominated by an olivine absorption.

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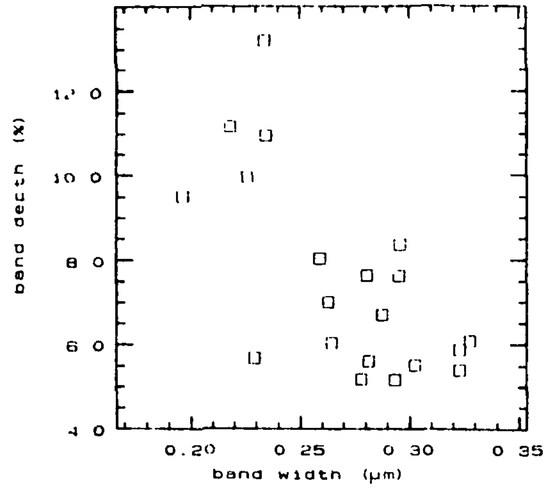

Figure 1. Scatter diagram plotting 1 μm band width versus percent band depth for spectra of Imbrium interior and exterior including the Apennine Bench Formation. Note the seperation of two spectral types. The group in the upper left of the plot is referred to as Class 1. The group in the lower right is referred to as Class 2. Class 1 occurs on the Apennine front and on the Apennine backslope. Class 2 occurs in the interior, on the front, and on the backslope.

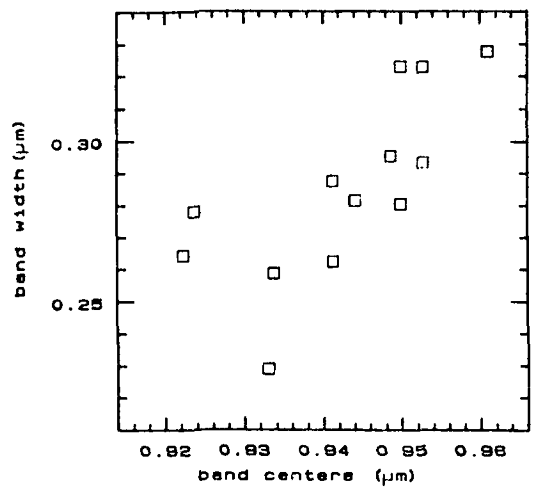

Figure 2. Scatter diagram of 1 μm band centers versus band width for Class 2 spectra. The linear trend shows a correlation with location as discussed in the text.

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SAMPLES AT THE APOLLO 15 LANDING SITE: TYPES AND DISTRIBUTION

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77 Kg of samples, consisting of more than 350 individually numbered samples of rock and regolith, were collected during the three EVA's on the Apollo 15 mission. The samples consist of rock specimens, and scooped, trenched, and cored regolith samples. Details of the collection of the samples were given in early reports [1,2,3], and an early catalog was published [4]. Those samples numbered as rocks are individually described, with analytical data summarized and complete referencing, in a new catalog [5]. A summary of data on the Apollo 15 regolith samples, not including cores, is included in the recent soil handbook (6).

The rock specimens were collected as individuals, some chipped from boulders, and as raked collections. The raked collections, with individuals ranging from about 0.5 cm to 6 cm, were taken at the edge of Hadley Rille (St. 9a) on the mare plains, and at St. George Crater (St. 2) and Spur Crater (St. 7) on the Apennine Front. Several of the samples collected and numbered as rocks are actually extremely friable regolith clods, and a few samples numbered as rocks are actually collections of small fragments of regolith breccias, regolith clods, and glassy materials which are not necessarily very closely related.

Regolith samples were collected at all sampling stations except 3, an unscheduled stop at which only one rock was picked up, and 10, at which no samples were collected. Most regolith samples were scooped, near-surface (upper few centimeters) materials, and include comprehensive samples picked up at the same localities as the raked rocks, and cover a range of environments. At St. 8 and 6, trenches were dug to about 30 cm depth, with samples taken from the top and the bottom. Regolith cores were taken at 4 locations: a deep drill at St. 8 (~2.4m; 6 x 40 cm), and drive tubes at St. 2 and 9a (~2 x ~30 cm) and St. 6 (~30 cm). The St. 6 core has not yet been opened. Three regolith samples were placed in Special Environment Sample Containers (SESC), which had pressure seals to preserve the extremely low pressures of the Moon. These SESC's were filled at St. 6 (15012), the LM (15013), and St. 8 (15014). 15013 failed to seal properly. 15012 and 15014 are trench bottom samples, but 15014 has never been allocated, under the mistaken impression that it is the LM exhaust gas sample (location correctly identified in refs. [2,4]; incorrectly in [1,3,6]).

ROCK TYPES

Apollo 15 lithologies comprise several major types, including mare basalts, regolith breccias, green glass clods, glasses and agglutinitic breccias, anorthosites, KREEP basalts, and highland impact melts. Varied volcanic and impact glasses are constituents of breccias, as are mare and KREEP basalt fragments. Apart from the anorthosites, other pristine igneous highlands lithologies are present as clasts in breccias, and include norites, troctolites, and spinel-troctolites.

Mare Basalts:

As expected, mare basalts were collected on the mare plains, but a few were also collected on the Apennine Front (Figs. 1a, 6). They were sampled almost in situ at the rille edge (St. 9a), and the only observation of in situ bedrock ever made on the surface of the Moon were those on the Hadley Rille wall. The mare basalts are low-TiO_2 varieties generally similar to Apollo 12 olivine- and pyroxene-normative basalts, but chemically distinct from them. The Apollo 15 mare basalts form two main distinct groups: one is olivine-normative, the other quartz-normative. Within analytical error they have identical ages (Rb-Sr ages ~ 3.35 b.y. [8]; $\lambda = 1.39 \times 10^{-11} yr^{-1}$) and initial Sr-isotopic ratios (~0.69930, adjusted to C. I. T.). The rare earth element patterns are the same although the quartz-normative basalts have slightly higher rare earth element abundances (Fig. 2). However, the two groups cannot be simply related by fractional crystallization of a common parent or partial melting of a common source (e.g., [8]).

Olivine-normative mare basalts:

These basalts range from fine-grained olivine-porphyritic to coarser-grained (pyroxenes up to about 3 mm) subophitic varieties. Many are vesicular. Olivine, generally less than 10%, is subhedral. The pyroxenes (60-70%) have pigeonite cores and generally zone to ferroaugite and pyroxferroite. Plagioclase (20-30%) is lathy in finer-grained varieties and poikilitic in coarser-grained varieties. The chemical variation and textural evidence suggests that the group forms a series related by a small amount of olivine fractionation, but whether the more Mg-varieties are cumulate or equivalent to parental magma composition has not yet been established. The olivine-normative mare basalts are richer in iron, titanium, and magnesium, and lower in silicon and most LIL elements than the quartz-normative mare basalts. Dowty et al [9]

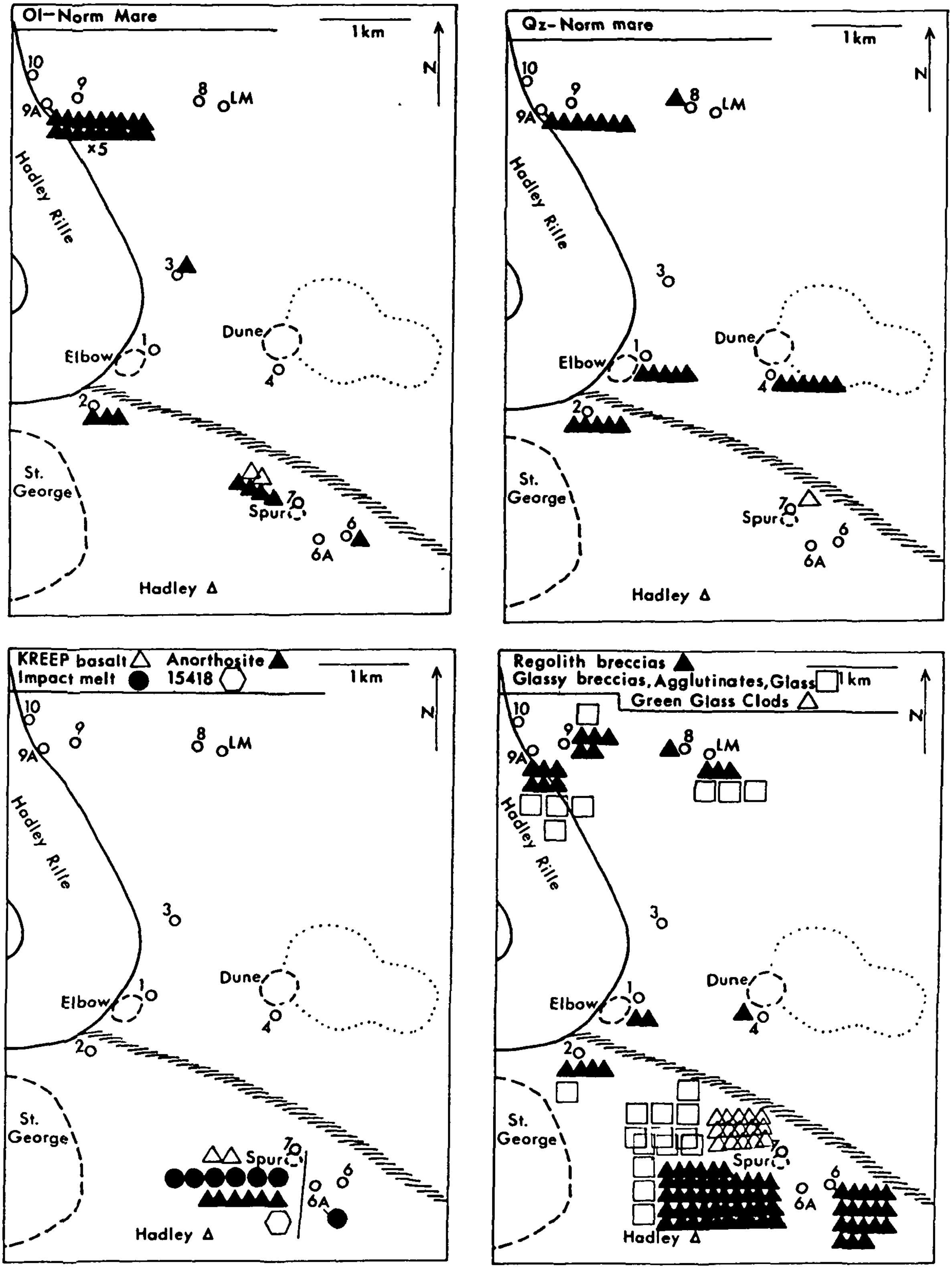

Figure 1. Distribution of rock types around the Apollo 15 landing site. (1a) open triangles are "feldspathic peridite". On (16), open triangle is "feldspathic microgabbro". Others as keyed. Numbers are stations.

divided the group into finer-grained olivine-phyric basalts and coarser olivine "microgabbros" (which they also divided into two subgroups), but at present there is little chemical evidence suggestive of their being from different flows.

The olivine-normative basalts dominate the rake sample collected at St. 9a, and a few were individually picked up at that location. They were also collected as a few small fragments on the Apennine Front (Fig. 1a), and the single fragment collected at St. 3 because of its conspicuous vesicular nature is an olivine-normative basalt (15016). Two samples (15385, 15387) from Spur Crater are "feldspathic peridotite" [9], similar to the olivine microgabbros, but even coarser and with more olivine (~30%). Data for 15385 suggest they are closely related to the olivine-normative basalts: similar rare earth pattern [8, 10], age [11], and a Sr-isotopic measurement compatible with the other mare basalts [12]. One sample from the Apennine Front, 15296, is a shock-melted equivalent of an olivine-normative basalt.

Quartz-normative mare basalts:

These basalts are porphyritic with pigeonite phenocrysts in all samples. They range from vitrophyric with tiny phenocrysts to coarse-grained groundmasses containing phenocrysts up to several centimeters long [13]. Tridymite is a conspicuous late-stage mineral in the coarser samples. Olivine is only rarely present. The chemical variation of the basalts is small and consistent with a small amount of pigeonite fractionation. The glassy varieties (15597) have been taken to represent erupted liquid compositions and have been the subject of many crystallization experiments, particularly to determine the natural cooling rates and environments of samples (e.g. [13, 14]). The composition is multiply saturated within lunar crustal pressures, suggesting that it is not a primary magma [15].

The quartz-normative basalts are ubiquitous (Fig. 1b), but they were not found as individual rocks in the Spur Crater region. At St. 9 they are poorly represented in the rake sample, but were collected from boulders at a lower stratigraphic level. At Spur Crater, a "feldspathic microgabbro" (15388), which lacks olivine and has coarsely intergrown pigeonite and feldspar, is a mare basalt which might be a member of the quartz-normative mare basalt group, but present information is inadequate for positive identification.

KREEP basalts:

Only two samples of volcanic KREEP basalt are present among individually numbered samples (15382, 15386, from Spur Crater; Fig. 1c) but they are prominent clasts in boulder samples 15405 and 15205, and occur commonly among coarser fines samples, in regolith breccias, and as a chemical component of most regoliths. The basalts are subophitic to intersertal to variolitic, and range from rather coarse-grained to aphanitic. They contain roughly cotectic proportions of plagioclase and low-Ca pyroxene, and a glassy mesostasis. They have the highest rare earths of Apollo 15 materials (Fig. 2), except for fragments of "quartz-monzodiorite", found only with KREEP basalt fragments in sample 15405

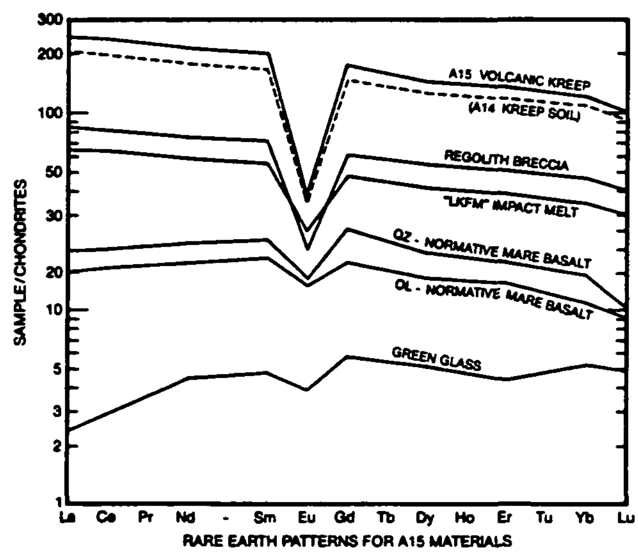

Figure 2. Examples of rare earth patterns for Apollo 15 rock types. All data from [12].

[16]. The KREEP basalts have an age indistinguishable from that of Imbrium (~3.85 b.y.; several sources), and are recognized as volcanic by their negligible siderophile concentrations, their clast-free, homogeneous textures, and their major and trace-element chemistry. Although they were originally believed to have been brought to the site in rays from a major impact (Aristillus or Autolycus) they are equally likely to be of more immediate origin, i.e., the Apennine Bench which may underlie the site [17]. The quartz-monzodiorite clasts have yielded zircon ages considerably older i.e., 4.35 b.y. [18].

Highland Impact melts:

Crystalline, clast-bearing impact melt samples of highland origin are not common, even on the Apennine Front (Fig. 1c). Two aphanitic samples, 15445 and 15455 (St. 7) are similar and appear to be representative of a nearby 1-m boulder. They contain clasts of pristine igneous lithologies including norite, troctolite, and spinel troctolite, to the exclusion of shallow-level-derived materials, and have been proposed to be Imbrium impact melts [19, 20]. They have a low-K Fra Mauro composition ("LKFM" on Fig. 2), slightly poorer in rare-earths and richer in magnesium than Apollo 17 impact melts proposed to be Serenitatis melt. One of the pristine clasts, the norite in 15455, yielded a Rb-Sr isochron age of 4.52 b.y. [21]. Other impact melt samples are generally much smaller and little work has been done on them; my own work (accompanying abstract) suggests a wide range in compositions ranging up to that of the 15405 matrix which is similar to Apollo 15 volcanic KREEP. Some may be Serenitatis-like. One has a flat rare-earth pattern at about 10 x chondrites with a positive Eu anomaly. These melts suggest that the Apennine Front is made up of material from a variety of sources. A few highlands impact melts have been found as clasts in regolith breccias.

