TR 76-27c

PETROGRAPHIC AND PETROLOGICAL STUDY OF LUNAR ROCK MATERIALS

Stephen R. Winzer
Martin Marietta Corporation
Martin Marietta Laboratories
1450 South Rolling Road
Baltimore, Maryland 21227

April 1976
Final Report, April 21, 1975 - April 21, 1976

Prepared for
GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Petrographic and Petrological Study of Lunar Rock Materials		5. Report Date April 1976 6. Performing Organization Code
7. Author(s) Stephen R. Winzer		8. Performing Organization Report No. TR 76-27c
9. Performing Organization Name and Address Martin Marietta Corporation Martin Marietta Laboratories 1450 South Rolling Road Baltimore, Maryland 21227		10. Work Unit No. 11. Contract or Grant No. NAS5-22363
12. Sponsoring Agency Name and Address NASA, Goddard Space Flight Center Greenbelt, Maryland 20771 (Dr. D. F. Nava, Code 691.1)		13. Type of Report and Period Covered Final Report 4/22/75 - 4/21/76 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Three samples returned from Apollo 14 (14171, 14305, 14319), one from Apollo 15 (15255), two from Apollo 16 (61175, 67455), and one from Apollo 17 (77215) have been studied optically and selected polished sections by SEM/Microprobe. Splits and separates from 77215, 67455, 61175 and 15255 were prepared; 77215 and 67455 have been analyzed for major, minor and LIL trace elements. The data indicate that 77215, a noritic breccia clast found in the Station 7 boulder, is a norite cumulate similar to and probably derived from the same body as 78235. The Apollo 17 boulders are found to be part of the same melt sheet, which was formed by a major impact event (Serenitatis ?) about 4 B.Y. ago. The Apollo 14 and 16 breccias are polymict, their clast populations indicating quite different provenance. The Apollo 14 breccias are possibly the result of multiple impacts, while the other breccias studied appear to have been formed by single impacts. ANT suite clasts included in 61175 are, for the most part, granulites resulting from subsolidus recrystallization of norites, anorthosites or gabbros. This metamorphism appears to have occurred prior to the impact event forming 61175.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Lunar Samples Petrology Petrography Chemical Analyses Breccias	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

*For sale by the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151.

CONTENTS

PREFACE

Objective and Scope of Work

The objectives and scope of the work performed under this contract were to examine petrographically lunar highlands breccias designated by senior scientific personnel at Goddard Space Flight Center; to choose and prepare appropriate samples for large-ion-lithophile (LIL) trace element and major element analyses; to interpret these data; and, with these results as a guide, to initiate new work with the idea of gaining further understanding of the nature of the lunar highlands crust.

Conclusions

Samples -- chips, polished thin sections and polished probe mounts -- from Apollo 14, 15, 16, and 17 were examined during the course of this study. Major, minor and trace element compositions of samples from the Apollo 17, Station 7 boulder have been completed. These new data, and data from other Apollo 17 boulders and rocks indicate that breccias and melt-rocks from this site come from a single melt sheet formed by impact melting about 4 B. Y. ago. It is most likely that this melt sheet was formed by a major impact event, possibly that which formed the Serenitatis Basin. The rocks excavated and melted by this impact were chiefly norites, possibly norite cumulates which were 4.4-4.5 B.Y. old.

Examination of samples from the other three sites allows the following preliminary conclusions to be made: Apollo 14 site breccias examined are polymict and, unlike those at the 15, 16, and 17 sites, appear to be the product of multiple impacts. They appear predominantly basaltic in provenance. Apollo 15 sample 15255 is monomict, while the Apollo 16 and 17 samples are polymict. Apollo 16 breccia 61175 contains a number of different rock types, including basalts (mare and non-mare) and anorthosite, norite and gabbro. The latter three types generally have been subjected to high temperature metamorphism which possibly took place prior to impact excavation and incorporation in the matrix of 61175.

Summary of Recommendations

It is recommended that consortium studies of 61175 be continued and detailed petrographic and petrologic studies of the existing and new thin sections be completed. Apollo 15 sample 15255 should be analyzed by a small consortium for isotopic composition and age (Rb/Sr, Ar^{39}/Ar^{40}) and for major, minor, LIL and volatile trace elements. Detailed petrography and petrology should be completed. At least one of the Apollo 14 samples, probably 14305, should be made the subject of a major consortium effort. Detailed petrographic and petrologic analysis of all three Apollo 14 breccias should be in process while the consortium is being set up.

The preliminary results from cross-comparative studies are encouraging. The detailed studies should be continued, and an effort made to integrate the results with detailed studies of terrestrial impact analogs and their associated breccias and melt rocks.

Introduction

This is a report of studies made on a number of lunar breccias from the Apollo 14, 15, 16, and 17 landing sites as part of a study of major and trace elemental and isotopic abundances, mineralogy and petrology, solar wind radiation effects and magnetic properties of returned lunar samples being conducted at Goddard Space Flight Center. The purpose of these studies was to provide information to be used in cross-comparative studies of lunar breccias, especially highlands breccias. The object of the study was to identify and characterize provenance of the breccias and process of formation; to locate crystalline clasts; and, where possible, to separate the clasts from the matrix for isotopic, major and trace element analysis. The first two parts of this task provide data which can be related to the lithology of the lunar crust in the sampled region and to the impact history of that region from the time of formation of the crust to cessation of activity in that region. The latter, identification and characterization of crystalline clasts, provides data on individual, pre-impact lithotypes which may or may not be primary material, early lunar differentiates, or pre-mare basalts. Deducing the historical development of the crystalline rocks can be expected to provide clues to the early history of the lunar crust.

Petrographic and Petrological Analysis

Thin sections and polished probe mounts of rocks from the Apollo 14 landing site (14171, 14305, 14319), Apollo 15 landing site (15255), Apollo 16 landing site (61175, 67455) and Apollo 17 landing site (77215) have been examined. All of the above samples are designated consortium samples (by LSAPT), and one (77215) is a sample from the Apollo 17, Station 7 boulder consortium led by Dr. E. C. T. Chao.

All the above samples were examined in polished thin section and polished probe mount by transmitted light microscopy, reflected light microscopy and, in the case of 61175, by scanning electron microscope and electron microprobe. Three samples were chosen for consortium study on the basis of optical microscopy. Requests for consortium study were made to LSAPT, the details to be found in our transmittals of July 7, 1975; July 11, 1975; October 17, 1975; and November 13, 1975.

Details of petrography, modal analysis and petrology are contained in these four submissions. A summary of all samples is given below.

Apollo 14 Breccias: Of all sections from the three rocks studied, most indicate that these breccias are polymict fragment-laden melts which may have resulted from multiple impacts. In general, matrix xenocrysts (or surviving fragments of the original target rocks) are plagioclase, olivine, opaque phases (ilmenite or iron metal) and pyroxene in that order of abundance.

The amount of glass (melt) present is variable, but is usually around 25-30%. Differences among the three samples are largely to be found in differences in the mafic component (olivine or pyroxene). For instance, 14305 contains more olivine than pyroxene, 14319 is the reverse. The clast population is variable from section to section, but, in general, breccia clasts are the most abundant, followed by basalt. ANT suite clasts are present, but are not usually more abundant than 10% of the total clast population.

Apollo 15: 15255 is the only sample from this site which has been examined. 15255 is a dark gray to black matrix breccia with numerous plagioclase and pyroxene fragments scattered throughout a glassy matrix. 15255 contains a few small clasts of unshocked norite or anorthosite, but the bulk of the clasts present are heavily shocked norites or breccias which are unidentifiable as discrete rock types. This breccia differs from the Apollo 14 breccias in that it appears to be monomict, does not appear to be the result of multiple impacts, and contains virtually no basalt clasts.

Apollo 16: 61175 and 67455 have been examined. These two breccias differ in the amount of melt present in their respective matrices and in the variety of included clast lithotypes. 67455 most closely approximates the fragment-laden melts found at the Apollo 17 landing site texturally, but it is difficult to ascertain whether or not 67455 is polymict. Most of the sections have textures similar to those of terrestrial suevite breccias. Few discrete, crystalline clasts are present in the sections; however, regions containing mainly breccia and little glass can be found within more melt-rich areas. The overall composition of the rock is noritic or anorthositic. 61175, by contrast, is a friable polymict breccia containing a wide variety of clasts. The matrix is dominantly plagioclase, and SEM photographs indicate that the matrix is composed of small feldspar fragments and very small glass shards. The clast population is made up of breccia, basalt, anorthosite, troctolite and norite in that order of abundance. Clasts of the ANT suite are dominantly metamorphosed (granulites), while most basalt clasts retain their original igneous texture.