Anorthosites and 15418:

A few small fragments, all from Spur Crater (Fig. 1c), are pristine anorthosites, all belonging to the ferroan anorthosite group. The best known is 15415 "Genesis Rock", which was sitting on a small regolith pedestal. This rock is not a typical ferroan anorthosite in that it contains high-Ca pyroxenes as its dominant mafic mineral [22, 23] rather than low-Ca pyroxene or olivine. It also had a complex history of fragmentation and metamorphism, resulting in a low Ar-Ar age of ~4.1 b.y. [24, 25]. The other fragments are less well-studied. 15418, also from Spur Crater, is unique. It is variedly shock-melted, appears to have been essentially a granulitic rock prior to melting, and has an anorthositic norite bulk composition (about 26% Al_2O_3) [26]. Because of its deformation, little is yet known about the ultimate origin of this rock. Anorthosites and anorthositic norites are not as common a component in the Apennine Front as they are at the Apollo 16 landing site.

Regolith breccias, glassy breccias, agglutinates, and glass:

Regolith breccias were collected at all stations (except 3 and 10, Fig. 1d), and range from extremely friable clods, barely deserving designation as rocks, to coherent samples. They were originally subdivided on whether or not they contained mare basalt clasts [4] but that distinction appears to be unreal: virtually all contain a mare basalt component. Most regolith breccias contain rather fine-grained clasts (~2 mm), with only a few containing several conspicuous large fragments (e.g., 15205, 15459). Most contain at least some KREEP basalt fragments and green glass balls or other such debris. Agglutinates are generally uncommon. The chemistry of most regolith breccias is similar to the local soil, indicating a local derivation (Korotev, this volume) but several are conspicuously different, generally in that they contain greater amounts of incompatible elements. A smaller proportion of breccias are glassy or agglutinitic, and evidently of regolith origin. A few samples are glasses, ellipsoids or shells. Many rocks, including mare basalts and regolith breccias, have glass coats partially draping them. Little work has been done on such materials.

Green Glass Clods:

Two green clods were specifically collected at Spur Crater. These disintegrated into several pieces which were numbered 15425, 15426, and 15427, each consisting of several pieces, and none specifically the original two pieces collected. These clods vary from very pure green glass chunks (e.g., 15426,26) to more typical mixed regolith. Several other green clods were sorted from the Spur Crater rake samples, and such were even found in the drill core at St. 2. The green glasses which constitute the clods are volcanic ultramafic glasses, distinct in composition and parentage from the crystalline basalts at the site (see Delano, this volume). Those richest in green glass appear to be pristine, unmixed deposits. The green glasses are not all identical, several slightly but distinctly different groups having been recognized [27].

REGOLITH

The regolith has been the subject of intensive petrographic and chemical studies, particularly in deciphering the nature of its components (see Basu, this volume; Korotev, this volume). The chemistry (partially shown on Fig. 3) has geographical variations reflecting the dominance of mare basalts on the plain and especially at the rille edge (high Sc, Ti), and "LKFM" (low Sc, low Ti) and green glass (high Sc, low Ti) on the Apennine Front. KREEP basalts contribute much of the rare earths, and appear to be most common around the LM and on parts of the Front. The drive tube and drill core sections at least at the LM and St. 2 are fairly homogeneous in both chemistry and mode (e.g.[28]). Apart from the lithologies briefly described above, the regolith samples also contain small amounts of yellow, red, and orange volcanic glasses (see Delano, this volume). Impact glasses, including a distinctive yellow variety, are common regolith constituents.

FINALE

The Apollo 15 samples are consistent with an Apennine Front composed of feldspathic and "LKFM" (~basaltic) breccias, with ages of 3.9 b.y. and older, and including basin-derived materials. However, these are poorly represented in samples. In down faulted or depressed regions they were overlain by volcanic KREEP flows analytically indistinguishable in age from the Imbrium event. Exactly where these flows were emplaced at the site cannot be observed but must be inferred. Immediately prior to the emplacement of the mare basalt lavas at ~3.3 b.y. ago, the area, at least the Apennine Front, was partly blanketed with pyroclastic, ultramafic green glasses. The olivine-normative mare basalts appear to have been emplaced at least locally above the quartz-normative mare basalt, as a thin flow(s). At least the latest flows would seem to have been related to Hadley Rille, or the rille cut into them. Subsequently, the evolution of the site has been once again exogenic, with the development of regolith and glassy breccias. A few samples (e.g. boulders parental to 15205, 15405) are exotic but contain local samples types and may not have travelled very far.

Whether or not one believes we actually sampled a fairly complete sequence depends on ones concept of KREEP basalt; if it is local and underlies the mare basalts then we did. If it is exotic, then we may not have. Petrographic and chemical evidence suggests that there is so much KREEP it must be local. There is an abundance of KREEP on the LM "ridge"; possibly the unfortunately unvisited North Complex is a KREEP volcanic center or at least exposure.

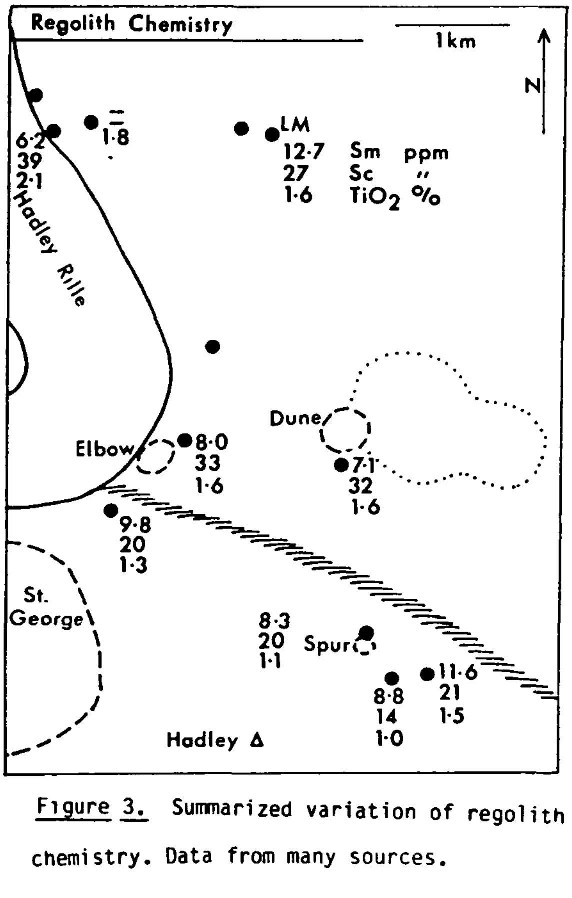

Figure 3. Summarized variation of regolith chemistry. Data from many sources.

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Apollo 15 Mare Basalts: A Diverse Suite or Two Distinct Groups?

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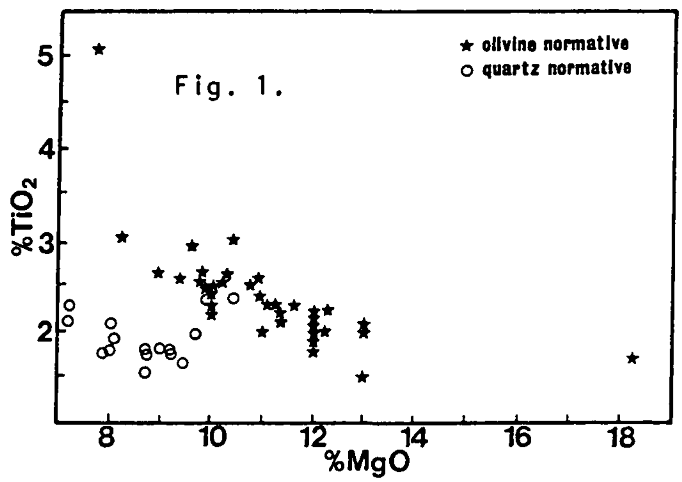
Apollo 15 mare basalts comprise a suite of lunar samples which fall neatly into two groups - olivine-normative and quartz-normative basalts. The two groups were recognized early in the study of Apollo 15 samples on the basis of major- and trace-element chemistry (e.g.,1-5) and display distinctly different pyroxene compositional trends (6). Previous work has interpreted the olivine-normative samples to be closely related members of a group whose major-element chemistry is controlled by olivine fractionation. Similarly, the quartz-normative samples have been interpreted also to be closely related but controlled by pigeonite fractionation (3,4,7). However, an experimental study of the quartz-normative samples, indicates that fractional crystallization is unlikely to have played an important role in their evolution (8). Furthermore, there have been some suggestions, based on trace element modelling, that within one or both groups there exist subgroups, representing magmas derived from different source regions (4,5,9). Thus, an understanding of the petrogenesis of the Apollo 15 mare basalts is far from complete.

Most of the previous work on the Apollo 15 mare basalts has involved restricted sets of samples for which major- and/or trace-element data have been presented, with few attempts to synthesize the two types of geochemical data. The result is a data base for these basalts composed of diverse sets of oxide and element analyses produced by a number of geochemical laboratories. In order to evaluate possible intra-group relationships, we have compiled from the literature geochemical data for 60 Apollo 15 mare basalts for which there are both major-element and trace-element data, particularly the REE. Averaged data are used for those samples on which there are multiple analyses, as suggested by (10). The classification of samples as either olivine or quartz normative, as used here, was compiled from the literature.

The separation of the two groups on a chemical basis is demonstrated well in Figure 1. Except for two instances, the groups have distinct concentrations of TiO2 and MgO. The olivine-normative and quartz-normative groups range from 1.5 to 5.1 wt% and 1.57 to 2.39 wt% TiO2, respectively, and 7.7 to 18.2 wt% and 7.1 to 10.4 wt% MgO, respectively. The two trends defined on Figures 1 for the olivine-normative and quartz-normative samples have been regarded as due to olivine and pigeonite fractionation, respectively (1,4). However, fractionation of olivine and pigeonite within sets of closely related samples should also produce clear trends on variation diagrams of FeO vs. MgO, such as Figure 2. The two arrows on this figure denote the trends expected for fractionation of olivine (Fo70) and pigeonite (Wo5 En70Fs25). No trend is discernible for the olivine-normative samples, and if a trend does exist within the quartz-normative samples, it is weak at best. This suggests that the samples within each group either are not closely related, or that the fractionation of some other phase(s) (e.g., ilmenite) is important. Thus we consider major-element character-



istics to be ambiguous. Perhaps the trace element data will permit a more meaningful interpretation.

Figure 3 is a variation diagram of La vs. MgO. The effects of olivine or pigeonite fractionation should be evident on such a diagram since their removal will cause a decrease in MgO and an increase in La, as denoted by the arrow. (However, we note that fractional crystallization is not the only mechanism that will produce correlations on this diagram.) The quartz-normative samples do not display a clear trend on Figure 3, tending to confirm the proposal that this group may represent a number of unrelated flow units. The data points for the olivine-normative samples appear to form two trends. One trend, made up of the "main group" of samples, has relatively high La. The other trend is characterized by lower La. This group is denoted by different symbols on Fig. 3 to facilitate their recognition on following diagrams.

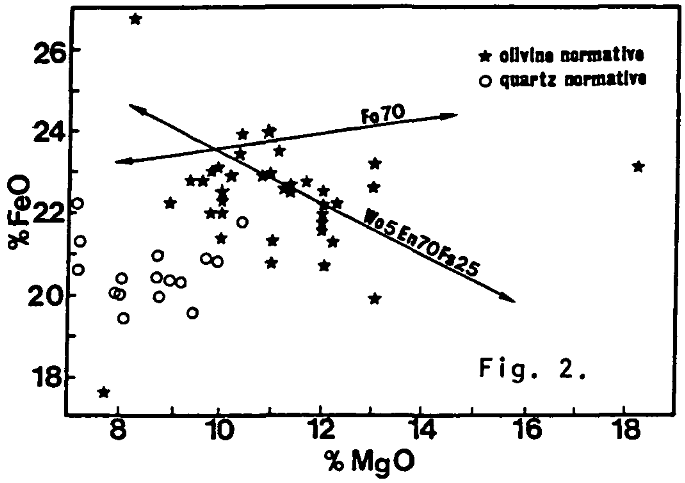


Fig. 2.

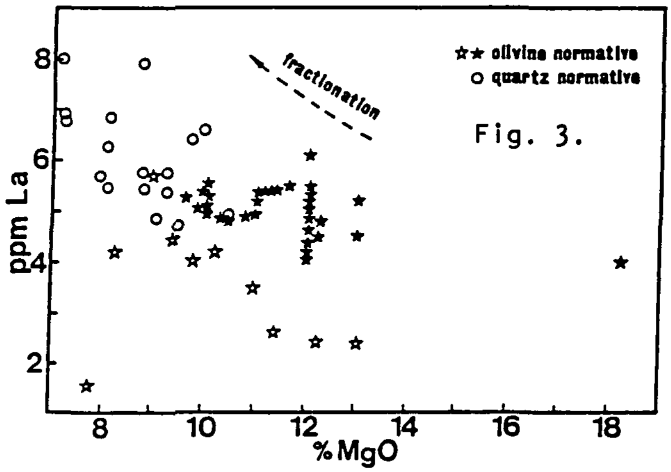


Fig. 3.

Figures 4 and 5 are plots of REE ratios against La. The utility of such plots is that the La concentration serves as an index of fractionation or partial melting, since it is not a compatible element in any likely fractionating (olivine, pigeonite) or residual (olivine, opx) phases. The element ratios, on the other hand, should remain unaffected by either process unless plagioclase or augite are involved, neither of which are primary liquidus phases. Some scatter is expected in the ratios plotted on Figures 4 and 5 due to analytical uncertainty. The horizontal lines on these two figures denote the maximum ranges of the average ratios of the olivine-normative samples if the uncertainty in the elements making up the ratios is 5%. A significant number of data points fall outside the ranges of uncertainty on both diagrams. Furthermore, the two groups tentatively identified in the olivine-normative samples tend to cluster together. There are trends in the data on Figures 4 and 5 showing increasing La/Sm and Sm/Eu ratios with increasing La concentrations. These trends might signifiy a series of unrelated flows, or they can be due to varying amounts of resid-

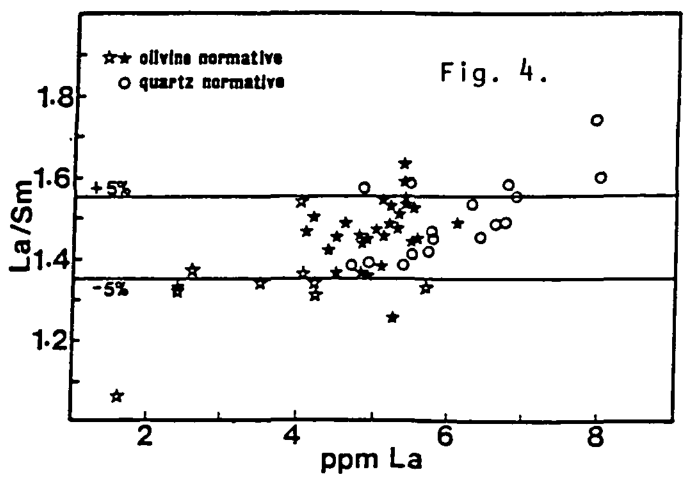


Fig. 4.

ual liquid in samples from the same flow (9,11). As discussed above, fractional crystallization and partial melting of a homogeneous source region are unlikely mechanisms to produce the patterns observed on Figures 4 and 5. Assimilation is equally unlikely. Increasing degrees of assimilation of ferroan anorthosite would decrease the concentrations of La while increasing the La/Sm ratio. Increasing degrees of assimilation of granite would produce a trend of decreasing La/Sm with increasing La. Increasing degrees of assimilation of KREEP should have no effect on the La/Sm ratio. Finally, assimilation of alkali anorthosite would produce the trend seen on Figure 4, but rather than increasing the Sm/Eu ratio with increasing La concentrations (Figure 5), this mechanism should decrease that ratio.

In conclusion, our analysis of major and trace elements in the expanded data set of Apollo 15 mare basalts is consistent with the existence of two broad categories of basalt: olivine normative and quartz normative. We recognize that the quartz-normative samples may represent a group of unrelated flows. Furthermore, olivine fractionation alone cannot account for the geochemical characteristics of the olivine-normative samples. Models have been developed which explain some of the trace-element characteristics of these samples as being consistent with their derivation from a single flow (e.g., 9,11). However, our treatment of the expanded data set indicates that they may have been derived from source regions with different chemical characteristics. The possibility of a large number of basalt types suggests a heterogeneous mantle beneath Apollo 15.

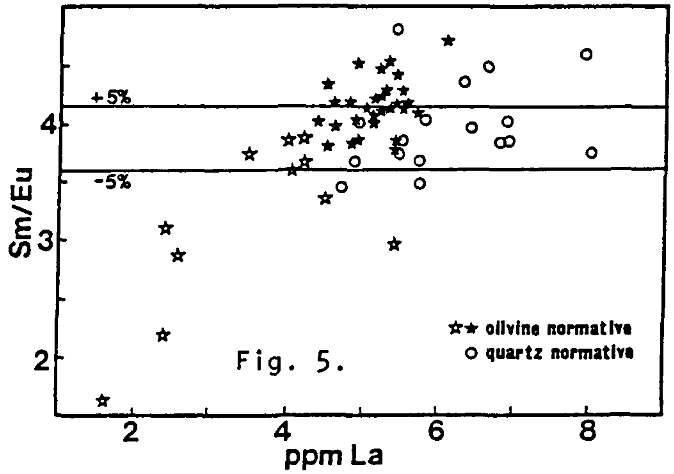


Fig. 5.

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EXOTIC COMPONENTS AT APOLLO 15: A RELOOK AT SECONDARY CRATERING.

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Crater rays extending more than 90° across the lunar surface demonstrated the ballistic transport of material at high velocities in pre-Apollo studies (e.g., 1, 2, 3, 4). Intuitive analogy suggested a simple model of transport and deposition: a concept implicity or explicity used by various researchers. Early studies by Shoemaker (1) and Baldwin (2), however, recognized the implications of high-velocity ejecta in the production of secondary craters and crater rays. For example, Baldwin suggested that rays are produced by downrange ejecta from both secondary cratering and the effects of impacting "rock flour" produced by high-velocity jets. The significance of secondary ejecta on the emplacement of ejecta deposits was not fully appreciated, however, until it became important to understand the evolution of the lunar regolith and the provenance of returned samples. This contribution briefly summarizes two contrasting (but necessarily conflicting) views of ejecta emplacement in order to provide a context for the provenance of exotic materials at Apollo 15.

The post-Apollo view of impact ejecta emplacement has been largely based on the studies by Oberbeck (5, 6), Oberbeck and Morrison (7), Oberbeck et al. (8), and Hörz et al. (9). These studies emphasized the effect of relatively large impact velocities (> 100 m/s) around large lunar craters. Laboratory experiments and energy-scaling relations established that an impact at such velocities excavates more than 200 times the projectile mass, thereby significantly diluting foreign material at any given location. In order to extend such laboratory analysis to the Moon, cratering effeciencies (displaced-target-mass/ projectile-mass) were calculated (8) by: (a) measuring the diameter of Copernicus secondaries; (b) assuming a diameter (D) to depth (d) ratio of 4 in order to estimate crater volume; and (c) using energy-scaling relations for terrestrial explosion crater to derive the cratering efficiency. It should be noted, however, that the energy-scaling relations derived from explosion cratering closely matched the smaller scale laboratory impact experiments in granular targets (10). As an example, the continuous ejecta deposits around a 25 km-diameter crater should contain 24-34% material locally excavated by secondary cratering (11), whereas continuous ejecta deposits around a 100 km diameter crater should contain nearly 50% locally derived debris (8). At greater distances, secondary craters and crater rays will be dominated (> 80%) by locally excavated ejecta (8). Thus the probability of finding a foreign component at large distances from a primary impact should be small. In a recent review, Hörz et al. (12) have been relatively successful in applying the model to the emplacement of the continuous ejecta deposits around the Ries Crater, Germany. Similarly, telescopic reflectance data of Copernicus continuous ejecta and rays reveal consistent results for far-rim ray (> 3 crater radii, 3R) but indicate an overestimate of the local component in the near-rim continuous deposits (13).

A different view of ejecta emplacement has evolved over the last several years (14, 15) by reconsidering several key elements of the cratering process: (a) the physical state of the ejecta; (b) the relative dimensions of the ejecta curtain and contained ejecta; (c) the process of low-velocity impact cratering; and (d) the dispersal of projectile material. In this revised model, a distinction is made between the relative thickness (referenced to crater dimensions) and absolute thickness of the ejecta curtain. Although the relative ejecta curtain thickness may be only 5-10% of the crater diameter, the absolute thickness for a 100 km-diameter will be substantial, i.e., of the order of 5-10 km. The curtain is reasonably assumed to be composed of a wide range in fragment sizes with the greatest fraction occurring at the smaller sizes. This assumption is largely based on the increased weakness of naturally occurring material with increasing size and the increased average shock pressures associated with increased ballistic range (16, 17). The impact of such a debris curtain occurs over significant time: 25 seconds at 0.3R from a Copernicus-size impact. Consequently, secondary cratering near the rim (< 2R) of a large crater may be better viewed as the result of a cluster of debris rather than a few large blocks. Farther from the rim (2R-5R), secondary craters result from either more dispersed debris clusters or weak breccias, and at large distances (> 5R) secondaries largely result from either individual, weak fragments or loosely clustered debris. With this perspective, cratering by clusters of projectiles or weak fragments need to be considered.

Laboratory experiments were designed to examine the effect of clustered impacts on cratering efficiency, crater profile, crater morphology, and projectile dispersal. A detailed account is given in (15). Clustered impacts were found to reduce cratering efficiency by a factor of 5-10 for the same velocity and mass. This reduction depends on cluster size, impact angle, and target strength; cluster mass densities from 0.6 to 0.013 g/cm^3 had little effect if a scaling relation including cluster radius is used (18). Targets with greater shear strength (compacted pumice) exhibited a greater reduction in cratering efficiency. In addition, clustered impacts at oblique angles (< 60^o from the surface) produced shallower craters with morphologies strikingly similar to lunar secondaries: floor mound, ridge-like rim, extensive herringbone structure, and a downrange ejecta fan. The distribution of post-impact projectile material was found to be concentrated on the floor for vertical impacts and strewn downrange for oblique impacts.

More recent studies have focused on the effects of projectiles deformed at impact and reveal a significant change in the scaling relations relative to impacts resulting in no projectile deformation (19, 20). When scaled to dimensions appropriate to large lunar secondaries (> 1 km), cratering efficiency is again reduced nearly a factor of 10. This process can be appreciated intuitively by the contrast in results between impacting a billiard ball and impacting a snowball onto sand.

When applied to lunar secondary cratering, the model predicts that the near-rim (excavation rim) ejecta deposits can be composed of more than 80-90% primary material, even at basin sizes. At greater distances, the proportion of local material increases. The downrange ricochet and areal dispersal of primary ejecta, however, is much more important than mixing ratios derived from cratering efficiencies alone. The primary ejecta component is least likely to be found uprange and in the near-rim ejecta deposits; it is most likely to be found on the floor/wall and widely dispersed downrange. Thus it is possible to find local concentrations of primary ejecta well below, as well as above, values previously predicted. At Apollo 15 the most likely contribution to an exotic component would be the following primary craters (referenced to the percentage of total amount from craters farther than 20 km): Autolycus (32%), Aristillus (25%), and Hadley (17%). All other craters within 800 km distance would contribute, on the average, less than 7%. The probability of finding such components would be lessened considerably by the process of ricochet/dispersal downrange, tertiary cratering, and subsequent local vertical mixing.

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APOLLO 15 REGOLITH BRECCIAS AND SOILS: COMPARATIVE PETROLOGY AND CHEMISTRY; S.B. Simon[1], J.J. Papike[1], and J.C. Laul[2], [1]Institute for the Study of Mineral Deposits, S.D. School of Mines and Technology, Rapid City, SD 57701-3995, [2]Chemical Technology Dept., Battelle, Richland, WA 99352

An important part of understanding the geology of a lunar landing site is understanding the evolution of the regolith at the site. Soils and regolith breccias contain clues to the geologic processes that contributed to the evolution of the local regolith over time. Thus we have conducted a study of a suite of ten regolith breccias from the Apollo 15 site and compared the results to previous studies on A-15 soils in order to learn more about the regolith evolution at that site.

One interesting feature of the A-15 regolith breccias is that they tend to be chemically similar to the soil at the station where they were collected [1], a strong indication of local formation of the breccias. Therefore the modal petrology of the breccias should be extremely useful in comparing the breccias and soils, and the breccia modal petrology is summarized in Fig. 1. The breccias average 52 vol.% <20 μm material and pore space; the 1000-20 μm fraction is summarized in Fig. 1, which shows the low fused soil contents which are typical of regolith breccias [e.g. 2, 3]. Ferromagnetic resonance maturity indices (I_s/FeO) measured by McKay et al. [3] on twenty-eight A-15 regolith breccias showed that half of the samples were immature, and only two were mature. Our observations agree with their results, in most cases. For example, we found the highest agglutinate content in 15086, and it has an I_s/FeO value in the 18-27 range (based on a range of assumed FeO contents) [3]. 15205 and 15015, with very low agglutinate contents, have I_s/FeO values of 0 and 3, respectively. Values that do not agree can be attributed to heterogeneity of the samples. Mineral clast contents are fairly high in the breccias, but glass contents vary. The averages of the breccia and soil modal data are illustrated in Fig. 2, which shows that overall the two sample suites are very similar except for the difference in fused soil content. This is a strong indication that the breccias were formed from the local soils when they were less mature.

Since the difference in maturities between breccias and soils makes detailed petrologic comparison of the two difficult, we present fused soil-free modes in Fig. 3. With this figure we compare breccias with soil from the same station. Station 2 soil has more plagioclase and less mare lithics than station 2 breccia 15205. The station 6 breccias are similar to each other and to soil 15271,

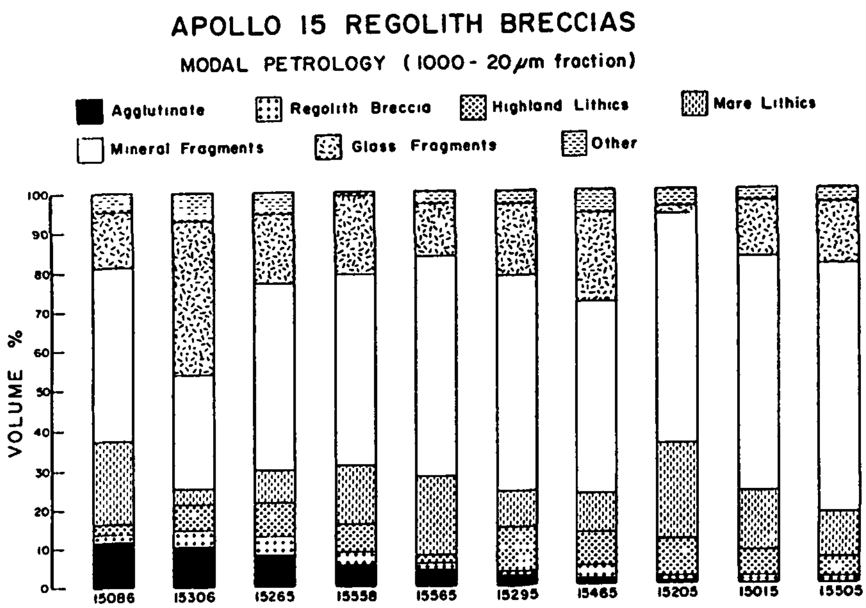

Fig. 1

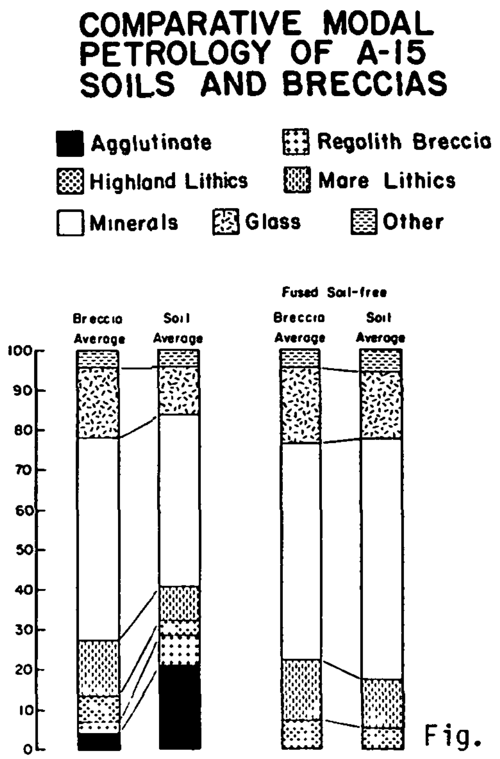

Fig. 2

though the breccias again contain more mare basalt fragments. Conversely, the Rille (9A) and LM breccias have more highland lithics and plagioclase than the corresponding soils. Walker and Papike [4] found that station 9A drive tube 15010/15011 was depleted in highland materials relative to the deep drill core (LM area). They suggested that at station 9A regolith tends to be lost into Hadley Rille. Thus this regolith has become more mare-rich and highland-poor as the lost soil is replaced by new regolith derived from the underlying basalt. Regolith at the edge of the Rille remains thin and rich in mare basalt fragments. Regolith breccias, however, would not be affected by this erosional process, and now contain more highland lithics, that were added at an earlier time, than the present-day local soil. In contrast, soils at Front stations 2 and 6 have probably become more highland-rich with time, as material slumped down the side of Hadley Delta.

The chemical data provide further evidence of local formation, even on a station-by-station scale. Fig. 4 shows the correlation of two elements in breccias and soils from the same stations. The Apennine Front soils and breccias have higher Al_2O_3 and lower FeO than samples from the mare stations. The uniformity of the chondrite-normalized rare earth element (REE) patterns (Fig. 5), with similar Eu anomalies and upward Th inflections, indicates that the breccias all contain the same KREEP component, in varying amounts. The pattern of station 6 breccia 15295 is almost identical to that of station 6 soil 15271 [5]. The overall similarity between the soils and breccias is summarized by a comparison of the chemical mixing models (Fig. 6). We used the same components as Walker and Papike [6] used for A-15 soils. Fig. 6 shows higher mare components at the Rille stations (1, 9, 9A) and lower mare components at the Front stations (2, 6, 7). The station 2 breccia (15205) is somewhat anomalous, however, having a very large (73%) med-K KREEP component.

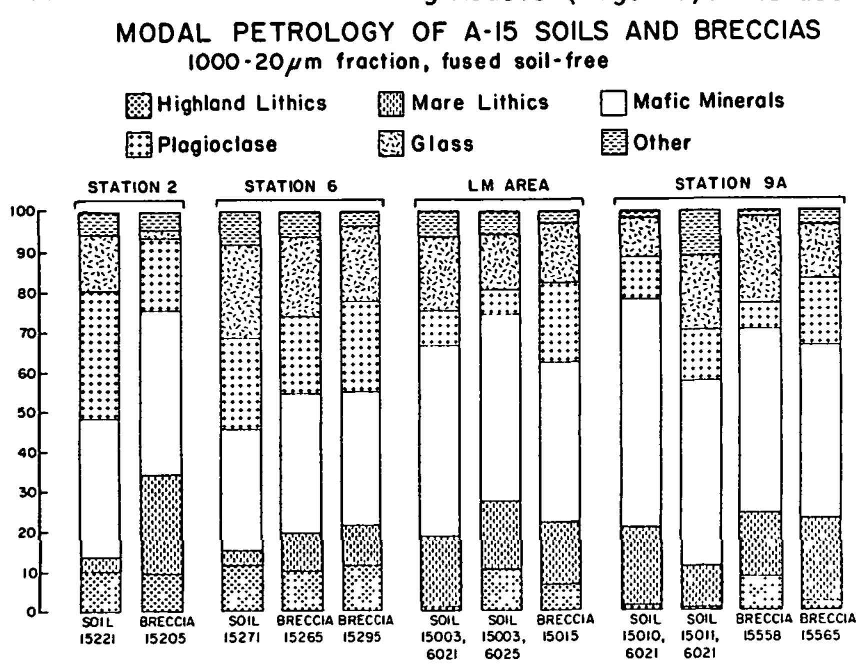

Fig. 3

We conclude that since the ten breccias studied are of local origin, they are useful as recorders of regolith evolution at the site. Our data indicate that, since the formation of the breccias, the regolith at the edge of Hadley Rille has become more basalt-rich, whereas the soils at the base of Hadley Delta have gained highland lithic fragments. We looked for, but did not find, evidence for addition of other components (e.g. KREEP, green glass) to the soils after the breccias became closed systems.