Apollo 17: Sections of 77215, a noritic breccia, were examined as part of the Chao consortium (Station 7 boulder). Descriptions of these samples can be found in Winzer et al., 1976 and Chao et al., 1976. Petrographically, the larger crystalline, non-brecciated sections of the two slides resemble, texturally, 78235, a norite cumulate (see Winzer et al., 1975a and Jackson et al., 1975). The brecciated matrix is dominantly noritic (plagioclase + orthopyroxene in approximately equal amounts), but contains irregular regions which are olivine-bearing. These regions are termed microbreccia by Chao et al., 1975. Major element chemistry of orthopyroxene and plagioclase, as well as trace element chemistries of separated phases from both 78235 and 77215, indicate that they are part of the same body (Winzer et al., 1976).

Comparison of Lunar Breccias Studied

All of the breccias except 61175 are fragment-laden melts; the chief differences between them are in overall composition and clast population. The Apollo 16 and 17 breccias are more anorthositic (plagioclase-rich) than Apollo 14 or 15 breccias. This has been well established chemically (see Lowman, 1976 for summary). These differences appear chiefly in the clast population which presumably bears some relationship to the target rocks in the area at the time of impact. The Apollo 14 breccias contain the highest proportion of basalt clasts of all those examined, with, surprisingly enough, 61175 (Apollo 16) second highest. Apollo 14 samples are also the only ones which contain clasts of breccias which themselves contain clasts. This texture is difficult to produce by any method other than multiple impact.

The petrographic evidence suggests that each site had a significantly different pre-impact target rock composition and lithology. It also suggests that the Apollo 16 site may exhibit the greatest heterogeneity, as evidenced by the variety of clasts present in 61175. It must be pointed out that this conclusion is partly based on the assumption that 61175 does not contain clasts that could not have survived the higher temperatures and shock pressures indicated by the fragment-laden melts found at the other sites.

The second major point of interest is that of the dichotomy indicated by textures of crystalline clasts in 61175, and, to a lesser extent, in 14305. Generally, the textures of basalt or microgabbro clasts are igneous, while the textures of anorthosites, norites or troctolites are metamorphic. Of the major ANT suite lithic clasts in 61175, most show textures which are indicative of subsolidus recrystallization at relatively high temperatures and for relatively long periods of time. (See transmissions of July 7, 1975 and October 17, 1975.) This dichotomy holds for 14305 as well, but, in this case, there are only one or two surviving clasts in the thin sections examined.

There are two possible explanations for the production of such textures. The first is that the ANT suite clasts were buried in a hot ejecta blanket for a long enough period of time to undergo extensive recrystallization. The second is that the original ANT suite igneous rocks underwent the lunar equivalent of regional metamorphism, with an internal heat source rather than heating in an ejecta blanket, prior to the formation of the breccia by impact.

Insufficient data exist to decide between the two possibilities, but some consideration may be made of the alternatives. Experimental tests of sintering in powders of basalt composition and mineralogy indicate that textures found in Apollo 14 breccias and Apollo 17 breccias can be produced in a short period of time (up to 100 hrs.) (Hallam, 1974). These times are on the same order as, or somewhat longer than, times needed to devitrify maskelynite (Bunch et al., 1968). These times are orders of magnitude less than those indicated for production of granulite textures in terrestrial metamorphic rocks of similar composition. This problem is further compounded by the lack of extensive sintering and successive recrystallization in the matrix of the 61175 samples. The textural evidence from the matrix suggests that this sample was never excessively hot.

The evidence is against 61175, at least, being held at any elevated temperature for a long period of time. The evidence also suggests formation by a single impact. Thus, at present it would be logical to suggest that the granulite textures were not formed as a result of metamorphism in an ejecta blanket. This leaves the possibility that the granulites were formed by the lunar equivalent of regional metamorphism.

Sample Preparation and Chemical Analysis

Four samples have been split, or have undergone mineral separations, or both prior to chemical analysis (large-ion-lithophile trace elements and major and minor element chemistry).

77215 samples were obtained from Chao as part of the Station 7 boulder consortium studies. Three of the samples received were further separated, these being 77215,130, 77215,152, and 77215,115 contact zone. As the separation procedure has not been described in detail in a previous transmission, the general separation procedure is described below.

The purpose of these separations was to provide clean glass, orthopyroxene, plagioclase and black glass separates for large-ion-lithophile trace element and major element analyses.

The initial sample contained fragments which were already somewhat enriched in the desired component or components. The sample was initially gently crushed and sieved on nylon screens into four fractions:

(1) Sock
(2) > 100 mesh < sock
(3) > 200 mesh < 100 mesh
(4) Pan (< 200 mesh)

The sock fraction, and the fraction lying on the 100-mesh screen, were handpicked for the desired component. Usually one or two fractions would be picked. The first fraction was pure when viewed under the highest power of the stereomicroscope (70 x). This fraction would be placed in a bottle marked pure separate. The second fraction was usually at least 80% pure, but needed further refinement.

The <200 >100 fraction would be processed next, usually through use of heavy liquid (Thallium Malonate Formate) adjusted to the density desired with distilled, demineralized water. This fraction would be successively sieved, separated gravimetrically and, where possible, hand picked until sufficient purity (99+ %) was attained, whereupon the pure separate would be placed in the bottle with the handpicked fraction. The remaining 80% pure material would then be crushed further and density separated until 99+ % purity was attained.

If, at this point, insufficient material was obtained, the pan fraction would be treated in the same manner as the above. The pure separate was then ground to fine powder in a boron carbide mortar, and aliquants provided for LIL trace element and major element analyses.

Samples from 67455 were handled in substantially the same manner. These samples were initially started by M. L. Lindstrom under the direction of S. R. Winzer, and were subsequently completed by M. L. Lindstrom.

Samples 61175 and 15255 were handled differently. These samples were approved for consortium study (61175, S. R. Winzer, consortium leader) and pre-consortium reconnaissance analyses (15255) by LSAPT. Chipping and splitting operations were carried out in the nitrogen cabinets at the Curatorial Facility in Houston, Texas. Accordingly, S. R. Winzer traveled to Houston to carry out the chipping operation in accordance with the LSAPT guidelines. A copy of these guidlines was transmitted to D. F. Nava at Goddard Space Flight Center, by the Curator. The details of the splits carried out at Houston are covered in our transmittal of January 28, 1976. All splits requested have been carried out, and all allocations to the members of the 61175 consortium have been made (see transmittal of January 29, 1976). Thin sections, and chips of matrix and clasts have been received, and preparations are being made for further separations for chemical analyses.

Major element analyses and large-ion-lithophile trace element analyses of splits and separates from the Station 7 boulder have been completed (Winzer et al., 1976; Winzer et al., in preparation, Appendix A). Major element chemistry has been completed for some of the samples from 67455, while two of these samples have been analyzed for large-ion-lithophile trace elements.

Electron Probe Microanalysis, SEM Petrography

Electron microprobe (SEM microscope with Energy Dispersive X-Ray Analyzer) analyses have been initiated on selected thin sections from 61175. This type of analysis, coupled with the capabilities for microscopic analysis of the SEM, has certain advantages over electron microprobe analysis alone. The analytical results tend, however, to be less accurate than those of the electron microprobe.

The reasons for differences in analytical accuracy are twofold. First, energy dispersive analyses are still in the developmental stage, although some authors now claim to be able to produce fully quantitative analyses on par with wavelength dispersive analyses (Reed and Ware, 1975). Differences are largely due to problems with obtaining background and correcting for peak overlap, escape peaks, etc. The deconvolution program used with the SEM at Martin Marietta Laboratories uses a multiple least-squares fit for sample and standard spectra to produce intensity ratios for use in the ZAF correction program. This method assumes the background to be part of the continium, and it is handled in the fit. This works well, providing the average Z of the sample is not radically different from that of the standard. Repeat analyses using this correction procedure have proven fully quantitative ($\pm$ 1% for major elements, $\pm$ 5% for minor elements, relative to the total amount present).