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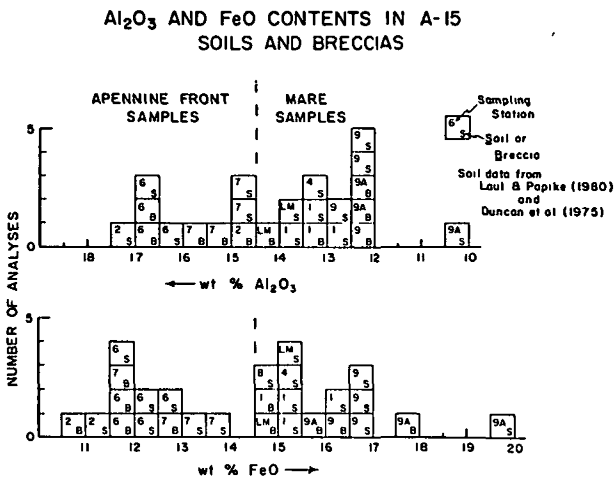

Fig. 4

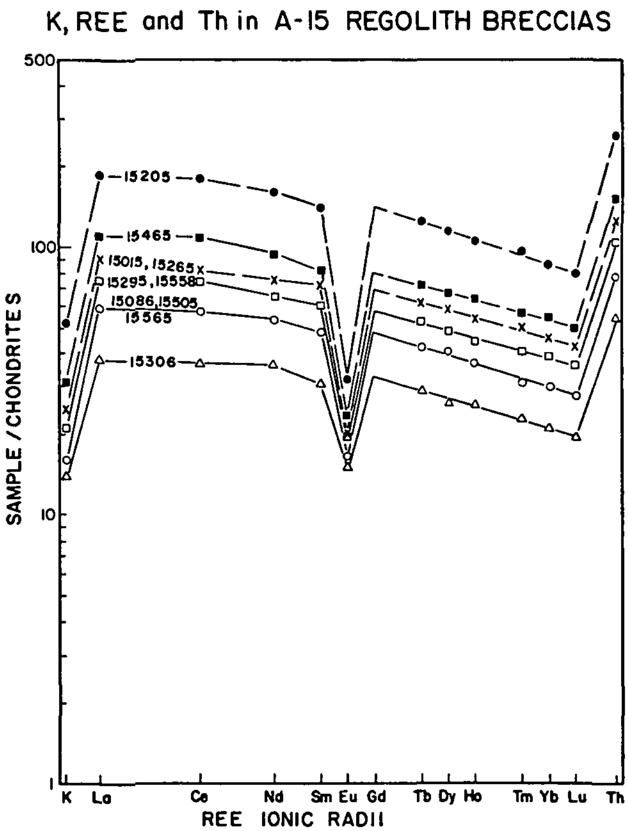

Fig. 5

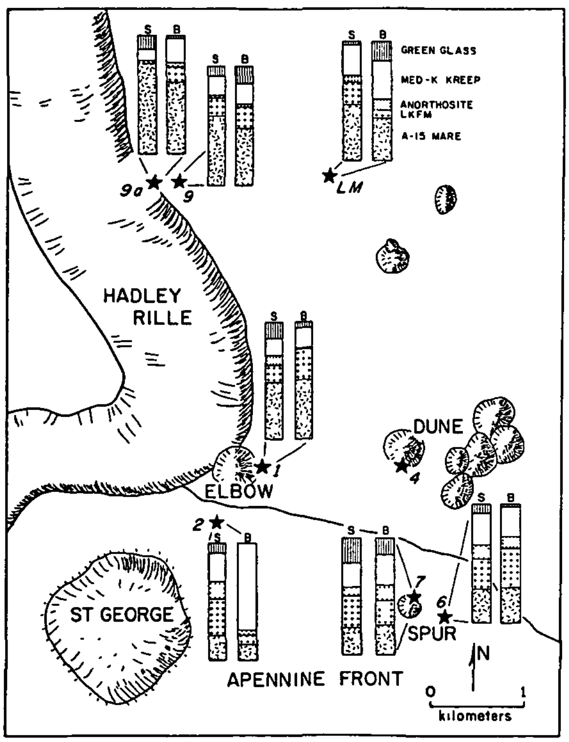

Fig. 6 Schematic map of A-15 site.

THE MATERIALS AND FORMATION OF THE IMBRIUM BASIN. Paul D. Spudis, U.S. Geological Survey, Flagstaff, AZ 86001

The Imbrium Basin, a conspicuous feature of the lunar nearside, has been the focus of intensive investigation by lunar geologists ever since G.K. Gilbert recognized its impact origin in 1893. The deposits around the basin form a widespread stratigraphic datum relative to which other geological units may be dated [1]. The Imbrium impact is considered such a key event in lunar history that Apollo missions 14 and 15 were sent to landing sites chosen specifically to enable us to address problems of Imbrium Basin geology.

More significantly, as a relatively well-preserved multi-ring basin, Imbrium provides an important target of geologic investigation of the processes involved in lunar basin formation and evolution. The purpose of this paper is to review what we know about the deposits of the Imbrium Basin, and what we can infer about the formational mechanics of lunar basins in general and about the relations of materials collected at the highlands adjacent to the Apollo 15 landing site to Imbrium and other basins.

Stratigraphy and Morphology of the Imbrium Basin. Although Imbrium is significantly modified by mare flooding, parts of the basin interior have not been flooded, and its associated deposits outside the basin are well-preserved in many regions. Thus, a reasonably complete reconstruction of Imbrium Basin stratigraphy and morphology is possible (Fig. 1), if we keep in mind that several key relations among basin units may be obscured by post-basin geologic units.

Imbrium Basin deposits are subdivided into several formal and informal rock-stratigraphic units that compose the Imbrium Group (provisionally named here; see also [2]). The informally named massif material is exposed as kipukas protruding through mare basalts of the basin interior and as segments forming the main basin rim. Massifs consist of large mountains that are, in some cases, transitional with large hummocks included within other rock units. At Imbrium, no unit of the basin interior is recognized that corresponds to the Orientale Basin's Maunder Formation (basin impact melt [2,3]). Although it has been proposed that the planar Apennine Bench Formation might be this basin impact melt unit [2,4], geologic studies (summarized in [5]) have shown that this material probably consists of post-basin volcanic KREEP basalts. Isolated pools of cracked material along the base of the Apennine scarp may be Imbrium impact-melt deposits [4,6].

Continuous basin deposits are subdivided on the basis of morphology. The informally named Apenninus material [7] consists of coarsely textured deposits that occur only in the southern Apennines (Fig. 1). This material appears to be about 1-2 km thick near the Apennine crest [8,9]; its concentric texture in this area suggests that post-basin slumping may be partly responsible for its morphology [9]. Apenninus material appears to be gradational with the more widely distributed Fra Mauro Formation [7,10]. This unit varies in morphology, ranging from strongly lineated textures (radial to Imbrium) east of Mare Vaporum to a more nondescript, hummocky texture elsewhere (e.g., near the Apollo 14 landing site; [10]). The Fra Mauro Fm. appears to be about 1 km thick in the Apennine backslope and thins to a feather edge south of Parry, where it is intercalated with smooth plains material. There is little evidence for flow lobes or melt ponds associated with the Fra Mauro Fm., but it commonly appears to have overridden previously formed secondary impact craters and chains [10,11], suggesting that some type of ground flow was important in its final emplacement.

Another extensive Imbrium stratigraphic unit (Fig. 1) is the knobby-textured Alpes Formation [12]. The knobs average about 10 km in size and occur within undulating terra plains. The Alpes Fm. extends locally as far as 800 km from the basin rim (discussed below); such a distribution is consistent with an origin by basin ejecta deposition. On the basis of morphologic similarity, some workers have equated the Imbrium Alpes Fm. with the Orientale Basin's Montes Rook Fm. [2,3]. However, the distribution of the Alpes Fm. is much more extensive than the Montes Rook Fm., which is almost completely confined within the topographic basin (local occurrence beyond the Cordillera rim rarely exceeds 50 km [3]).

Figure 1 shows a "bilateral symmetry" of basin deposits that may be of great, although elusive, significance. Fra Mauro Fm./Apenninus material is found in the northwest and southeast quadrants of the basin deposits; the Alpes Fm. is confined primarily to the northeast and southwest quadrants. Moreover, limited geochemical data for Imbrium Basin deposits (discussed below) suggest that a real lithologic difference exists between the Fra Mauro and Alpes Formations.

The outermost deposits of the Imbrium Basin consist of the light plains Cayley Fm. [13] and numerous secondary craters [4,14]. The Cayley Fm. is gradational with both Fra Mauro and Alpes materials. Results of the Apollo 16 mission and subsequent cratering studies [15] suggest that the Cayley plains were emplaced contemporaneously with deposition of basin ejecta by a "debris surge." The Cayley Fm. is widely distributed as fill deposits in both primary craters and in large-basin secondary craters (only regional exposures are shown in Fig. 1). The fraction of primary Imbrium ejecta in these plains is still under debate (cf. [15] and [16]).

The Imbrium Basin displays one of the most complex ring systems of any lunar multi-ring basin. Controversy has arisen over even the location of the main basin ring, a parameter critical to modeling basin cavities and ejecta volumes. It was first proposed [17] that the Apennine Mountains represent the main Imbrium rim, but the rim is represented by the trough of Mare Frigoris to the north. Later, it was suggested [7] that the north shore of Mare Frigoris is the rim remnant in the north. My interpretation of the Imbrium ring structure is shown in Fig. 2; the main topographic ring, 1160 km in diameter, consists of the Apennines in the southeast and the southern Caucasus, Alpes and Iridum rim to the north and west. This arrangement, first proposed in [18] and later in [6], avoids eccentric, egg-shaped Imbrium rims [7]. If this interpretation is accepted, then mare ridge and massif patterns (Fig. 1) define five additional rings, two inside the topographic rim and three outside. Although the outer rings have been suggested by some workers to represent an older, mega-basin ("Procellarum"; [19, 20]), at least part of the reason for the postulation of this basin was the eccentric position of Imbrium within a large regional concentric pattern [19]. By redrawing the main Imbrium ring as shown (Fig. 2), this pattern is easily explained as Imbrium related [21]. In this interpretation, Imbrium has six rings ranging from 550 to 3200 km in diameter. As such, it is the largest multi-ring basin on the Moon.

Regional Composition of Imbrium Deposits. Orbital geochemical data for Imbrium Basin deposits are few, and are confined to the Apennines and Central highlands/Fra Mauro region. The large field of view of the chemical detectors results in the inclusion of post-basin units, such as mare basalts and pyroclastic deposits, in regional compositions. Even so, these data are our primary source of information about variations in the regional composition of Imbrium ejecta.

Geochemical mixing-model results for Imbrium Basin deposits are presented in Table 1; models for the Apennines were made for this study and results for the Fra Mauro and Ptolemaeus regions are from [22]. Table 1 shows that the composition of Imbrium deposits is regionally variable. Within the continuous deposits, the northern Apennines are dominated by Alpes Fm. materials and the southern Apennines consist of Apenninus (Fra Mauro) materials (Fig. 1). These two units appear to be lithologically different (Table 1). The Alpes Fm. is dominated by norite with minor quantites of KREEP. The Apenninus material is more KREEP-rich at the expense of norite. Both units show substantial quantities of anorthosite and mare basalt, which is probably caused mostly by discontinuous dark-mantle deposits in the Apennines [7]. The discontinuous Imbrium deposits (Table 1) are even more diverse, probably as a result of local mixing dominating the distal ends of the Imbrium ejecta blanket [15]. Even so, the dominance of KREEP in the Fra Mauro and Ptolemaeus regions and in the southern Apennines (Table 1) suggests that at least some of this component may be related to Imbrium ejecta.

These results for Imbrium deposits suggest that the crustal target for the Imbrium impact was composed primarily of norite, with subequal amounts of KREEP and anorthosite. At least some mare basalt also contributed to the basin target [23], but the amount is difficult to quantify from the orbital data. The composition of the Imbrium Basin deposits contrasts with those of most lunar basin ejecta blankets, where anorthosite dominates over other rock types [24]. However, Imbrium deposits are not as noritic as Serenitatis Basin ejecta [25], where anorthosite is virtually absent.

The Imbrium Excavation Cavity. Because the Imbrium Basin was formed by impact, the problem of reconstructing the impact event is tied to the more general problem of scaling complex craters [26]. There is wide disagreement among workers in this field as to the original dimensions of basin cavities. Some workers [27, 28, 29] suggest that the main basin rim (the Apennine ring at Imbrium; 1160 km dia.) corresponds to the original excavation-crater rim. In contrast, evidence from terrestrial impact craters [30], analytical modeling [26] and lunar basins [24, 31, 32], suggests that the fundamental shape of an excavating crater is size-invariant. The resulting model, called the proportional-growth model, has been shown to be valid in size ranges over eight orders of magnitude [26, 31]. In the absence of any compelling evidence to the contrary, it is assumed to hold for the Imbrium Basin in this discussion.

For a lunar basin with a crater-rim diameter of 1160 km (Imbrium), the proportional-growth model suggests excavation-cavity diameters (D_e) ranging from 604±200 km [26] to 685±88 km [32]; the relation of [30], derived from study of terrestrial impact structures, predicts a cavity 667± 87 km in diameter. The maximum depth of excavation (d_e) of material from this cavity is related to D_e as follows: $d_e = 0.09$ to $0.12\ D_e$ [30]. This relation suggests that for the Imbrium basin ($D_e \sim 685$ km) the maximum depth of crater excavation is on the order of 62 to 82 km. The geometry of the Imbrium cavity is not known, but the "Z-model" [33,34] suggests that a spherical cap segment excavating a spherical moon is a good approximation [31]. Analysis of this geometric figure suggests that the total excavated volume of Imbrium is on the order of 12×10^6 km^3. Moreover, although such excavation depths would have excavated mantle material (assuming an average crustal thickness of 55 km; [32]), the mantle ejecta would constitute less than 4% of the total ejected volume. Additionally, 90% of the total ejecta volume would be derived from depths of less than 45 km.

Thus, the proportional-growth model predicts that the Imbrium Basin impact excavated most of the crustal column at its target site; it further predicts that most ejecta were derived from the upper two-thirds of the basin crustal target. This is consistent with what we know from lunar samples [29, 35]. It should be noted that basin-forming models that equate the main rim of the basin with the excavation cavity [27-29] must invoke mechanisms that produce shallowing-cavities with increasing crater size [e.g. 6] to explain the paucity of deep-crustal or mantle material in the lunar samples. The search for evidence of such mechanisms at basin scales has been inconclusive.

Implications for Apollo 15 Highland Samples. The Apollo 15 site lies close to the main (Apennine) ring of the Imbrium Basin. The highlands were sampled at Hadley Delta, a massif that is part of the main basin ring. Mixing-model results for Imbrium deposits (Table 1; N. Apennines) suggest that noritic rocks dominate this region. This noritic component may be reflected by the "LKFM" composition of most Front regolith material [36, 37]. Anorthosite is present in minor amounts at the Apollo 15 site [37], and orbital data suggest that here it may indeed be part of the Imbrium ejecta. KREEP is a minor component in Imbrium deposits in this region (Table 1), but geologic evidence suggests that the abundant KREEP at the Apollo 15 site is related mostly to post-Imbrium basin KREEP volcanism [5] and not to the Imbrium ejecta.

Because the total expected thickness of Imbrium ejecta at the crest of the Apennines ($\sim$1 km; [8]) is less than the 4-km relief of the Apennine scarp, it is likely that pre-Imbrian material would have been collected at Hadley Delta (MOR in Fig. 3). At Apollo 15, this material would consist mostly of Serenitatis ejecta, but because Serenitatis material is dominantly noritic [25], it may be difficult to identify purely clastic material. Impact melts may exist that could be identified [36], although the proportional-growth model predicts less total impact melt at this position in the basin than was sampled by Apollo 17 (Fig. 3). There is probably no coherent "melt sheet" mantling the massifs at the Apollo 15 site, but discontinuous patches and pods of ejected impact melt are probably present and were likely sampled at Apollo 15 [38]. Pre-Serenitatis material is probably present and may be represented in the samples by small, feldspathic granulitic breccias and rocks derived from them [39].

The Apollo 15 landing site provides us with key information on one of the most important lunar basins. Continued study of Apollo 15 samples will give crucial data to test models of basin formation and to help us decipher the complex history of the Moon.

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Table 1. Geochemical mixing-model results for Imbrium Basin deposits by region.

	Continuous deposits		Discontinuous deposits	
Component	N.Apennines	S.Apennines	Fra Mauro[1]	Ptolemaeus[1]
Anorthosite	21%	30%	-	9%
Anorthositic gabbro	-	-	5%	41%
Norite	42%	19%	-	-
A14 KREEP	9%	30%	82%	50%
Mare basalt[2]	28%	21%	13%	-

1. Results of [22]
2. Apollo 11 high-Ti basalt used in continuous deposits; Apollo 12 low-Ti basalt used by [22] for the Fra Mauro region.