Second, the electron gun system in an SEM is not as stable over a long period as the gun system in an electron microprobe. Our system does not, at this time, carry a specially stabilized power supply, thus we must monitor constantly to catch drift. It is not always possible to catch small drifts, and therefore our accuracy suffers. Periodic checks of standards indicate errors of $\pm$ 2-5% for major elements, up to $\pm$ 10% for minor elements relative to the total present. All analyses should be viewed with these error limits in mind.

Selected clasts from three polished probe mounts from 61175 have been analyzed with the SEM/Electron Microprobe. These sections are: 61175, 9 , 61175, 95 and 61175, 104. The clast types examined are norite, anorthosite, basalt and breccia. Analyses are presented in Table 1.

<u>61175, 9:</u> One large norite clast was analyzed. This clast contains anorthite (An_{95}), a low-Ca orthopyroxene ($Wo_4En_{63}Fs_{32}$) which hosts a high Ca pyroxene ($Wo_{25}En_{56}Fs_{19}$), and ilmenite. No olivine was found during the reconnaissance phase of the analyses.

<u>61175, 95:</u> One norite clast, one basalt clast and one anorthositic breccia clast were studied. The norite clast in this section differs from that in 61175, 9 in that it contains olivine, the An content of the plagioclase is lower and no high Ca pyroxene was found in the pyroxenes analyzed. The pyroxenes are more magnesian. Plagioclase (An_{84}-An_{95}) shows considerable variation. This variation appears to be just outside the error range for the analyses, and thus may be real. Olivine (Fo_{76-79} Fa_{24-20}) is present as small, round grains included in the plagioclase and as small, anhedral grains in interstices between plagioclase grains. Pyroxene ($Wo_7En_{73}Fs_{19}$) occurs as larger subhedral grains, and appears homogeneous except for a chrome-rich phase (Cr-Spinel?) found in complex exsolution features in some grains.

TABLE 1

SEM - Microprobe Analyses of Lunar Sample 61175

Standards

	Evans Garnet		Kakanui Kaersutite		Grunierite	
	EDS	WET	EDS	WET	EDS Ave (3)	WET
SiO_2	39.79	39.00	40.01	40.37	50.67	50.2
TiO_2	---	---	5.35	4.38	--	--
Al_2O_3	21.74	22.00	14.94	14.90	--	--
FeO	22.51	22.81	11.19	10.65	38.79	37.00
MgO	12.10	11.53	13.60	12.80	7.92	7.57
MnO	--	--	--	--	.89	.86
CaO	4.48	4.20	10.08	10.30	1.12	.80
Na_2O	--	--	4.45	2.60	--	--
K_2O	--	--	2.05	2.05	--	--
Total	100.62	99.54	101.67	98.05	99.39	96.43

61175, 9 Norite Clast

	"Ilmenite"	"Ilmenite"	Ilmenite	Low Ca Px	Low Ca Px	Low Ca Px	High Ca Px
SiO_2	5.45	6.11	--	54.38	53.37	54.05	53.83
TiO_2	50.37	48.44	57.08	0.62	0.48	0.31	0.45
Al_2O_3	2.33	1.84	--	1.93	1.26	1.95	1.99
FeO	32.31	31.75	36.28	18.73	18.62	19.21	11.47
MgO	6.56	4.11	6.66	21.53	23.53	21.65	19.08
MnO	--		--	0.36	0.49	0.72	0.12
Cr_2O_3	--	7.08	--	--	--	--	--
CaO	0.37	0.67	--	2.34	2.27	2.10	11.98
Na_2O	2.60		--		--	--	1.08
K_2O	--		--	0.11	--	--	--
Total	99.99*	100.00	100.02	100.00	100.02	99.99	100.00
Composition				$Wo_4En_{63}Fs_{32}$	$Wo_5En_{67}Fs_{30}$	$Wo_4En_{63}Fs_{32}$	$Wo_{25}En_{56}Fs_{19}$

*Analyses are normalized to 100% to correct for drift. The assumption is made, for these analyses, that the drift is linear for each element. This assumption may not be correct for elements present at < the 5% level.

TABLE 1 Continued

SEM - Microprobe Analyses of Lunar Sample 61175

61175, 95 Norite Clast

	Plagioclase	Plagioclase	Plagioclase	Plagioclase	Plagioclase	Plagioclase	Plagioclase
SiO_2	44.84	45.24	44.58	45.20	44.04	46.85	45.02
TiO_2	--						
Al_2O_3	33.10	34.11	34.02	33.50	33.79	32.90	34.61
FeO	--						
MgO	1.65	1.25			0.78		
MnO	--						
Cr_2O_3	--						
CaO	19.17	18.15	17.35	20.02	19.38	19.03	19.45
Na_2O	1.26	1.02		1.28	2.02	0.54	0.92
K_2O	--		0.72				
Total	100.02	99.77	96.67	100.00	100.01	100.00	100.00
Composition	An_{89}	An_{90}	An_{91}	An_{89}	An_{84}	An_{95}	An_{92}

	Plagioclase	Olivine	Olivine	Olivine	Low Ca Px	Low Ca Px
SiO_2	46.43	40.50	40.30	39.21	52.28	56.51
TiO_2				0.30	0.76	0.68
Al_2O_3	32.71		1.60	1.92	4.64	4.07
FeO		17.64	20.60	20.14	10.98	11.95
MgO		40.76	36.85	36.80	26.36	26.12
MnO		0.35			0.46	0.63
Cr_2O_3						0.56
CaO	19.45	0.74	0.66	0.77	2.54	3.56
Na_2O	1.08				1.96	
K_2O						
Total	100.00	99.99				
Composition	An_{90}	$Fo_{29}Fa_{20}$	$Fo_{76}Fa_{24}$	$Fo_{76}Fa_{24}$	$Wo_5En_{70}Fs_{17}Jd_7$	$Wo_7En_{73}Fs_{19}$

TABLE 1 Continued

SEM - Microprobe Analyses of Lunar Sample 61175

	61175, 95 Norite Clast	61175, 95 Basalt Clast				
	Chromium Phase in Px	Plagioclase	Plagioclase	Plagioclase	Pyroxene	Pyroxene
SiO_2	20.11	46.94	46.14	47.71	53.29	53.68
TiO_2	3.68		0.32			0.31
Al_2O_3	12.10	33.37	33.89	34.98	1.56	1.76
FeO	26.24				16.90	14.81
MgO	12.43	0.79	0.63		20.42	20.34
Mno					0.24	
Cr_2O_3	31.00					
CaO	1.40	17.76	18.51	19.59	7.59	8.98
Na_2O		1.03	0.52	0.27		0.13
K_2O		0.11				
Total	106.96	100.00	100.00	102.55	100.00	100.00
Composition		$An_{90}Ab_9Or_1$	An_{96}	An_{98}	$Wo_{16}En_{57}Fs_{27}$	$Wo_{19}En_{58}Fs_{24}$

	61175, 95 Basalt Clast			61175, 95 Breccia Clast	61175, 104 Anorthosite Clast	
	Pyroxene	Pyroxene	Olivine	Plagioclase (4 Anal.)	Plagioclase	Plagioclase
SiO_2	54.79	53.63	41.03	45.13	46.79	45.37
TiO_2	0.96	1.31			0.33	
Al_2O_3		2.21		34.04	33.04	30.48
FeO	15.85	12.17	29.10	0.24	0.77	4.04
MgO	22.97	15.03	28.72	1.81	0.95	0.90
MnO	0.37	0.59	.24			
Cr_2O_3	0.54					0.31
CaO	3.88	15.15	.92	18.32	19.03	18.77
Na_2O	0.64			0.36		
K_2O				0.11		0.13
Total	100.00	100.00	100.00	100.00	100.00	
Composition	$Wo_8En_{66}Fs_{26}$	$Wo_{34}En_{45}Fs_{21}$	$Fo_{63}Fa_{37}$	$An_{96}Ab_3Or_1$	An_{100}	$An_{98}Or_2$

TABLE 1 Continued

SEM - Microprobe Analyses of Lunar Sample 61175

	61175,104 Anorthosite Clast	61175,104 "Norite" Clast				
	Melt	*Plagioclase*	*Low Ca Px*	*High Ca Px*	*High Ca Px*	Olivine
SiO_2	46.15	47.97	54.12	52.37	53.12	39.03
TiO_2	0.45		0.90	1.97	1.60	0.16
Al_2O_3	29.47	31.39	2.39	4.12	2.90	1.72
FeO	3.38	0.49	16.44	9.44	8.01	26.87
MgO	3.61	0.32	23.14	15.78	15.58	31.46
MnO			0.23	0.35		
Cr_2O_3			0.13	0.26	0.28	0.12
CaO	16.23	18.69	2.65	15.72	18.51	0.64
Na_2O	0.49	1.03				
K_2O	0.22	0.12				
Total	100.00	100.00	100.00	100.00	100.00	100.00
Composition		$An_{90}Ab_9Or_1$	$Wo_5En_{67}Fs_{28}$	$Wo_{35}En_{48}Fs_{17}$	$Wo_{40}En_{46}Fs_{14}$	$Fo_{67}Fa_{33}$

	61175,104 Melt or Basalt Clast			
	Plagioclase (5 Analyses)	Plagioclase (2 Analyses)	Pyroxene	Olivine
SiO_2	47.93	46.51	51.39	40.40
TiO_2	0.17		1.21	0.30
Al_2O_3	30.25	34.04	3.76	2.26
FeO	1.41	0.37	16.96	27.12
MgO	2.16	0.48	19.47	28.57
MnO				0.59
Cr_2O_3	0.14		0.39	
CaO	18.19	18.09	6.83	0.77
Na_2O		0.52		
K_2O				
Total	100.25	100.00	100.00	100.00
Composition	An_{100}	$An_{95}Ab_5$	$Wo_{15}En_{57}Fs_{28}$	$Fo_{65}Fa_{35}$

The basalt clast contains mainly plagioclase, with two distinct compositions ($An_{90}Ab_9Or_1$ and An_{98}), with pyroxene and olivine subordinate. Pyroxene occurs as a low-Ca phase ($Wo_{16}En_{57}Fs_{27}$) and a high-Ca phase ($Wo_{34}En_{45}Fs_{21}$). These may be exsolved in one another, but the grains are small and the texture difficult to decipher. Olivine ($Fo_{63}Fa_{37}$) occurs as discrete grains interstitial to feldspar.

The breccia clast appears to be entirely feldspar ($An_{96}Ab_3Or_1$). Many of these grains, which appear homogeneous and unzoned, contain small FeNi spherules.

<u>61175,104:</u> One anorthosite clast, one norite or gabbro clast and one melt or basalt clast were examined. The anorthosite clast has an igneous texture, and appears to be entirely plagioclase (An_{100}-An_{98}). This clast contains melt, which is essentially plagioclase in composition with some added Fe and Mg. The norite clast is more interesting, containing plagioclase ($An_{90}Ab_9Or_1$), low-Ca pyroxene ($Wo_5En_{67}Fs_{28}$), high-Ca pyroxene ($Wo_{40}En_{46}Fs_{14}$) and olivine ($Fo_{67}Fa_{33}$). This norite or gabbro clast is similar to the one found in 61175, 95, except that the pyroxene is more calcic and the olivine less forsteritic.

The last clast examined appears, texturally, to be a quickly crystallized melt of basaltic composition. The texture is similar to some of the Apollo 12 basalts with skeletal clinopyroxene crystals ($Wo_{15}En_{57}Fs_{28}$) containing small, rounded olivines ($Fo_{65}Fa_{35}$) in a matrix of glass and almost acicular euhedral to subhedral plagioclase ($An_{96}Ab_5$ - An_{100}). Small, rounded ilmenite grains and FeNi and FeNiS spherules are found scattered throughout. Usually ilmenite occurs included in pyroxene, and the FeNi and FeNiS spherules in plagioclase.

Too few clasts have been analyzed to reach any firm conclusions about the units sampled. However, it does appear that the norites examined so far exhibit considerable variability. More detailed work on all five mounts is needed.

Conclusions

The Station 7 boulder consortium has studied samples returned from the various units found on the surface of the boulder. Our initial conclusion (Winzer *et al.*, 1974) was that the three major textural types found in the boulder matrix (77115, 77135, and 77075) were chemically identical and could be explained by formation during a single impact event. From volatile element studies, it was concluded that this impact could have been that which formed the Serenitatis Basin. Further work has expanded this initial conclusion to encompass all the consortium boulders sampled at the Apollo 17 site (Boulder 1, Station 2; 73215 boulder; Station 6 boulder) (Winzer *et al.*, 1975a;1975b and Winzer *et al.*, in prep., Appendix A). Furthermore, it appears that the boulder at Station 8 (78235), a norite cumulate (Winzer *et al.*,1975a), is very nearly identical chemically and petrographically to the noritic breccia clast found in the Station 7 boulder (77215) (Winzer et al., 1975a; 1975b). The presence of norite cumulates as clasts in breccia boulders, and as rocks (shocked, but not included as clasts) at points around the Apollo 17 landing site, suggests that such rocks are part of the pre-impact lithology at the site (Winzer *et al.*, 1976 and in preparation). Major element composition of melt rocks (the matrix of the boulders) indicates that the norites make up the bulk of the target rocks at the site (Winzer *et al.*, 1975b). Major, minor and trace element composition, ages and Rb/Sr systematics indicate that all the boulder samples were derived from a single melt sheet, which probably makes up the hills surrounding the valley of Taurus-Littrow.

Regarding the other breccias from the remaining highlands landing sites, some preliminary conclusions can be made. First, 61175 and 67455 appear to be polymict breccias which exhibit different degrees of shock metamorphism. 61175 has been subjected to considerably lower shock pressures than 67455. 61175 contains a wider range of lithic types in its included clasts, whereas 67455 seems to be mainly anorthositic. ANT suite clasts from 61175 are generally metamorphic (granulites), and these metamorphic textures cannot be explained by heating from inclusion in the matrix of 61175. The texture of 61175 does not suggest multiple events (breccia clasts do not contain breccias within them), nor are the granulites included in melt-rock breccias, thus suggesting that the event which created the 61175 breccia exhumed and included pieces of a metamorphic complex. This metamorphism must have occurred prior to impact.

The pre-impact crust at the Apollo 16 site, judging from these two breccias, may have been dominantly anorthosite or gabbroic anorthosite; however, basalts must also have been present. This lithology contrasts to that of the crust at the Apollo 14 site, which, from the three specimens examined, appears to be basaltic. The Apollo 14 site also appears to have been subjected to multiple impact events, thus differing from Apollo 15, 16 and 17, which, at present, appear to contain breccias from only one impact.

The Apollo 15 site cannot be explained or characterized conclusively with one small sample. The single sample studied would suggest a site composed largely of anorthosite, which is clearly incorrect. Chemical comparisons suggest that the Apollo 14 and 15 sites are more closely related than Apollo 16.

Recommendations for Further Work

Apollo 16: Determination of the fundamental age relationships between clast types derived from 61175 must be undertaken in order to answer the questions raised by the observed textural differences between basaltic and ANT suite clasts. This work is presently being done by two of the consortium members (Geiss and Tatsumoto).

Detailed petrology of the different clasts present must be completed. Reconnaissance electron microprobe/SEM analyses have begun on coarse-grained igneous and metamorphic members of the ANT suite. These analyses should be concluded, and analyses of basalt clasts conducted. The matrix fragments are likely to have been derived largely from the clasts, but analyses of the matrix material must be completed to confirm this conclusion.

The origin of the matrix 61175, and limits to temperatures and pressures to which it has been subjected, need to be determined. Origin of matrix and breccia clasts included in the matrix can be investigated by petrography and microprobe analyses coupled with rare-gas studies and volatile element analyses. Both of the latter are now being undertaken by consortium members Geiss and Anders. In order to be able to establish the temperature history of the matrix, high temperature sintering experiments need to be carried out on analog materials. A simple experiment could be performed using a heating stage microscope and powdered anorthosite of terrestrial origin. Peak temperatures indicated by experimental and theoretical studies of impact cratering would be used as starting temperatures. Time decay curves would then be derived by controlling the cooling rate of the stage, and textures resulting would be studied optically and by scanning electron microscope. Such an experiment would at least provide qualitative cooling histories for the textures observed.