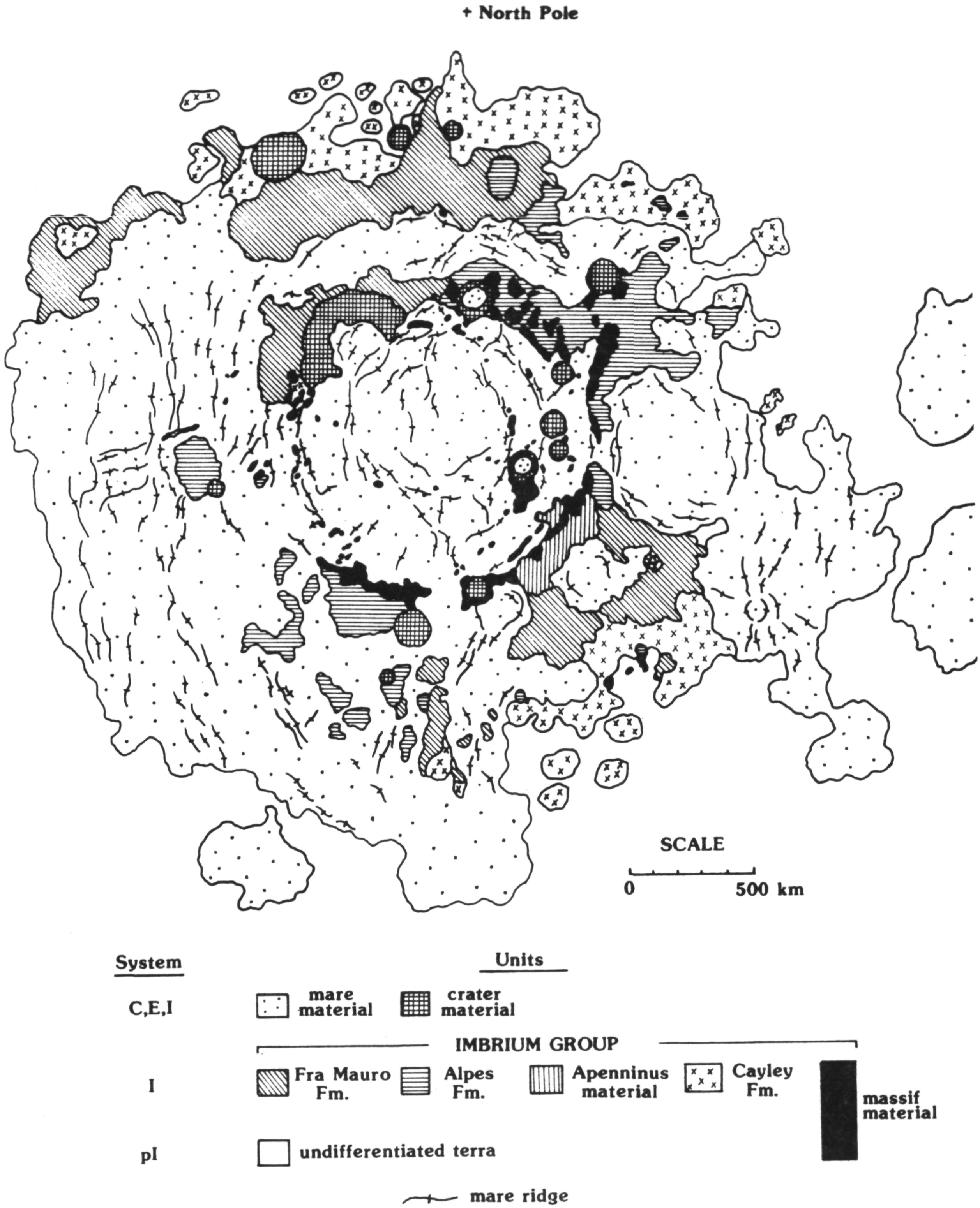

Figure 1. Geologic sketch map of Imbrium Basin deposits, adapted from [7, 14, 40, 41] and new mapping in progress by the author. Secondary crater field omitted for clarity. Base is a Lambert Equal-area projection centered on 35°N, 17°W (Imbrium basin center).

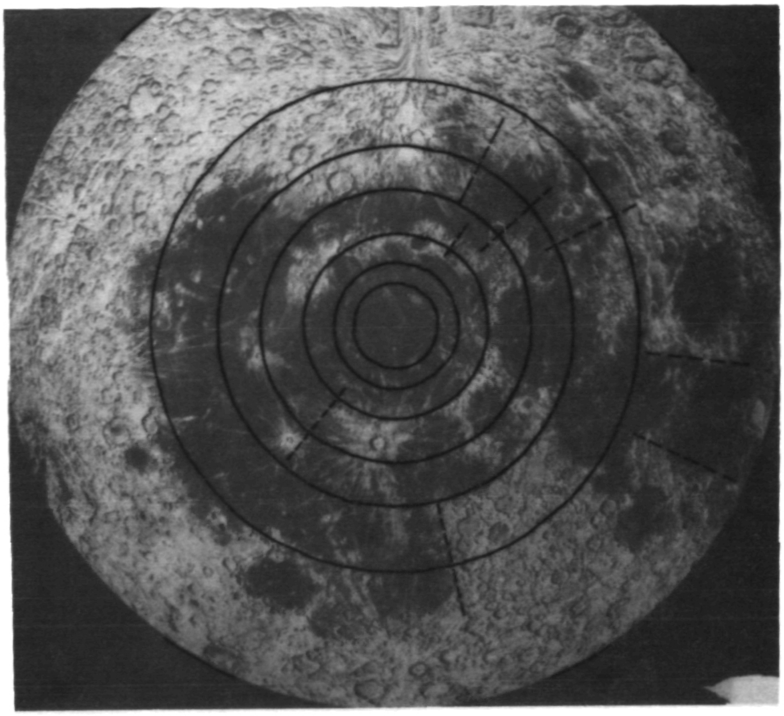

Figure 2. Ring map of the Imbrium Basin. Six concentric rings of diameters 550, 790, 1160, 1700, 2250, and 3200 km are identified. Major radial mega-structures are indicated by dashed lines. Base is a Lambert Equal-area projection centered on 35°N, 17°W (Imbrium basin center).

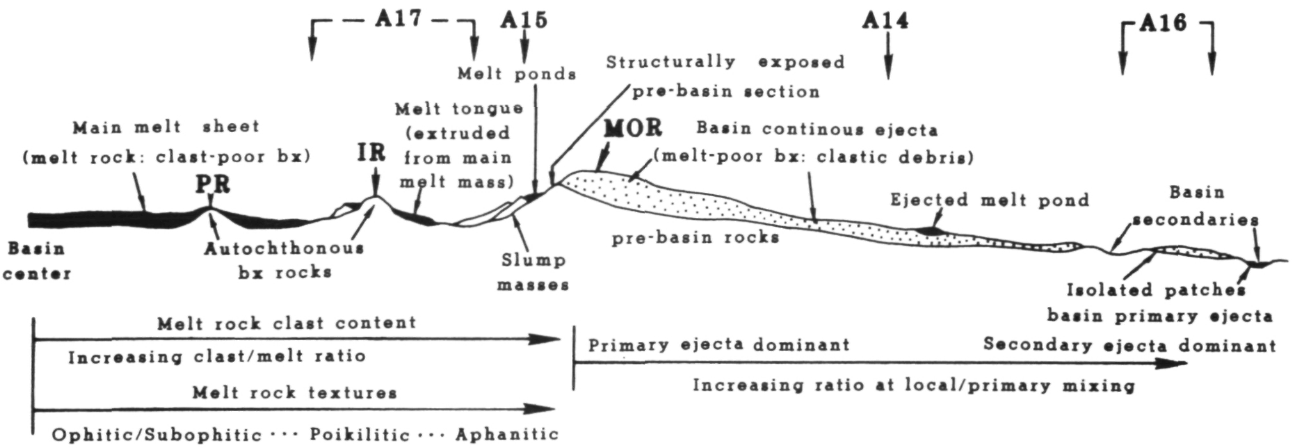

Figure 3. Inferred geologic relations for lunar basin ejecta deposits. MOR is the main topographic rim of the basin [34]. Relative positions of Apollo landing sites shown at top. Apollo 16 position shown relative to Imbrium.

THE APENNINE BENCH FORMATION REVISITED

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Introduction. The Apennine Bench Formation consists of pre-mare light plains materials that crop out south of the crater Archimedes, inside the Imbrium basin [1]. This material has been ascribed either impact [2,3] or volcanic origins [1,4,5]. Several studies [4,5,6] have argued that the Apennine Bench Formation is represented in the lunar sample collection by Apollo 15 KREEP basalts, which have been interpreted as endogenically-generated volcanic rocks [e.g., 7,8]. Recently, Taylor [9] has challenged the concept that the Apennine Bench Formation consists of volcanic KREEP basalt flows on two grounds: 1) The Apollo 15 KREEP basalts are not volcanic; and 2) the Apennine Bench Formation morphologically resembles an expected "melt sheet" produced by the Imbrium impact. The purpose of this note is to briefly review the characteristics of both Apollo 15 KREEP basalts and the Apennine Bench Formation, demonstrate that their characteristics are compatible with a volcanic origin and that both topics are important cornerstones in the deciphering of Apollo 15 site geology and history.

Apollo 15 KREEP Basalts. Among other things, the Apollo 15 site is remarkable for a collection of numerous, small basaltic fragments with KREEP trace-element patterns. The petrology of these basalts is described in [7,8,10,11]; they consist of glassy intersertal to subophitic-textured basalts that totally lack clastic inclusions and have no detectable meteoritic siderophile element contamination. Modally, they consist of 40-50% plagioclase, 30-40% pyroxene (usually orthopyroxene rimmed with pigeonite or augite), and minor phases including cristobalite, ilmenite, apatite, and brown, Si- and K-rich glass [7,10]. In bulk chemistry, they are equivalent to high-Al basalt (Al_2O_3 ~15-18%), with trace element concentrations at about the same level as Apollo 14 soils (="medium-K Fra Mauro basalt"). The Apollo 15 KREEP basalts have been dated by Rb-Sr (internal isochron age- 3.85 ± 0.02 b.y.; [12]), ^{40}Ar-^{39}Ar (3.85 ± 0.05 b.y.; [13]), and Sm-Nd (internal isochron age- 3.85 ± 0.08 b.y.; [14]) techniques. The isotopic data are consistent with crystallization of these basalts at 3.85 b.y., an age at present indistinguishable from that of the Imbrium basin impact [15].

Apollo 15 returned several unequivocal impact-melt rocks, none of which resemble the Apollo 15 KREEP basalts in any way. Moreover, clast-poor impact-melt rocks from elsewhere on the Moon (e.g., 14310; 68415) also differ from the Apollo 15 KREEP basalts in that: (1) they invariably contain xenocrystic debris, consisting of undigested (refractory) clasts; 2) they have high contents of siderophile elements, indicating meteoritic contamination. Taylor [9; p. 215] argues that lack of siderophile contamination does not prove an endogenic origin. While true, we contend that both the lack of clastic debris and low siderophile concentrations are strongly suggestive of an endogenic origin; such data certainly would be conclusive in the case of a mare basalt. Taylor [9] further states that "model ages for KREEP point back to the initial differentiation of the Moon, not to more recent volcanic events" [9; p. 216]. But model ages for mare basalts also point back to initial lunar differentiation [16], yet no one doubts their volcanic origin. We conclude that all petrologic, chemical, and chronologic data are consistent with Apollo 15 KREEP basalts being true, endogenically-generated volcanic rocks, extruded onto the lunar surface at the time of or shortly after the Imbrium basin impact.

The Apennine Bench Formation. As shown by orbital geochemical data [6], an area strongly enriched in radioactive elements (indicative of KREEP) occurs southwest the Apollo 15 landing site. The dominant geologic unit in this area is the Apennine Bench Formation, a light plains unit originally interpreted to be of volcanic origin [1]. Intensive study of impact melt deposits in lunar craters and basins has resulted in a fuller appreciation of their importance in lunar history and some workers have assigned such an origin to the Apennine Bench Formation [e.g., 2,3,9]. However, comparison of the occurrence, distribution, surface texture, morphology, and stratigraphic relations displayed by the Apennine Bench Formation with recognized melt deposits in the Orientale basin [e.g., 4,5] suggests that the Apennine Bench Formation does not represent an Imbrium basin impact melt sheet.

The Apennine Bench Formation occurs within the Imbrium basin in the vicinity of the Archimedes ring (790 km diameter), the ring just inside the main basin ring (Apennine ring; 1160 km diameter). At the Orientale basin, the analogous geologic setting (i.e., Outer Rook/Cordillera rings) contains a knobby-textured unit, the Montes Rook Formation [3,17]. This unit is not similar to the Apennine Bench Formation [cf. 9; p. 38]; an Orientale unit which does bear superficial resemblance to the Apennine Bench material is the Maunder Formation [3], but this unit is totally confined within the Outer Rook ring [3,17,18] and does not extend outward to the main basin ring. Moreover, the Apennine Bench Formation has a relatively flat, smooth surface as opposed to the rough, pitted, and cracked texture of the Maunder Formation. The Apennine Bench Formation does not drape pre-existing topography, as does the Maunder Formation, but rather, displays an embayment relation with terra islands, as do the mare basalts [4,5].

A more important line of evidence for the origin of the Apennine Bench Formation comes from its chemical composition as determined from remote-sensing data (Table 1). Early studies [4,5,21] noted a rough chemical correspondence between the Apennine Bench Formation and Apollo 15 KREEP, based on early reductions of the orbital chemical data. In recent years, these data have been refined [6,18,19] and the resemblance of the Apennine Bench Formation to Apollo 15 KREEP is remarkable (Table 1). The Apennine Bench Formation does not correspond to the composition of probable Imbrium impact melt (15445 and 15455 black matrix; [22]), but closely resembles Apollo 15 volcanic KREEP basalt (Table 1). Taylor's argument that portions of the Apennines (Imbrium ejecta) possess the same Th concentrations as the Apennine Bench Formation [9, p. 215] is incorrect; the highest Th concentration in Apennine material is 7.6 ppm [6]. Thus, the orbital data strongly support the contention that Apollo 15 volcanic KREEP basalt and the Apennine Bench Formation have identical compositions.

Finally, we note that the KREEP-basalt composition of the Apennine Bench Formation (Table 1) precludes an Imbrium impact melt origin. If the Imbrium basin target had a pure Apollo 15 KREEP-basalt composition, much higher heat-flow values would be seen at the Apollo 15 landing site than are recorded [4, 23]. In fact, the crust would have been so enriched in radiogenic elements, that it would have been partially molten. We conclude that considerations of the probable chemical nature of the Imbrium basin crustal target suggests that the presently exposed portion of the Apennine Bench Formation cannot represent an Imbrium basin impact melt sheet.

Conclusions. We contend that a variety of data support previous interpretations [1,4,5,21] that the Apennine Bench Formation consists of post-Imbrium, volcanic KREEP basalt lava flows. The observations leading to this conclusion are: 1) petrologic, chemical, and isotopic data suggest Apollo 15 KREEP basalts are of volcanic origin; 2) the morphology of the Apennine Bench Formation is more consistent with a volcanic origin than with an impact-melt origin; and 3) the Apennine Bench Formation and Apollo 15 KREEP are chemically identical. Additionally, it has been found recently [24] that Apennine Bench Formation may be in the shallow subsurface within 10 km of the Apollo 15 site, supporting the likelihood that this material was probably sampled during the mission.

As a major, preserved surface exposure of post-Imbrium volcanic KREEP flows, the Apennine Bench Formation is an important target for future lunar exploration. At this locality, the geology and processes of lunar KREEP volcanism may be studied and eventually deciphered.

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Table 1. Comparison of the compositions of the Apennine Bench Formation, Apollo 15 volcanic KREEP, and Imbrium basin impact melt.