Apollo 15: Apollo sample 15255 should be studied in detail by a small consortium. Detailed petrologic analyses should be carried out, as well as age dating. Volatile elements should be determined as an indication of provenance of the projectile. The two chips derived from the sample and allocated by LSAPT should be analyzed for major, minor and trace elements prior to arranging a consortium effort.

Apollo 14: A major consortium effort should be undertaken on at least one of the three samples studied, probably 14319. Detailed petrographic and petrologic analysis should be completed on all three samples.

Cross-Comparative Studies of Lunar Breccias

The work carried out to date has provided some preliminary data for comparison of breccias from the four sites from which highland material was returned. The results are encouraging and suggest that further detailed work, coupled with studies of terrestrial analogues, will provide understanding of the similarities and differences among the four sites.

References

Bunch, T.E., A.J. Cohen and M.R. Dence (1968). Shock-induced structural disorder in plagioclase and quartz, in French, B.M. and Short, N.M., Shock Metamorphism of Natural Materials, Mono Book Corp., Baltimore, 509-519.

Chao, E.C.T., J.A. Minkin and C.L. Thompson (1976). The petrology of 77215, a noritic impact ejecta breccia. Lunar Sci. VII, 129-131.

Hallam, M.E. (1974). Preliminary results of experiments to duplicate boulder textures by thermal sintering of powders, in Wood, J.A., Interdisciplinary Studies of Samples from Boulder 1, Station 2, Apollo 17 (preprint), 111-121.

Jackson, E.D., R.L. Sutton and H.G. Wilshire (1975). Structure and petrology of a cumulus norite boulder sampled by Apollo 17 in Taurus-Littrow Valley, the moon. Geol. Soc. Amer. Bull. 86, 433-442.

Lowman, P. (1976). Crustal Evolution in silicate planets: Implications for the origin of continents. J. Geol. 84, 1-26.

Reed, S.J.B. and N.G. Ware (1975). Quantitative electron microprobe analysis of silicates using energy-dispersive X-ray spectrometry. J. Petrol. 16, 499-520.

Winzer, S.R., D.F. Nava, S. Schuhmann, C.W. Kouns, R.K.L. Lum and J.A. Philpotts (1974). Major, minor and trace element abundances in samples from the Apollo 17 Station 7 boulder: Implications for the origin of early lunar crustal rocks. Earth Planet. Sci. Lett. 23, 439-444.

Winzer, S.R., D.F. Nava, R.K.L. Lum, S. Schuhmann, P. Schuhmann and J.A. Philpotts (1975a). Origin of 78235, a lunar norite cumulate, Proc. VI Lunar Sci. Conf., 1219-1230.

Winzer, S.R., D.F. Nava. S. Schuhmann. R.K.L. Lum and J.A. Philpotts (1975b). Origin of Station 7 boulder, a note. Proc. VI Lunar Sci. Conf. V-1, 707-711.

Winzer, S.R., D.F. Nava, P.J. Schuhmann, S. Schuhmann, M.M. Lindstrom, R.K.L. Lum, D.J. Lindstron and J.A. Philpotts (1976). Origin of melts, breccias and rocks from the Apollo 17 landing site. Lunar Sci. VII, 941-943.

APPENDIX A

In preparation for submission to Earth and Planetary Science Letters, April 1976

The Apollo 17 "Melt Sheet," Chemistry, Age and Rb/Sr Systematics

by

Stephen R. Winzer
Martin Marietta Laboratories
1450 South Rolling Road
Baltimore, Maryland 21227

D.F. Nava[1], P.J. Schuhmann[2], R.K.L. Lum[2], S. Schuhmann[1], M.M. Lindstrom[2], D.J. Lindstrom[2] and J.A. Philpotts[1]

1) Astrochemistry Branch, Laboratory for Extraterrestrial Physics, Goddard Space Flight Center, Greenbelt, Maryland.

2) Department of Geology, University of Maryland, College Park, Maryland.

Abstract

Major, minor and trace element compositions, age data and Rb/Sr systematics of Apollo 17 boulders have been compiled, and additional analyses performed on a norite breccia clast (77215) included in the Apollo 17, Station 7 boulder. The Apollo 17 boulders are found to be identical or nearly so in major, minor and trace element composition, suggesting that they all originated as an impact melt analagous to melt sheets found in larger terrestrial craters. The matrix dates ($^{40}Ar/^{39}Ar$) and Rb/Sr systematics available indicate that this impact melt formed by a single impact about 4 billion years ago. This impact excavated, shocked, brecciated and melted norites, norite cumulates and possibly anorthositic gabbros and dunites 4.4 billion years old or possibly slightly older. The impact was likely a major one, possibly the Serenitatis basin-forming event.

Introduction

The large boulders at the Apollo 17 landing site have been studied extensively over the past two years by a number of consortia (1-4). These studies have resulted in a series of highly detailed discussions of each individual boulder, but, with the exceptions of (5-7), little effort has been made to integrate these studies and relate them to other samples returned from the Apollo 17 site. Sufficient data now exist to attempt a more coherent approach to the origin of the non-mare rocks found at the Apollo 17 landing site. In this paper we will attempt to relate chemical and isotopic studies of all the boulders, and of a few other relevant samples.

The guidelines by which we will relate these studies are as follows:

(1) In general, petrographic studies are not compared in this discussion. To some extent this has already been done by (5). Petrography is generally too subjective a technique to provide firm answers to the questions raised by the lunar breccias when the author has not personally examined sections from each boulder. From photographs of impact melts and breccias presented in various papers (8-11) and extensive personal examination of shock metamorphosed rocks from 30 or more terrestrial craters, it is concluded that textures found in the Apollo 17 boulders are compatible with an impact origin, and that the range of textures found in the boulders can be produced by a single impact event.

(2) The similarities among samples and groups of samples are emphasized, and small differences are not considered to be germane to a first-order discussion. The reason for de-emphasizing small differences lies in the overall petrographical evidence that all the boulders are impact melts, and that the impact process, by its nature, produces considerable heterogeneity on small scales.

(3) In taking analyses from other laboratories, laboratory errors are taken into account where quoted. However, no attempt has been made to evaluate interlaboratory bias, as pertinent data are not usually given. Problems encountered with bias should be smaller when the data are taken by the same technique; but where the same chemical data are derived by different methods (i.e., microprobe and atomic absorption for major elements), systematic errors can occur. Where considered a problem, attention will be called to the possibility of bias. An additional problem introducing scatter into analytical data is that of sample size. Most analyses are made on samples of less than 50 mg. Defocused beam analyses of clasts in thin sections or of matrix, and INAA or RNAA analyses, are often made on much smaller samples. In a heterogeneous breccia, such small sample size can be expected to produce scatter because the scale on which sampling is made is below the size of many of the petrographic heterogeneities found in lunar breccias.

With the above assumptions in mind, and with the major and trace element data for the norite clast from the Station 7 boulder presented here, we will discuss the chemical and isotopic similarities (and significant differences) among the Apollo 17 boulders and the few other relevant breccia and non-breccia samples for which data exist.

Station 7 Boulder

Major Element Chemistry

We have completed eight new major element analyses by Atomic Absorption Spectrophotometry of phases from 77215 and 77135. The methods are described in earlier papers (12, 13). The results are presented in Table 1 and graphically in Fig. 1.

77215 is a brecciated clast considered to be the oldest material present in the returned samples from the Station 7 boulder (4, 14). The major lithic component of this brecciated clast is a coarse-grained norite, similar in modal mineralogy to the norite cumulate 78235. "Clasts" or veins of dark grey to black impact glass, olivine-bearing breccia, and an assemblage of troilite, FeCo metal, a silica phase and a phosphate mineral are minor components (14). Two thin sections in our possession are dominated by coarse-grained norite, with textures indicative of cumulate origin (Fig. 2) enclosed in or cut by veins of glassy breccia, some of which contain olivine-bearing zones. Unfortunately, samples of sufficient size and coherence are lacking, so no firm textural evidence for cumulate origin can be obtained.

Major element compositions of all Station 7 rocks analyzed by us have been plotted in Fig. 1, along with the compositions of breccias (matrix) from boulder 1, Station 2 (15, 16); 73215 Boulder (17); Station 6 Boulder (18), and the norite cumulate 78235 (19). Also plotted are the mineral compositions obtained from the Station 7 breccias (4, 20), and 78235 (19, 21, 22). This diagram (which reflects the major mineral chemistry exclusive of ilmenite) illustrates the striking similarities in the compositions of the matrix of the four boulders and the norites, and shows that the Station 7 matrix types are indistinguishable from each other. Samples from the Station 6 boulder and three of the samples from 73215 reported by (17) are also indistinguishable from each other and from the Station 7 matrix samples. Samples from boulder 1, Station 2 are more varied. Generally, the PET average composition for 72275 and breccias from 72275 (boulder 1, Station 2) are indistinguishable from those of all the other boulders, but many of the samples from 72255 and 72215 plot in a group which is more aluminous and somewhat lower in MgO

+ FeO than the other matrix breccias sampled. One sample from 73215 (17) plots with this group, as does the bulk rock (as opposed to the melt rind) 78235.

The analyses of the 73215 samples were obtained by defocused beam electron microprobe analysis. Thus, some systematic differences might be expected, because of complications in the correction of the data. The remaining samples were analyzed by atomic absorption spectrophotometry, thus the grouping should not reflect systematic variation due to differences in analytical technique.

Two interpretations of this plot are possible. Either the more aluminous segment of the Station 2 boulder could be a new unit not sampled, and perhaps not present, in the other three boulders, or the segment could be a more plagioclase-rich pod, schlieren, or other relatively large-scale heterogeneity which is part of a continuous chemical variation within a melt sheet of which all four boulders are a part. The first interpretation raises the possibility of separate melt sheets, and thus a multiple event, while the second interpretation is compatible with a single event sampling different lithologies within the crater. To shed more light on this problem requires data other than major element analyses; thus these data will be presented before further discussion of the above points.

Another point which can be made from Fig. 1 is that all breccia matrices fall close to or along the orthopyroxene-plagioclase mixing line defined by the end-member mineral compositions derived from 78235 and the Station 7 boulder rocks. This suggests the interpretation that the matrix material (and the clasts) are derived primarily from noritic source rocks. The norites 78235 and 77215 are reasonable representatives of possible target material. The melt from 78235 (the rind glass) is probably more representative of the bulk sample than the "whole rock" (19). These two shock-melted rocks (78235 glass rind and 77215) fall in the center of the melt compositions of the other four boulders. This is certainly strong evidence that rocks chemically similar to 78235 were part of the target area.

Trace Element Chemistry

Large-ion-lithophile trace element abundances have been determined for orthopyroxene, plagioclase and gray glass separates from 77215, matrix and breccia from 77215 and three dikes cutting the 77215 clast. The method is described in (12). These data are presented in Table 2 and Fig. 3. Comparison of these data indicates that the lithophile trace element chemistry of the phases making up the bulk of norite 77215 is similar to that of the phases from 78235. The orthopyroxenes are nearly identical to those found in 78235 (V-3 opx especially (19)); the plagioclase is enriched 30% in light REE's and up to 2x in heavy REE's over 78235 plagioclase. Opx/Plag partition coefficients are given for both rocks in Table 2. They are virtually identical for Ce $\rightarrow$ Dy, deviating by about a factor of 2 for Ba and Er. The available major element analyses of coarse-grained anorthite from 78235 and 77215 are virtually identical (An_{89}). The pyroxenes, more nearly identical in lithophile trace element abundances, differ more than the plagioclases in major element composition. 78235 pyroxenes ($Wo_6En_{76}Fs_{18}$) are more magnesian than 77215 pyroxenes ($Wo_5En_{67-73}Fs_{29-32}$). The major and trace element compositions, grain size and texture, and overall modes strongly suggest that these two rocks came from the same body, and the presence of 77215 as a clast in the melts suggests that it was excavated by the same impact that produced the melts. The melts, then, are at least partly (and from major and trace element composition, probably to a great extent) derived from fusion of norite cumulates.

Examination of the LIL trace element composition of the melt rocks, and the glass rind from 78235, indicates some difficulties which need explanation. The norite breccia (77215, 45) and matrix (77215, 152) are almost identical, and enriched in LIL trace elements by about a factor of 2 over the glass rind from 78235. Three samples from "dikes" which cut the norite (77215, 115; 119; and 121) are identical to the matrix composition of the Station 7 boulder and to the LIL trace element compositions of the matrices of the other Apollo 17 boulders. The dikes and breccia matrices of the boulders contain from 3 to 10 times the LIL abundances of the norites and norite breccias.

These data suggest that another component is present in the target area, and that this component is high in K and REE's. Two possible components have been found: (1) "granitic" clasts and glasses found in boulder 1, Station 2 and 77215 (14, 20, 23); and (2) KREEP-rich mesostasis present in the cumulates. Neither of these components presents an entirely satisfactory explanation, although insufficient data are available to resolve the problem. No trace element analyses exist for the granitic glasses, thus it is not possible to calculate any mixing proportions. If we assume abundances of about 1000x chondrites, which is higher than those of any known lunar rocks, for light RE elements (Ce, Nd) in the granitic component, about 10% of the component would be needed to provide the enrichment seen. There is no evidence to suggest that the "granitic" portions of the Station 2 boulder, or of 77215, are present at that level; indeed, the major element composition of the matrix material virtually rules out such an addition. Similar problems exist for mesostasis; however, microprobe analyses indicate higher trace element levels for whitlockites in 78235 mesostasis (to 20, 000x chondrites) (21), thus considerably less material would be needed. Mesostasis amounts for 78235 are estimated at close to 1% (21), which, if the average enrichment were about 10, 000x chondrites, would explain the enrichment in the melts. To satisfactorily answer this question, large amounts of sample would have to be analyzed to eliminate the possibility of heterogeneous distribution of mesostasis biassing the results. Some evidence exists for LIL-enriched non-brecciated material in the Station 7 boulder. One troctolite clast was found to be enriched in REE's over all melts analyzed (24).

A conclusive statement is therefore not possible with the available evidence. On the basis of major element chemistry of the breccias, however, it appears that another rock type (such as "granite") is not present in significant enough amounts to account for the enrichment of the matrix in LIL trace-element composition. At this time, it appears more likely that mesostasis accounts for the elevation in K + REE's and P in the matrix breccias and melt rocks over those of the norite target rocks.

Age and Rb/Sr Systematics

Dates have been obtained for all of the boulders. Most of the matrix samples, however, have been dated by only one technique (i.e., $^{40}Ar/^{39}Ar$). The fact that clast-laden melts are difficult to date, means that a spectrum of dates is present and, without corroboration by more than one method, their interpretation is difficult. K/Ar age dating of terrestrial craters (29, 30) indicates that ages most closely approximating the time of impact will be obtained from pure glasses which show little or no devitrification. Rb/Sr systematics for terrestrial craters (30-32) indicate that glasses and melt rocks tend to form tight clusters which lie along or near isochrons defined by country rocks, but do not tend to yield isochrons which are meaningful themselves. It is possible that internal isochrons may be obtained from crystallized melt sheets, provided few xenocrysts remain.

$^{40}Ar/^{39}Ar$ and Rb/Sr dates obtained for Apollo 17 boulders are presented in Table 3. Good plateau ages from lunar breccias are difficult to obtain. It is not possible to sort out the range of $^{40}Ar/^{39}Ar$ ages found in 73215, as the complete data have not been published. The error on all the dates is approximately the same ($\pm$ 0.04 to 0.06 billion years). It is immediately obvious that most of the dates fall around 3.9 to 4.0 billion years, for $^{40}Ar/^{39}Ar$ and the two Rb/Sr "matrix" isochrons. 77135 and 77115 yield lower dates. The problem of differences in age for the three samples 77075, 77115 and 77135 is discussed by (6, 25), and it is sufficient to say here that these differences cannot be regarded as real age differences.