	Apennine Bench Fm[1]	Apollo 15 KREEP[2]	Probable Imbrium Impact Melt[3]
TiO_2	1.7-2.3%	1.8-2.3%	1.35-1.70%
Al_2O_3	16.0%	14.8-17.8%	16.2-17.5%
FeO	9.5-12.4%	8.6-11.1%	7.9-10.2%
MgO	5.7%	6.3-8.2%	13.4-16.0%
Th	10.7-12.0 ppm	10.5-12.0 ppm	2.4-2.9 ppm

1. Values from [18] (Al, Mg), [19] (Fe, Ti) and [6] (Th).

2. Values from [8,10].

3. Values for black matrix of 15445 and 15455, compiled in [20].

SOME OBSERVATIONS ON THE GEOLOGY OF THE APOLLO 15 LANDING SITE. G.A. Swann, U.S. Geological Survey, Flagstaff, AZ 86001

The Apollo 15 Lunar Module (LM) landed July 30, 1971, on the mare surface of Palus Putredinus at the east edge of Mare Imbrium. The major geologic objectives of the mission were observations and sampling of, in order of decreasing priority, the Apennine Front, Hadley Rille, and the mare. Apollo 15 was the first of three "J" missions, which were devoted primarily to science. The first Extravehicular Activity (EVA), or stand-up EVA (SEVA), was performed by Commander Scott when he opened the top hatch of the LM and described the surface from this vantage point. Three traverse EVA's were performed, when the Lunar Roving Vehicle (LRV) was used for the first time (Fig. 1). During the mission, the LRV covered 27.9 km, and the crew collected 77 kg of samples and took 1,152 still photographs on the surface. These photographs were supplemented by moving pictures taken with the Data Acquisition Camera (DAC) and television whose pan and zoom were controlled from the Mission Control Center. An Apollo Lunar Surface Experiments Package (ALSEP), consisting of an array of geophysical instruments, was deployed near the LM. High resolution (panoramic) and high geometric fidelity (metric) photographs were taken from orbit that included coverage of the landing site; in addition, gamma-ray and X-ray fluorescence spectroscopic measurements were made from orbit to determine regional chemical compositions of the Moon.

In his SEVA and LM window descriptions, Scott described a rolling and hummocky surface, and commented that all of the rock fragments he could see were either white or light gray, with the exception of two black ones (one of which was subsequently collected and identified as a glassy regolith breccia). He also described lineaments, which are clearly visible on the photographs, of the mountains. With the exception of those on Silver Spur, these lineaments have been shown to be artifacts of illumination (Wolfe and Bailey, 1972). Those on Silver Spur appear to be topographic benches, but whether or not these benches reflect layering or structure remains uncertain.

During the first EVA, the crew traveled south, partly along the rim of Hadley Rille, to Station 1 at Elbow crater. Samples collected at Elbow are dominantly pyroxene basalt, presumably excavated from the mare near the rim of Hadley Rille by the impact that formed Elbow crater. The crew then proceeded up the "front," or lower slopes of Hadley Delta, to Station 2, where they collected mostly breccias, many containing mare basalt clasts. They also sampled a breccia boulder 1 m across and took several soil samples.

They then returned to the LM, making one quick stop to collect a vesicular olivine basalt at what was later designated Station 3. Upon returning to the LM, they deployed the ALSEP.

On EVA II, they again traversed a southerly route to Stations 6, 6a, and 7, all on the lower slopes of Hadley Delta above the mare surface. Nearly all of the samples collected at these stations are regolith breccias, many containing mare basalt clasts. Apparently, most true "highlands" samples, including an anorthosite (15415), were collected at Spur crater (Station 7). The crew then started back toward the LM, stopping on the south rim of Dune crater in the South Cluster at Station 4. They sampled a large vesicular pyroxene basalt boulder on the rim of Dune, and collected other samples, mostly mare basalts, near the rim of Dune. Upon returning to the LM, they performed the "Station 8" activities at the ALSEP site, which included a trenching operation for the Soil Mechanics Experiment and the drilling of the "deep" (3m) core hole.

On the third EVA, they first removed, with some difficulty, the core barrel from the drill hole, and then proceeded west toward Hadley rille. Station 9 is at a very fresh, 15-m-diameter crater with cloddy ejecta about 300 m east of the rille edge. Samples taken there are all glassy, poorly indurated regolith breccias. Station 9a is in a basalt-boulder field on the rille edge, and the boulders appear to be nearly in place, virtually bedrock. Samples of olivine basalt were collected from one boulder and pyroxene basalt from another at a slightly lower elevation nearer the rille, therefore probably at a lower stratigraphic level. Regolith at Station 9a is nearly absent because the rille serves as a repository for fines moved by meteorite impact (Swann and others, 1972). Station 10 was a stop to take photographs of outcrops on the far side of the rille that would form stereopairs with those taken at Station 9a.

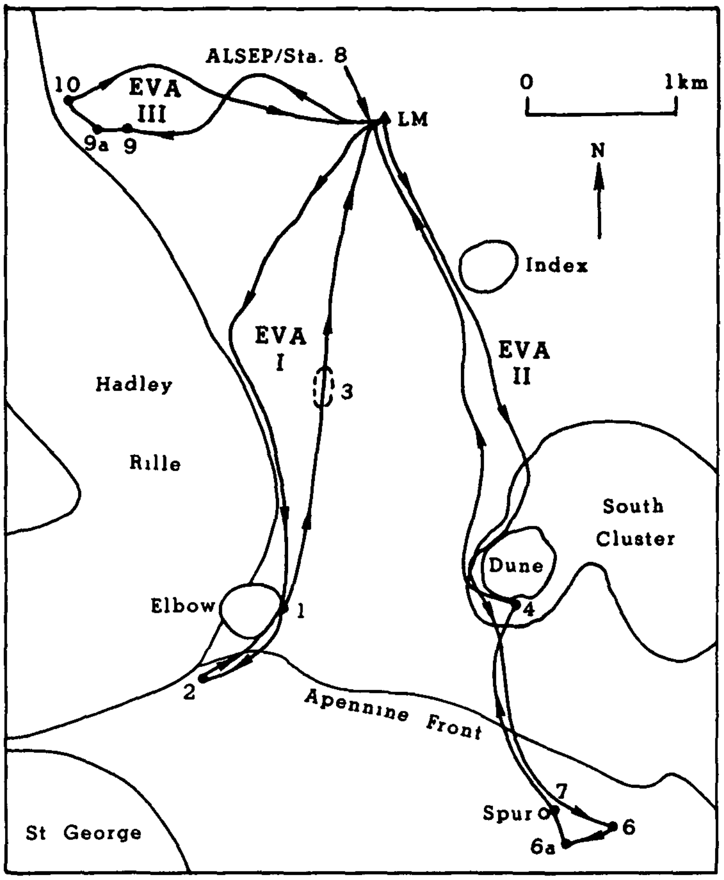

Figure 1. Apollo 15 traverse map

The primary interest in the Apennine Front stemmed from the hope of collecting "primordial" pre-Imbrian material. Prior to the Imbrium impact, the site was undoubtedly blanketed with ejecta from the Serenitatis Basin underlain by debris from older impact events. The search for "primordial" material is of necessity an almost random process of finding, and hopefully recognizing, a piece of such material among the many layers and mixtures of debris created by countless impacts of all sizes. Perhaps at some place within the massifs such material exists, but it is not clear that it was collected by Apollo 15. Anorthosite 15415, the "Genesis Rock," is probably a pre-Imbrian rock, but how much of its "primordial" character has been altered by intense shock events after its original crystallization remains unclear.

Nearly all of the rock samples collected at the front are regolith breccias containing mare basalts. Station 2, however, is well within the range of ejecta from Elbow crater, and Stations 6, 6a, and 7 are within range of ejecta from the South Cluster and other craters in the mare. The regolith on the front is mature and thoroughly gardened and, in the areas sampled, ejecta from the nearby mare have been intermixed into most of the breccias. Station 7 at Spur crater, however, occurs at the break in slope that appears to be the top of the talus apron along the base of Hadley Delta and, as previously mentioned, most true "highlands" samples were collected there. A north-south profile through Spur crater (Fig. 2), with the projection of the upper steeper slope (19°) beneath the lower gentler slope (10°) representing the contact between the original massif surface and the talus, shows that the deeper part of Spur crater penetrates this contact. Thus, massif material that should be relatively free of accumulated regolith was penetrated and ejected by the Spur impact.

It was expected prior to the mission that the mare surface in the vicinity of the landing site would be contaminated with nonmare materials. Material from impacts on the massifs would certainly be present in some undetermined amount, and most mappers thought that they could

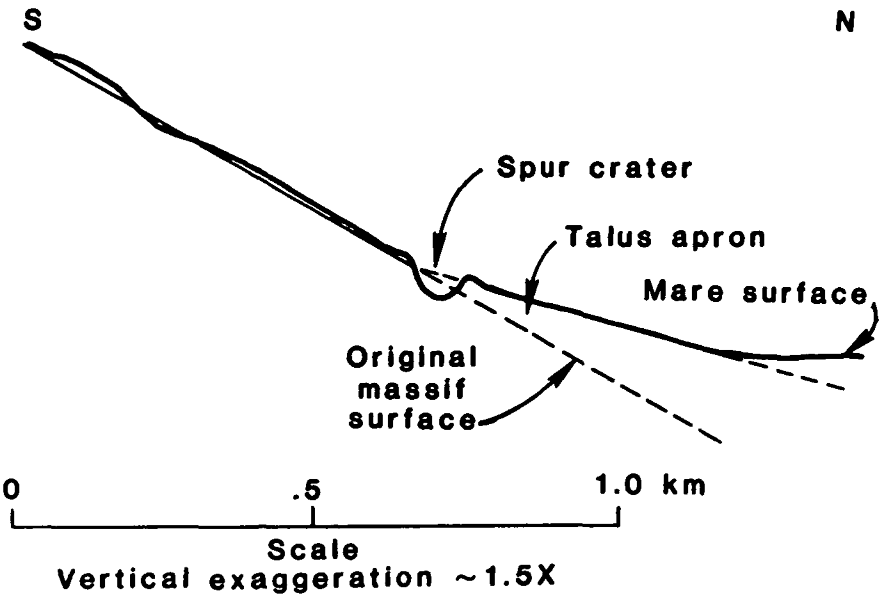

Figure 2. North-south profile through Spur crater.

identify the presence of a very faint ray crossing the site from either Aristillus or Autolycus. Spudis (1978a), however, has pointed out that the topographic highs (such as the North Complex) in the vicinity of the site, which are almost certainly Apennine massif material possibly partly covered by a thin mantle of mare basalt, are probable contributors of non-mare materials by post-mare impact. He also suggested that the gentle ridge on which the LM landed (Fig. 3) may be a reflection of premare topography covered by a thin mantle of mare basalt. The "high-lava mark" along the west flank of Mt. Hadley (Fig. 3) that was described and photographed by the crew suggests a drainback of lava that would leave topographic highs draped with basalt (Swann and others, 1972). Significant segments of the EVA I and II traverse routes were along the aforementioned ridge, and craters penetrating into underlying premare material could be the source of much of the nonmare materials at the surface.

KREEP basalts are abundant in the Apollo 15 samples. Hawke and Head (1978), Spudis (1978b), and Spudis and Hawke (1985), have shown with remote-sensing data that the Apennine Bench Formation exposed south of Archimedes (Hackman, 1966) is probably KREEP basalt. Carr and El-Baz (1971) showed extensive exposures of Apennine Bench Formation 40 km northwest of the site that were not recognized by Hackman. Two more exposures of Apennine Bench Formation, 50 and 100 km southwest of the site, are apparent in metric and panoramic camera photographs. In addition, the large exposure of Apennine Bench Formation south of Archimedes extends to within 75 km west of the site, not 125 km as mapped by Hackman (1966). These determinations by Carr and El-Baz (1971) were made possible by Lunar Orbiter IV photographs and by the author with Apollo 15 metric and panoramic camera photographs, none of which were available to Hackman at the time of his mapping. Furthermore, two areas, one 12 km north of the site and the other 6 km northeast of the site, appear, from scarps and depression features of the type that typify the Apennine Bench Formation, to be Apennine Bench Formation covered by a thin mantle of basalt (Fig. 3). The proximity of widespread exposures of Apennine Bench Formation to the north, west, and south of the site, and of Apennine Bench-like structures even nearer, suggest that the site may be underlain in the shallow subsurface by Apennine Bench Formation. Additional Apennine Bench Formation material was probably introduced at the surface of the site by the Autolycus event 140 km to the north, which almost certainly impacted into the Apennine Bench Formation (Carr and El-Baz, 1971; Carr and Meyer, 1974).

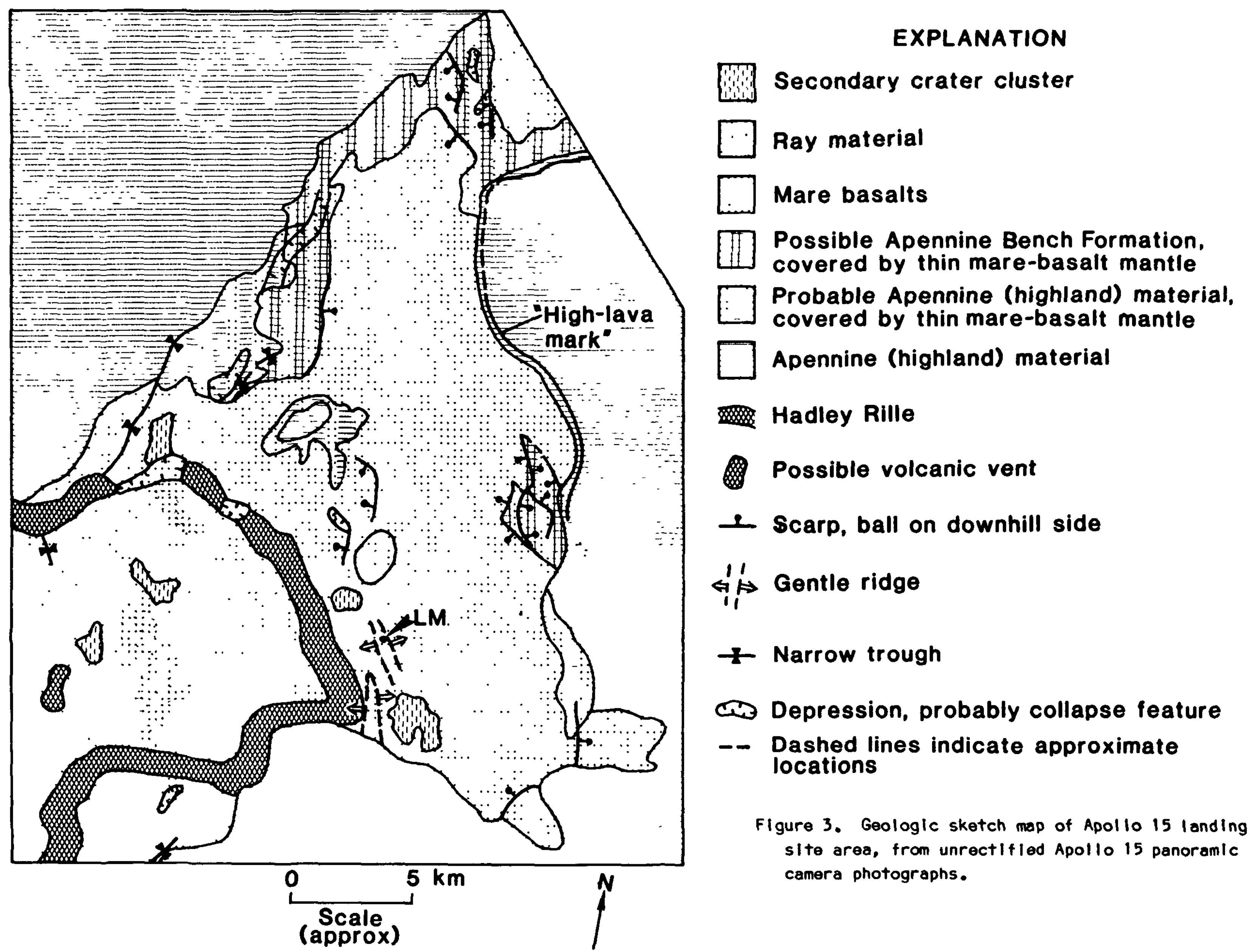

Figure 3. Geologic sketch map of Apollo 15 landing site area, from unrectified Apollo 15 panoramic camera photographs.

A reasonable stratigraphic sequence for the site consists of pre-Serentitatis Basin impact breccias, Serenitatis Basin ejecta, Imbrium Basin ejecta, Apennine Bench Formation, and mare basalts, the uppermost 60 m being the lower layered unit, middle massive unit, and upper dark unit exposed in the rille wall (Howard and others, 1972). The upper dark unit may be olivine basalt and lower units pyroxene basalt (Swann and others, 1972).

The origin of sinuous rilles has long been debated, and a mechanism involving lava channels and/or collapsed lava tubes is probably the most widely accepted explanation. It has also been noted that some sinuous rilles, such as Hadley Rille, consist of straight segments connected at rounded corners which suggests that the trends are structurally controlled (e.g., Howard and others, 1972).

Some of the most distinctive features of the Apennine Bench Formation are its northeast- and northwest-trending scarps, troughs, and elongate depressions. Mozart Rille, 100 km west-southwest of the landing site, is a sinuous rille confined mostly to the Apennine Bench Formation, but extending 10 km into the mare. The zigs and zags of this rille appear to be controlled by scarps in the Apennine Bench Formation; it is also aligned with an apparent collapse structure about 2 km to the east that extends at right angles from Bradley Rille. Structural control of Mozart Rille seems obvious.