To place confidence in the age of any event, it is helpful to arrive at the same date via different methods. Rb/Sr and Sr isotopic systematics have been determined for some of the boulders studied. The dates resulting from this work are presented in Table 3. The matrix Rb/Sr dates agree relatively well with the $^{40}Ar/^{39}Ar$ dates determined. If the Rb/Sr dates were derived from phases which crystallized from the melt, then some confidence can be placed in the statement that the time of formation of the melts was about 4 billion years ago.

In order to examine more closely the isotopic compositions of all the melts, values given for Rb/Sr and Sr isotopic compositions of matrix and phase separates from all published work were plotted on a Rb/Sr evolution diagram (Fig. 4). These data are derived from the determinations of (3, 28, 33, 34). The analytical results from the various authors were treated using the York least-squares regression (35). It should be noted that the errors shown could result from interlaboratory variation or from differences in technique. The slope of the line gives an "age" of 4.08 $\pm$ .04 billion years, and an initial ratio of 0.69929 ± .00008 for the matrix and mineral separates, whereas the "age" for the matrix exclusive of mineral separates is higher (4.14 ± .04 billion years). The initial ratios are the same within the error range shown.

The 4.6-billion-year reference isochron also is plotted in Fig. 4. It is clear from this plot that the material represented by the point does not retain Rb/Sr ratios and $^{87}Sr/^{86}Sr$ ratios of 4.6-billion-year-old (possibly primary) material or the ~ 4.4 billion year age for some of the igneous clasts. The line derived for the matrix material (whole rock) has a very high correlation coefficient (0.9923), but the date differs from those derived by $^{40}Ar/^{39}Ar$. The aggregate date (matrix plus mineral separates) is intermediate between the dates determined for crystalline clasts (up to 4.5 billion years) and the Rb/Sr matrix and $^{40}Ar/^{39}Ar$ dates determined for the matrices from the different boulders. It would appear likely that the matrix line and the matrix-plus-mineral separate line are mixing lines which do not have age significance. The difference between matrix and matrix-plus-mineral isochrons suggests that the mineral phases separated are mixtures of younger phases crystallized from the melt ~ 4 billion years ago, and older xenocrysts. Regression lines can be fitted to points from each separate boulder, with similar results, suggesting that mixing of similar varieties of material is responsible for all the breccia "isochrons."

The behavior of the Rb/Sr system in the matrix material is similar to that observed for glasses and melt rocks from terrestrial craters. It is more difficult to illustrate this point for the lunar melts because so few whole-rock points from crystalline clasts exist, but the pattern (matrix compositions intermediate between and near isochrons defined by end-members) is similar to that found for terrestrial rocks. It is also worthwhile to note that all breccias plot together (i.e., no groups can be distinguished). LG (light gray) matrix from boulder 1, Station 2 has the highest Rb/Sr ratio, but falls close to the mixing line. The Rb/Sr systematics are consistent with the interpretation of impact fusion and mixing of 4.4- to 4.5-billion-year-old target rocks, the spread on the evolution diagram being due to small variations in the end-member compositions of the target rocks and to incomplete re-equilibration of Rb and Sr isotopes during fusion. The position of the LG matrix from 72255 suggests the presence of a component with a higher Rb/Sr ratio, and more radiogenic strontium, which has, as yet, remained unidentified. One of the whole-rock points for 77215 (Tatsumoto, pers. comm.) falls near the LG matrix point, and is consistent with an end-member composition for the melt rocks. 72417, a dunite, lies close to the other end of the mixing line. No single point is available for 72417, but the "whole-rock" chips have low $^{87}Sr/^{86}Sr$ and low $^{87}Rb/^{86}Sr$ (36).

Discussion

Four independent lines of evidence suggest that the four boulders from the Apollo 17 landing site were derived by a common process from a common source during a single impact event occurring about 4 billion years ago. Petrographic, chemical and isotopic similarities abound, although differences, especially petrographic, do exist. Chemically and isotopically it appears that the breccias and melt rocks found in the Station 7 and 6 boulders, in 73215, and in parts of boulder 1, Station 2 are the same, quite probably originating from the same melt sheet. Portions of boulder 1, Station 2 have slightly different major element chemistry, reflecting a higher plagioclase content. The trace element and isotopic similarity to the other boulders, as well as the age, suggest that 72255 is neither a product of a different impact nor a different melt sheet, but simply a more plagioclase-rich portion of the breccia.

Insufficient data exist to explain or model in detail physical processes by which the boulders were formed, but the textural similarities to terrestrial impact melts and the similar behavior of major and trace elements and Rb/Sr isotopes, suggest that these melts were derived by impact. The details of the process will have to await further studies of terrestrial impact craters where geological controls are available.

Enough data exist to provide a sketch of the original target area. Clast populations of the Boulders, and boulders like 78235, which appear as heavily shocked clasts (like 77215) in the matrices of the Apollo 17 breccias, indicate that the source area was a differentiated norite or gabbro body, possibly containing a small amount of dunite (see also (22)). These rocks are about 4.4 to 4.5 billion years old. We can say nothing conclusive about their depth beneath the lunar surface, although cratering dynamics do suggest that they could have been relatively shallow (37, 38).

This differentiated crust was impacted about 3.9 to 4 billion years ago, judging from the preponderance of dates ($^{40}Ar/^{39}Ar$) clustering around that time. It is not certain that this is the time of impact because all dated samples contain small lithic fragments and xenocrysts from the original target rocks, and because good agreement with Rb/Sr dates does not exist. Most of the $^{40}Ar/^{39}Ar$ plateau ages are derived from portions of the release spectrum, because either the lower or higher temperature portions of the pattern are irregular. This type of age analysis has not yet been done systematically on terrestrial impactites. Such analyses would aid in understanding the age significance of the release spectra.

The available data from other rocks at the Apollo 17 site suggest that the breccias at this site were all derived at the same time, by a single impact event. Whether or not this event corresponds to one of the large gasin-forming events cannot be conclusively proved, although meteoritic trace elements do suggest that the Serenitatis event produced this melt (39). It does appear that the Apollo 17 site melt rocks and breccias belong to a single melt sheet. Finally, it is of interest to note that the matrix composition is quite different from the highland component in the Apollo 17 soils. This is odd, and suggests that the common assumption that the soil compositions reflect the rock compositions at a landing site needs to be reevaluated.

References

(1) James, O.B., A. Brecher, D.P. Blanchard, J.W. Jacobs, J.C. Brannon, R.L. Koroten, L.A. Haskin, H. Higuchi, J.W. Morgan, E. Anders, L.T. Silver, K. Marti, D. Braddy, I.D. Hutchean, T. Kirsten, J.F. Kerridge, I.R. Kaplan, C.T. Pillinger and L.R. Gardiner (1975). Consortium studies of matrix of light gray breccia 73215. Proc. VI Lunar Sci. Conf., 547-578.

(2) Wood, J.A. (1974). Investigations of a KREEPY stratified boulder from the South Massif. Lunar Sci. V, Supplement A, 4-7.

(3) Phinney, W.C., E. Anders, D. Bogard, P. Butler, E. Gibson, W. Gose, G. Heiken, C. Hohenberg, L. Nyquist, W. Pearce, M. Rhodes, L. Silver, C. Simonds, D. Strangway, G. Turner, R. Walker, J. Warner and D. Yuhas (1974). Progress Report: Apollo 17, Station 6, Boulder Consortium. Lunar Sci. V, Supplement At, 7-13.

(4) Chao, E.C.T., J.A. Minkin and C.L. Thompson (1974). Preliminary petrographic description and geologic implications of the Apollo 17 Station 7 boulder consortium samples. Earth and Planet. Sci. Lett. 23, 413.

(5) Simonds, C.H., W.C. Phinney and J.L. Warner (1974). Petrography and classification of Apollo 17 non-mare rocks with emphasis on samples from the Station 6 boulder. Proc. V Lunar Sci., Conf., 319-337.

(6) Winzer, S.R., D.F. Nava, S. Schuhmann, R.K.L. Lum and J.A. Philpotts (1975). Origin of Station 7 Boulder, a Note. Proc. VI Lunar Sci. Conf. V-1, 707-711.

(7) Reed, V.S. and E.W. Wolfe (1975). Origin of the Taurus-Littrow Massifs. Proc. VI Lunar Sci. Conf., 2443-2461.