The two main trends of Hadley Rille are northeast for the south half and northwest for the north half. Individual segments of the rille also follow these trends (Howard and others, 1972). The trends are consistent with the structural trends in the Apennine Bench Formation; furthermore, the northern terminus of Hadley Rille merges with two northeast- and northwest-trending straight rilles of the Fresnel system in the Apennine Bench Formation. It is proposed here that Hadley Rille is a lava channel or collapsed lava tube that first formed on the structurally controlled topography of the Apennine Bench Formation as did Mozart Rille, and that these trends were maintained as mare flooding continued and the rille completed its development.

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THE ORIGIN OF PRISTINE KREEP: EFFECTS OF MIXING BETWEEN URKREEP AND THE MAGMAS PARENTAL TO THE MG-RICH CUMULATES

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The two main varieties of lunar basalt, mare basalt and KREEP basalt, are seldom difficult to distinguish. Besides having far higher contents of incompatible elements, KREEP basalts generally have higher Al_2O_3 and lower Ca/Al (reflected in lower contents of high-Ca pyroxene). Both types of basalt are widely assumed to be derived by remelting of late products of the Moon's "magma ocean" (a.k.a. magmasphere). But the sharpness of the distinctions between the two basalt types, and more importantly the paradox that KREEP basalts have far higher contents of incompatible elements and yet have similar mg ratios, seem inconsistent with both basalt types having formed simply by remelting of a series of different products of a single former magma.

The mg ratio - incompatible elements paradox is also difficult to explain with a "serial magmatism" model, in which the Moon's crust forms in the absence of a magmasphere [Walker, 1983]. Under such a scenario, complexities such as assimilation and magma mixing would occasionally lead to geochemical anomalies, including basalts with high incompatible element contents and moderate mg ratios. But such cases would presumably be exceptional. Most basalts with high incompatible element contents would have low mg.

Assuming that KREEP is derived from magmasphere residual liquid (urKREEP), one possible means of raising its mg ratio is by assimilation reactions between urKREEP and lower crustal material [Warren and Wasson, 1979]. But this model, originally suggested by Hubbard and Minear [1976] and Dowty et al. [1976], has never been tested quantitatively. Most estimates of the bulk composition of the Moon hold that its mg is less than 0.84 [for a review, and arguments that these estimates are probably somewhat low, see Warren, 1985b]. Most estimates of the bulk mg of the crust are of course much lower still. Taylor's [1982] estimated bulk highlands crust composition has mg = 0.65. One way to estimate the mean mg of the upper nonmare crust is to consider the compositions of mare-free soils, which generally have mg in the range 0.66-0.69; including the ALHA81005 regolith breccia extends the range to 0.73 [Warren, 1985b]. Thus, it seems unlikely that the upper nonmare crust's mg is much greater than 0.70. In the simple magmasphere - plagioclase flotation model of crustal genesis, the crust grows from the top down, so the upper crust presumably acquires an mg ratio that is at least as high as that of the lower crust. As the final residuum of the magmasphere, urKREEP must have had a modest mg. It seems unlikely that any type of assimilation reaction with mg-0.70 material could transform urKREEP into liquids with the mg ratios of the Apollo 15 pristine KREEP basalts. Among pristine Apollo 15 KREEP basalts mg ranges from 0.35 to 0.73, and most are in the range 0.50-0.70 [Irving, 1977]. Irving [1977] even suggests that these basalts were all derived by fractional crystallization of a more magnesian parent melt with mg = approx. 0.72 (and K_2O = approx. 0.5 wt%). The pristine KREEP basalt from Apollo 17 (72275c) also has a moderate mg ratio: approx. 0.52 [Ryder et al., 1977]. At equilibrium, assuming K_D = 0.30 (numerous experimental studies, cited by Warren [1985b], indicate that K_D for both olivine and pyroxene at low pressure and oxygen fugacity will be in the range 0.25-0.35), a solid with mg = 0.70 will coexist with a liquid with mg = 0.41. The numerous Apollo 15 KREEP basalts with mg $\geqslant$0.65 would only be in equilibrium, as melts, with solids with mg $\geqslant$0.86; the Apollo 15 KREEP basalt with mg = 0.73 would be in equilibrium with solids with mg = 0.90. Even assuming K_D = 0.35, the basalts with mg ≥0.65 would be in equilibrium with solids with mg ≥0.84, and the basalt with mg = 0.73 would be in equilibrium with solids with mg = 0.89.

Dowty et al. [1976] appeal to assimilation as a process in which "equilibrium was strictly maintained only between the liquid and the outermost surface layer of the ANT crystals," as a result of which, these authors suggest, "the Fe/Fe+Mg ratio would tend to approach that of the melted ANT crystals." In this model, the assimilation process resembles continual ultra-low-degree partial melting of the crustal rocks through which the urKREEP is supposed to percolate. However, in any partial melt, the melt mg ratio increases as the degree of melting increases. Thus, the transient sort of equilibrium invoked in this model would probably tend to yield liquids with modest mg ratios, even lower than in the case of a slower, more thorough type of assimilation; and in any case far below the mean mg ratio of the crust with which the liquid undergoes the assimilative reactions.

The magmasphere's urKREEP residuum must have initially collected as a "sandwich horizon" at the top of the mantle. Barring vigorous convective mixing of the mantle, assimilation reactions between urKREEP and the mantle would be unlikely to raise the mg ratio of the urKREEP, however, because the cumulates in the uppermost mantle (the presumed sources of the mare basalts) formed late in the differentiation of the magmasphere, and therefore had modest mg ratios; moreover, the low density of urKREEP probably caused it to slowly rise into the crust [Shirley and Wasson, 1981].

The mg ratio - incompatible elements paradox is readily explained by a model that considers not only the magmasphere, but also its aftermath. A widely accepted model for the origin of the Mg-rich cumulates (i.e., the nonmare cumulates other than ferroan anorthosites; the latter are presumed to have formed atop the magmasphere) holds that they formed in more or less conventional layered intrusions, emplaced into older, ferroan-anorthositic crust within a few hundred Ma of the origin of the Moon [e.g., Warren and Wasson, 1980; James, 1980]. As discussed by Warren and Wasson [1980], the source regions of these melts were probably concentrated in the lower-middle mantle, where the mg ratio was at least nearly as high as the bulk-Moon mg ratio. In any event, these melts yielded cumulates with olivine mg raios frequently ≥0.90, and occasionally as high as 0.92 [Warren, 1985b]. Assuming K_D = 0.30, oliivine with mg = 0.90 implies the parent melt's mg was 0.73; olivine with mg = 0.92 implies the parent melt's mg was 0.78.

Pristine Mg-rich rocks range in age from 4100 to 4500 Ma, and thermal models suggest that the magmasphere completed 99% of its crystallization, yielding the ferroan anorthosites plus a thin layer of urKREEP immediately below, within 200 Ma of the origin of the Moon [Warren, 1985a]. Thus, the onset of Mg-rich plutonism apparently came shortly after, or even overlapped, the final stages of magmsphere crystallization. The magmasphere's final urKREEP residual liquid, representing only a few tenths of a percent of the original magmasphere, had such high contents of U, Th and K, it could have remained molten at the base of the crust for many hundreds of Ma. Left undisturbed, its low density would have caused it to slowly migrate toward the surface [Shirley and Wasson, 1981]. But soon after urKREEP formed, and perhaps even during its final stages of formation, Mg-rich magmas apparently plowed through the urKREEP collection layer (the crust/mantle boundary) on their way to the crust. These rising parcels of Mg-rich melt presumably mixed with, or at least partly assimilated, whatever urKREEP that they passed through. Implications of this mixing for the composition of the melts parental to Mg-rich rocks have been appreciated for some time [e.g., Warren and Wasson, 1980]. But if mixing between urKREEP and Mg-rich melts was pervasive enough, the composition of most of the basalts derived from urKREEP would also have been affected.

As noted by Longhi and Boudreau [1979] in relationship to their model for crystallization of the magmasphere, systematic mixing of primitive, Mg-rich material with residual liquid could account for the paradox that KREEP basalts, despite their high incompatible element contents, have moderate mg ratios. For example, assume that urKREEP with a U content of 400 x chondrites was mixed into a 10 times more massive parcel of Mg-rich melt, with U = 5-10 x chondrites and an mg ratio of 0.75. The resultant mixture has a primitive major element composition, including mg ratio (assuming that the FeO content of the urKREEP is similar to that of the Mg-rich melt, the mg ratio of the mixture will be at least 0.73), but 5-10 times more U than the Mg-rich melt would otherwise have contained. As this melt proceeds to crystallize as a "mini magma ocean" in the crust, its residual, KREEP-like liquid (a sort of second-generation urKREEP) will have 5-10 times more U for any given reduction in its mg ratio. Again, the U, Th, and K enriched in the residual melt might produce enough heat to prevent complete, or in this case even nearly complete, crystallization, until finally the melt migrates (or is ejected by a mega-impact) to a cooler environment closer to the surface of the Moon. Alternatively, crystallization might go to completion, but the upper portion of the intrusion might later remelt (perhaps in the aftermath of heating of the lunar interior by a basin-forming impact). The melt produced by this process would have roughly 5-10 times more U than a melt of equivalent mg ratio produced by direct melting of magmasphere cumulates.

This mixing process could also help to account for the higher Al_2O_3 contents and Al/Ca ratios of KREEP basalts, in comparison to mare basalts. The Al_2O_3 content of melts co-saturated with a low-Ca mafic silicate plus plagioclase tends to correlate with the melt mg ratio [e.g., Longhi, 1977]. Thus, the Al_2O_3 content of a KREEP basalt derived from a mixture of urKREEP and primitive, Mg-rich melt will tend to be higher than the Al_2O_3 contents of basalts produced by direct remelting of late-stage magmasphere cumulates. In addition, the Mg-rich melt will tend to assimilate plagioclase from ferroan anorthosite country rock as it solidifies [Warren, 1985c]. Besides increasing the melt Al_2O_3 content, plagioclase assimilation would have a moderating effect on the Ca/Al ratio of the residual liquid.

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SELECTION OF THE APOLLO 15 LANDING SITE; D. E. Wilhelms, U. S. Geological Survey MS-946, Menlo Park, CA 94025

Telescopic studies in the early 1960's pinpointed the future Apollo 15 landing site as a potential exploration site because it includes one of the largest lunar sinuous rilles, Rima Hadley, and some of the Moon's highest mountains, Montes Apenninus. Interest in the site was aroused largely by a striking photograph taken by G. H. Herbig with a primitive camera attached to the 120-inch telescope of Lick Observatory (while he was waiting for the bothersome Moon to set). The Apennines are the southeastern segment of the most prominent ring of the Imbrium basin. Imbrium is the most conspicuous ringed impact basin on the lunar nearside, and its deposits constitute a valuable stratigraphic datum plane for vast areas of the Moon. The Apennine-Hadley region also includes clearly determinable stratigraphic relations that proved that lunar basins and maria differ in age and origin.

Because of this early interest, the site was placed high on the list of targets for the Lunar Orbiter 5 mission in August 1967, whose purpose was to explore sites for advanced manned exploration. A mode of four widely spaced camera exposures was employed that left gaps in the high-resolution coverage.

Peculiar features often attracted more attention in the early stages of the site-selection process than did basic geologic units such as those of ringed basins. Thus, in 1967 many mission planners considered the rille to be the region's center of interest. Knowing the process of rille cutting was considered important for understanding lunar processes and materials; investigators alternatively favored an origin as a tectonic fissure, a lava channel or tube, or as a groove eroded by lava, nuées ardentes, or water. The head of the rille was thought to be a possible still-active source of, or trap for, volatiles. Other conspicuous rilles, such as Vallis Schröteri and Rimae Prinz, were also photographed by Orbiter 5 and were briefly considered as alternatives to the Hadley mission.

Interest in volatiles subsided, however, when earlier missions found no traces of them. Interest in the Apennines persisted and grew to prime importance. Their evident uplift indicated that they would expose a section of crustal rock several kilometers thick. Both Imbrium-basin and pre-Imbrian rock should be present, in unknown proportions. Analogy with the overturned ejecta flaps of simple terrestrial impact and explosion craters suggested that a complete section of Imbrium ejecta would be present in or on the massifs, and that the top of this section was derived from greater depths than was the Fra Mauro Formation at the Apollo 14 site. It was hoped that the very deep crust, or even the mantle, might have been excavated. Samples of the Imbrium ejecta would also provide an absolute age for the Imbrium basin by which the lunar stratigraphic column could be calibrated, and would help to elucidate basin-forming processes. The underlying pre-Imbrian section was predicted to include rock from such pre-Imbrian basins as Serenitatis or, many planners hoped, relatively undisturbed primitive crustal rock. These exciting possibilites kept Apennine-Hadley on almost all lists of potential landing sites.

Additional targets were identified once Apennine-Hadley emerged as a potential landing site. It offered another mare, Palus Putredinis, in addition to the two, apparently older, mare units that had been visited by

Apollos 11 and 12 in 1969. Constructional volcanic features were thought to occur at the arrowlike source of Rima Hadley, along the Apennine front, and in the "North Complex." The 5.5-km-diameter crater Hadley C presumably excavated a thick stratigraphic section that could be sampled in its ejecta. Some planners believed that Hadley C might be a maar because of its anomalously soft-textured rim and position near volcanic features; it would then expose materials from even greater depths than would an impact crater. Secondary craters of the distant Copernican impact craters Aristillus and Autolycus were recognized as potential sources of rock that could date the craters and of samples from units far from the landing site. Several alternative landing points within the Orbiter 5 coverage were considered to take maximum advantage of these objectives.

Before a specific site was assigned to it, Apollo 15 was planned as an "H" mission (with an ALSEP, two EVA's, and other improved capabilities over the Apollo 11 "G" mission, but with no roving vehicle). The small, young, very bright crater Censorinus (0.4° S., 32.7° E.) and a contact between mare material and dark mantling material near Rimae Littrow (21.7° N., 29.0° E., west of the eventual Apollo 17 site) were contenders for this Apollo 15 H mission almost until May 1970, when Fra Mauro was chosen for Apollo 14. However, the site favored by many scientists of the Group for Lunar Exploration for an H-type Apollo 15 mission was a spot along Rima Davy that could profitably be explored by walking (11.0° S., 6.4° W.). Rima Davy, a near-linear chain of small, closely spaced craters, is another eye-catching feature. It was widely thought to be a chain of maars and a likely source of deep lunar material. Representative samples of the uplands and "upland fill" (light plains or mantles) could also be reached in places along the Davy chain. A "J" (advanced capablility) mission was even designed for Davy to exploit these multiple objectives and visit an adequate number of "vents."

The failure of Apollo 13 in April 1970 caused all later missions to be postponed. During the resulting breathing space, four developments shifted interest away from Davy. The first was extra time to fabricate the J-type Lunar Module (LM) and Rover (LRV), and by August 1970 these appeared near enough to completion that the next mission after Apollo 14 could be a J mission. Second, a steeper approach trajectory was devised, so that the LM could clear the high Apennine crest during an Apennine-Hadley landing from the east. Both these changes would have benefitted Davy, but they benefitted Apennine-Hadley even more. The third factor was the cancellation, in September 1970, of two Apollo missions, the original 15 and 19, in addition to the Apollo 20 mission that had already been dropped in January 1970 in favor of Skylab. The constricted mission schedule put pressure on planners to select the best possible sites for the three remaining missions. Apennine-Hadley was generally considered more interesting than Davy because of its obvious multiple objectives, as opposed to the more theoretical ones of Davy. Moreover, its high-latitude location gave Apennine-Hadley the advantages of a good geophysical spread and a high inclination of the orbit of the Command and Service Module (CSM). The inclined orbits would carry the CSM's geochemical and geophysical experiments and cameras over new parts of the Moon, over the mascon basins Serenitatis and Imbrium, and over a wider latitudinal belt than would orbits over the near-equatorial Davy. The fourth change that shifted interest away from Davy to Apennine-Hadley was in the requirements for photographic site-certification. Very high-resolution photographs were no longer thought to be required. Therefore the gaps between the Orbiter 5 high-resolution frames were not a cause for rejecting the site as they would have been earlier. The safety of landings at scientifically interesting areas covered by moderate-resolution frames could now be certified by extrapolating terrain information from nearby high-resolution coverage. However, some good stereoscopic coverage at moderate resolution was still required, and this could not be provided for Davy in time to prepare an Apollo 15 mission for that site. Apollo 14 might have provided such coverage, but the new month-dependent orbital path chosen for it favored photography of Descartes instead. The Descartes photographs would be available in time to plan Apollo 16 but not Apollo 15.

There were four other leading contenders for the first J mission in addition to Apennine-Hadley and the ambitious J-type Davy mission. The first was Descartes, which was set aside because the Apollo 14 photography would not be available soon enough. The second was Copernicus, which lost out to Apennine-Hadley for reasons that were partly operational and partly scientific. Because of the economic need to space missions closely, a J mission would be flown in mid-1971 whether the LRV was ready or not. If the LRV were not developed in time for Apollo 15, or if it malfunctioned on the Moon, Apollo 15 would become a J-type walking mission. Palus Putredinis offered a smooth "landing field" for access to the Apennines and Rima Hadley even for a walking mission, whereas no such access lay close enough to the main object of interest in Copernicus, its central peaks. Copernicus was also considered the only good backup to Descartes for the Apollo 16 highland mission that was shaping up. The third site, Tycho, was every scientist's favorite as a sampler of a thick section of terra crust, a geophysical station far removed from the others, a datable young stratigraphic marker, and a calibration point for the Surveyor 7 compositional analysis. However, it was opposed and finally vetoed by operations specialists because of questions of safety and orbital-mechanics difficulty. It lay at one end of the cross-shaped area that was accessible to Apollo landings (arms along the prime meridian and equator), and its surface looked rough on the Orbiter 5 photographs. As a result, the only remaining strong contender besides Apennine-Hadley for the first J slot as of September 1970 was the Marius Hills, yet another eye-catching feature. Marius' steep, rugged cones and other rare landforms were considered likely to consist of young, highly differentiated volcanic rock. It finally lost to Apennine-Hadley mainly because of the latter's favorable high-latitude position and multiple surface and orbital objectives.

The mission planners settled on the northernmost (at 26.1° N., 3.6° E.) of the several alternative landing sites within the Apennine-Hadley region. The Apollo Site Selection Board approved Apennine-Hadley for Apollo 15 on 24 September 1970.

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GEOLOGIC SETTING OF THE APOLLO 15 LANDING SITE; D. E. Wilhelms, U.S. Geological Survey (MS-946), Menlo Park, CA 94025

General setting

Apollo 15 was a multipurpose mission to investigate both the multiringed Imbrium impact basin, represented by Montes Apenninus, and the mare that fills the basin, represented by Palus Putredinis (Fig. 1). Although the sinuous rille Rima Hadley that cuts Palus Putredinis was actually the initial attractant to the site, the Apennines eventually became its prime object of geologic interest [1].

The landing site is at 26.1° N., 3.65° E., in an inlet of Palus Putredinis that is bordered on the SE by the Apennine front and almost enclosed on the NW by two linear hills parallel to the front. The main part of the palus is bordered on the NW by the mare-filled Upper Imbrian impact crater Archimedes (83 km diam, 29.7° N., 4.0° W.) and on the SW and NE by the Apennine Bench. The Bench consists of low hills and of the Apennine Bench Formation, a Lower Imbrian light-colored plains deposit [2]. This deposit is overlain by secondary craters of Archimedes, and floods hills of the Apennines and the rugged Montes Archimedes. The northern arm of the Bench lies south of the Copernican impact craters Autolycus (39 km diam, 30.7° N., 1.5° E.) and Aristillus (55 km diam, 33.9° N., 1.2° E.), and is overlain by their deposits and secondary craters. Rays and crater clusters show that ejecta from one or both of these craters impacted near the landing site.

Imbrium basin

The Apennines, the lunar nearside's highest mountain range, are the most prominent component of the concentric-ring system of the Imbrium basin. The Apennine front is a major topographic and geologic discontinuity and encloses the Imbrium topographic basin. Palus Putredinis and the adjoining belts of the Bench trend normal to the Apennines, that is, they are radial to the basin center. Faults on the basinward side of the Apennines are oriented both concentrically and radially; few Imbrium-related faults occur outside the Apennine front. Many hummocks atop the mountains and near the front are concentric with the basin, but those farther out are predominately radial (Fig. 1). South and SE of the Apennines, this roughly radial hummocky deposit, the Fra Mauro Formation (FMF), obliterates pre-Imbrian craters to distances of 350 to 600 km and extends to distances of 600 to 800 km [3-5]. Many Imbrium secondary craters as large as 20 km, and some as large as 30 km in diameter, form giant clusters and chains beyond the FMF to as far as 2600 km from the Apennines [5,6]. A similar, though less well defined, transition from the FMF to secondary craters occurs north of Mare Frigoris. NE and SW of the basin, the coarse, knobby variety of hummocky Imbrium material known as the Alpes Formation forms a belt as wide as 600 km [3,5]. Imbrium ejecta and secondary craters therefore constitute a datum plane relative to which stratigraphic units can be dated over a large area. Thus, samples from both the Apennines and the FMF at the Apollo 14 site (1100 km SW of the Apollo 15 site) may provide absolute ages and compositional data relevant to the Imbrium basin, if the samples are primary basin ejecta. Premission modeling based on simple craters suggested that samples from the Apennines might represent deeper crustal layers than the Apollo 14 samples [1].

The nature and origin of the Imbrium rings, including the Apennines, are less well understood than its ejecta and secondary craters. The major mountain arc on which the Apennines lie also includes Montes Carpatus and southern Montes Caucasus. Otherwise, even the connection between the exposed segments of the Imbrium rings is uncertain. The northern Caucasus diverge eastward from a circular extrapolation of the arc, so that the main ring may continue, alternatively, through the northern shore of Mare Frigoris, the Mare Frigoris trough, or Montes Alpes [3,7-9]. Corresponding alternative diameters of the main ring are 1500 km, 1340 km, and 1180 km, respectively. Centers have been plotted from 38° N., 19° W. to 34° N., 17° W. Lineations in the northern, deflected part of the Caucasus point to the latter center, suggesting that it is the true center and that the basin has a larger radius in the north than in the south. Reconstructions of inner rings also vary. The most obvious topographic elements (including mare wrinkle ridges) indicate rings 950 km (connecting Montes Archimedes and Montes Alpes) and 670 km in diameter (connecting smaller peaks).

Significant unresolved questions concerning basin rings in general and the Apennines in particular include whether basins were shallow or deep when formed, and whether the rings (a) are unique features or are scaled upward from central peaks and(or) terraces of complex craters, (b) developed during or after the excavation, (c) formed by active processes, such as undulations of the target material, or by passive processes, such as centripetal faulting or megaterracing, (d) formed inside or outside the excavation or in both positions, and (e) are influenced by the thickness and physical properties of the target rock [4,5,9-12]. The identification of the original boundary of excavation (and thus of the original diameter of the basin) is a major unsolved problem. A currently popular view is that the Apennines and other topographic basin rims were formed outside the excavation cavities and were isolated when the cavities collapsed catastrophically. The hypothetical originally smaller Imbrium cavity is now mostly buried by Mare Imbrium and is represented by one of the partly exposed rings or by no preserved ring. Another view, which prevailed during the planning for Apollo 15, is that the topographic rims represent the rims of the basins' excavation cavities except as enlarged by relatively minor slumping. I still favor this view because the Apennines are such a massive ring segment and mark sharp discontinuities in topographic trends and ejecta textures. The mountain front is marked by a line of massifs that slope in both directions (Fig. 1), not by a simple scarp, as would be the case in passive gravity-fault origins; the steep inward-facing slope is a complex, scalloped landslide slip surface. Mons Hadley delta is the nearest such massif to the site and the only part of the front that was sampled.

In most interpretations, the Apennines consist of uplifted prebasin rock overlain by Imbrium ejecta [2-5,13-15]. The proportion between pre-Imbrian rock and Imbrium ejecta in the mountains is a premission question that remains unanswered.

Several subtypes of Imbrium-basin material overlie the mountains except, judging from the textures, on the tops of the most rugged massifs (Fig. 1) [3,14,15]. Some of this Imbrium material might have slid down to the site in talus, which coats all the steep slopes and obscures the original stratigraphy of the mountains. The samples collected from the front came from an apronlike accumulation of this doubtlessly highly mixed debris (which was noted before the mission [13]). The subtype of hummocky material called Material of Montes Apenninus [3] lies in the intermassif terrain nearest the site; it consists of uneven elongate blocks roughly concentric with the front and has been interpreted as a mixture of structurally emplaced blocks and ejecta [3,14]. Other hummocky facies of Imbrium material are the Alpes Formation, interpreted as Imbrium ejecta emplaced from high-angle trajectories, and the FMF, thought to be Imbrium ejecta emplaced at lower angles. These facies are geochemically different [16]. Knowing the proportions of impact-melt rock and clastic debris in each facies would help in identification of sample provenance, interpretations of isotopic ages, and estimates of impact magnitude and velocity [10-12]. Pools of cohesive material on the Apennine flank indicate to me that considerable impact melt was ejected (Fig. 1).

The rings of older basins apparently controlled the present form of the Imbrium rings and suggest what pre-Imbrian materials might be found in the Apennines. The Serenitatis basin to the east is the most obvious nearby older basin. Its topographic rim, represented by Montes Haemus, is truncated by the Apennines at 25° N., 5° E. Serenitatis material must constitute part of the Apennines or their basement at that point. Projection of the Serenitatis rim inside the Apennine-Caucasus arc shows that the depressed part of Serenitatis occupied the space between the Apennines and Caucasus, explaining the gap [3,15]. The eastward deflection of the northern Caucasus is explained by the absence of resistance to the expansion of the Imbrium rim north of the Serenitatis rim. Another pre-Imbrian basin that affected the present structure of Imbrium is Insularum [3-5]. Some of Insularum's outer-flank material may be incorporated in the Imbrium rings. If present in Mons Hadley delta, the Insularum material would have been first incorporated in the deposits or uplifted in the massifs of the younger Serenitatis basin. Distinguishing among the contributions of Imbrium, Serenitatis, Insularum, and possibly other basins is a major challenge to petrologists and geochemists. These basin materials may be stratified in their sequence of formation or may be inextricably mixed.

The third and oldest basin that may have contributed to Imbrium has been called "Gargantuan" [17] or Procellarum [18]. In my opinion, this controversial basin exists and had a profound effect on Imbrium by thinning the pre-Imbrian crust and lithosphere [4,5,17,18]. Procellarum may have three rings, a diameter of 3200 km, and a center under Mare Imbrium at 23° N., 15° W. [18]. Such a basin would have been a site of pre-Imbrian basalt extrusions that became part of the Imbrium ejecta; a concentration of KREEP in the Procellarum-Imbrium region may reflect a KREEP-rich composition of this basalt [17]. Alternatively, Procellarum could have exposed lower KREEP-rich layers of the terra crust, possibly explaining why the FMF at the Apollo 14 site is KREEP-rich and why many Apennine samples (and Serenitatis samples from Apollo 17) are richer in the Mg suite and low-K KREEP than is the Apollo 16 material [17].

Interpretations of the Apennine Bench Formation have shifted back and forth between volcanic and impact-melt rock ever since it was first recognized. Its pre-mare, pre-Archimedes age shows that it is either contemporaneous with the basin (if the formation is impact melt [14]) or only slightly younger (if volcanic [19]).

Mare and related materials

Before the Apollo 15 flight, the age of the mare near the landing site was correctly estimated as late Imbrian or early Eratosthenian on the basis of crater frequencies, crater morphologies, and, mistakenly, albedo [13]. No subdivisions were recognized. The mare's "reddish" reflectance spectra apparently result from its low TiO_2 content [20,21]. Both in age and spectra, the mare is typical of the units of Mare Imbrium proper that lie west and north of the Archimedes-Apennine Bench barrier. Studies of the large collection of quartz- and olivine-normative basalts from the landing site have not established their genetic or chronologic relation or their role in the formation of Rima Hadley [21,22].

Like most lunar mare margins, the region has its share of dark mantling materials. The apparently dark-mantled hills called North Complex (possibly a volcanic construct) were on the list of mission objectives but were not visited. Some dark mantles also overlie the Apennines [3].

Sampling summary

Viewed in the context of the landing site's geology [22], the returned samples already have or potentially can provide a remarkably comprehensive sampling of the Moon's cross section and geologic history: (a) the deep mantle, probably represented by pyroclastic glasses; (b) a shallower zone or zones of the mantle, represented by the mare basalts (and possibly by fragments excavated directly by the basins); pre-Imbrian pristine rock from (c) KREEP-rich and (d) Mg-suite layers or zones; (e) recycled crustal rock in the deposits of one or more pre-Imbrian basins; (f) Imbrium-basin ejecta; (g) the Apennine Bench Formation of volcanic or Imbrium impact-melt origin (KREEP basalt), transported by impacts from exposures or buried beds of the formation [19]; (h) the target material of Autolycus and(or) Aristillus, possibly including geochronologically reset samples that can date the craters; and (i) the regolith.

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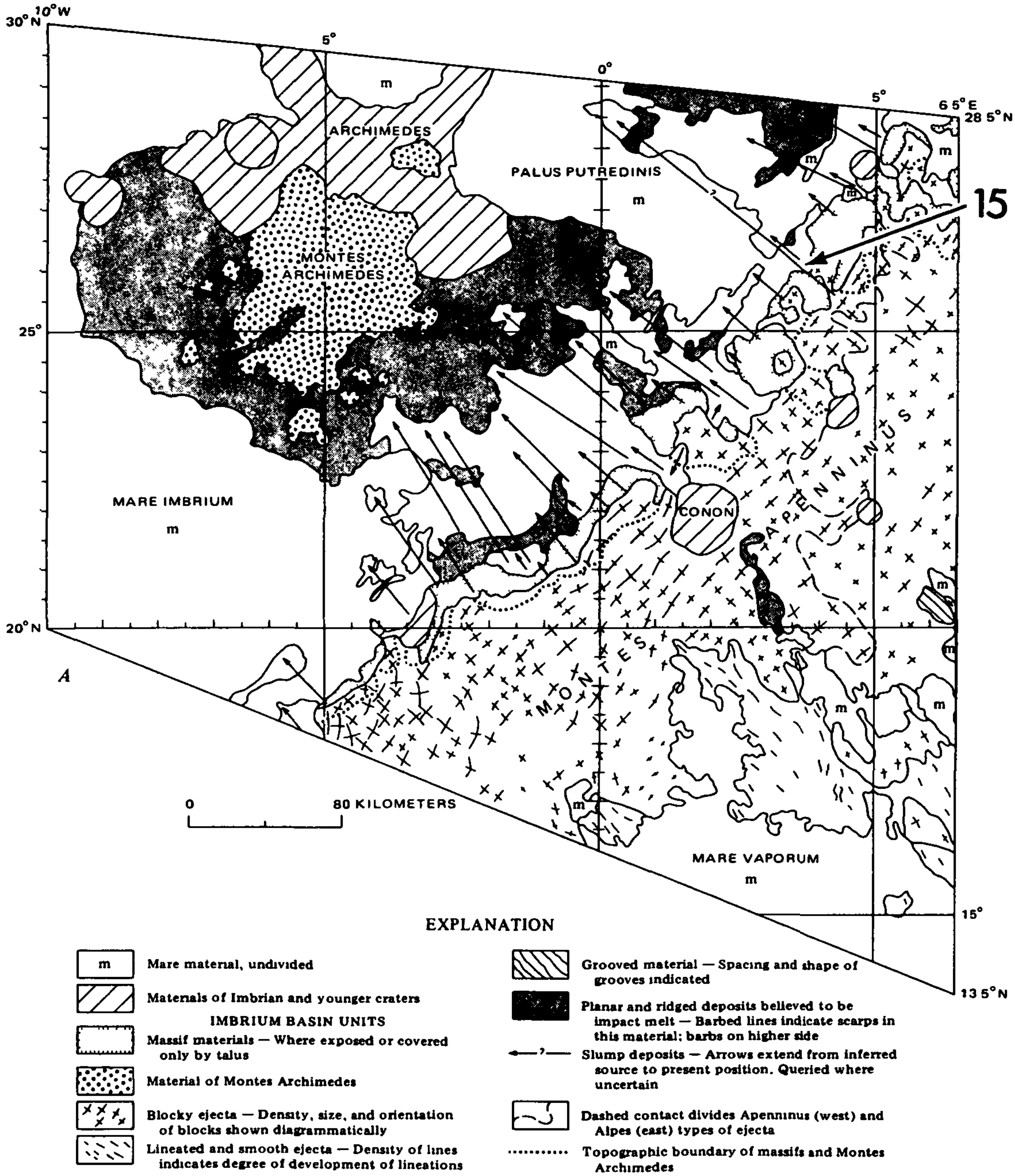

Fig. 1. Geologic map of the Apollo 15 landing site (large arrow, 15), based on Apollo 15 and 17 mapping-camera frames (ref. 14).

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