(8) Grieve, R.A.F. (1975). Petrology and chemistry of impact melt at Mistastin Lake Crater, Labrador. Geol. Soc. Amer. Bull. 86, 1617-1629.

(9) Grieve, R.A.F., A.G. Plant and M.R. Dence (1974). Lunar impact melts and terrestrial analogues: Their chracteristics, formation, and implications for lunar crustal evolution. Proc. V Lunar Sci. Conf. V-1, 261-273.

(10) Dence, M.R. (1971). Impact Melts. Jour. Geophys. Res. 76, 5552-5565.

(11) Winzer, S.R. (1972). The Steen River Astrobleme, Alberta, Canada. Proc. 24th Int. Geol. Congr. Sec. 15, 148-156.

(12) Schnetzler, C.C., J.A. Philpotts and H.H. Thomas (1967). Rare-Earth and barium abundances in Ivory Coast tektites and rocks from the Bosumtwi Crater area, Ghana, Geochim. et Cosmochim. Acta 31, 1987-1993.

(13) Nava, D.F. and J.A. Philpotts (1973). A lunar differentiation model in light of new chemical data on Luna 20 and Apollo 16 soils. Geochim. Cosmochim, Acta 37, 963-973.

(14) Chao, E.C.T., J.A. Minkin and C.L. Thompson (1976). The petrology of 77215, a noritic impact ejecta breccia. Lunar Sci. VII, 129-131.

(15) Blanchard, D.P., L.A. Haskin, J.W. Jacobs, J.C. Brannon and R.L. Korotev (1974). Major and trace elements in rocks 72215, 72235, 72255 and 72275 from Boulder 1, Station 2, Apollo 17 in Wood, J.A., Interdisciplinary Studies of Samples from Boulder 1, Station 2, Apollo 17 (preprint).

(16) Haskin, L.A., D.P. Blanchard, R. Korotev, J.W. Jacobs, J.A. Brannon, R.S. Clark and A.G. Herrmann (1974). Major and trace element concentrations in samples from 72275 and 72255 in Wood, J.A., Interdisciplinary Studies of Samples from Boulder 1, Station 2, Apollo 17, V-1 (preprint), 121-130.

(17) James, O.B., D.P. Blanchard, J.W. Jacobs, J.C. Brannon, L.A. Haskin, A. Brecher, W. Compston, K. Marti, G.W. Lugman, J. Gros, H. Takahashi and D. Braddy (1976). Consortium studies of aphanitic lithologies and two anorthositic gabbro clasts in breccia 73215. Lunar Sci. VII, 423-425.

(18) Simonds, C.H. (1975). Thermal regimes in impact melts and the petrology of the Apollo 17 Station 6 boulder. Proc. VI Lunar Sci. Conf., 641-672.

(19) Winzer, S. R., D. F. Nava, R. K. L. Lum, S. Schuhmann, P. Schuhmann and J. A. Philpotts (1975b). Origin of 78235, a lunar norite cumulate. Proc. VI Lunar Sci. Conf., 1219-1230.

(20) Chao, E. C. T., J. A. Minkin, C. L. Thompson and J. S. Huebner (1975). The petrogenesis of 77115 and its xenocrysts: Description and preliminary interpretation. Proc. VI Lunar Sci. Conf., 493-516.

(21) McCallum, I. S., E. A. Mathez, F. P. Obamura and S. Ghose (1975). Petrology of noritic cumulates: Samples 78235 and 78238. Lunar Sci. VI, 534-536.

(22) Dymek, R. F., A. L. Albee and A. A. Chodos (1975). Comparative petrology of lunar cumulate rocks of possible primary origin: Dunite 72415, troctolite 76535, norite 78235 and anorthosite 62237. Proc. VI Lunar Sci. Conf., 301-342.

(23) Stoeser, D. B., R. W. Wolfe, J. A. Wood and J. F. Bower (1974). Petrology in Wood, J. A., Interdisciplinary Studies of Samples from Boulder 1, Station 2, Apollo 17, VI, 35-110.

(24) Winzer, S. R., D. F. Nava, S. Schuhmann, C. W. Kouns, R. K. L. Lum and J. A. Philpotts (1974). Major, minor and trace element abundances in samples from the Apollo 17 Station 7 boulder: Implications for the origin of early lunar crustal rocks. Earth and Planet. Sci. Lett. 23, 439-444.

(25) Stettler, A., P. Eberhardt, J. Geiss, N. Grogler and S. Guggisberg (1975). Age sequence in the Apollo 17 Station 7 boulder. Lunar Sci. VI, 771-773.

(26) Nunes, P. D., N. Nakamura and M. Tatsumoto (1976). 4.4 B. Y.-old clast in boulder 7, Apollo 17. Lunar Sci. VII, 631-632.

(27) Leich, D. A., S. B. Kahl, A. R. Kirschbaum, S. Niemeyer and D. Phinney (1974). Rare gas studies of Boulder 1 rocks 72255 and 72275, in Wood, J. A., Interdisciplinary Studies of Samples from Boulder 1, Station 2, Apollo 17.

(28) Gray, C. M., W. Compston, J. J. Foster and R. Rudowski (1975). Rb/Sr ages of clasts from within Boulder 1, Station 2, Apollo 17, in Wood, J. A., Interdisciplinary Studies of Samples from Boulder 1, Station 2, Apollo 17, V-2.

(29) Hartung, J. R., M. R. Dence and J. A. S. Adams (1971). Potassium-argon dating of shock metamorphosed rocks from the Brent impact crater, Ontario, Canada. J. Geophys. Res. 76, 5437-5448.

(30) Winzer, S. R., R. K. L. Lum and S. Schuhmann (1976). Rb, Sr and Sr isotopic compositions, K/Ar ages and large-ion-lithophile trace element abundances in rocks and glasses from the Wanapitei Lake impact structure. Geochim. Cosmochim. Acta, 40, 51-57.

(31) Schnetzler, C.C., W.H. Pinson and P.M. Hurley (1966). Rubidium-Strontium age of the Bosumtwi Crater area, Ghana, compared with the age of the Ivory Coast tektites. Sci. 151, 817-819.

(32) Schnetzler, C.C., J.A. Philpotts and W.H. Pinson (1969). Rubidium-Strontium correlation study of moldavites and Ries Crater material. Geochim. Cosmochim. Acta 33, 10-15-1021.

(33) Compston, W. and C.M. Gray (1974). Rb/Sr age of the Civet Cat Clast, 72255, 41, in Wood, J.A., Interdisciplinary Studies of Samples from Boulder 1, Station 2, Apollo 17, 139.

(34) Tatsumoto, M., P.D. Nunes, R. J. Knight and D.M. Unruh (1974). Rb-Sr and U-Th-Pb systematics of Boulders 1 and 7, Apollo 17. Lunar Sci. V, 774-776.

(35) York, D. (1966). Least-squares fitting of a straight line. Can. Jour. Phys., 44, 1079-1086.

(36) Papanastassiou, D.A. and G.J. Wasserburg (1975). Rb/Sr study of a lunar dunite and evidence for early lunar differentiates. Proc. VI Lunar Sci. Conf., 1467-1490.

(37) Schoenfeld, E. (1975). A model for anorthositic gabbros. Lunar Sci. VI, 715-717.

(38) Head, J.W., M. Settle and R. Stein (1975). Volume of material ejected from major lunar basins: Implications for the depth of excavation of lunar samples. Lunar Sci. VI, 352-354.

(39) Morgan, J.W., R. Ganapathy, H. Higuchi, U. Krähenbühl and E. Anders (1974). Lunar basins: Tentative characterization of projectiles, from meteoritic elements in Apollo 17 boulders. Proc. V Lunar Sci. Conf., 1703-1736.

TABLE 1

Major Element Abundances in Samples from Station 7 Boulder*

	77135, 52 Troctolite	77135, 82 Matrix	77135, 91 Matrix	77215, 115 Black Dike	77215, 119 Dike	77215, 121 Dike	77215, 130 Gray Glass	77215, 152 Matrix
SiO_2	44. 4	47. 5	46. 3	46. 8	47. 2	46. 0	51. 1	51. 1
TiO_2	0. 24	1. 45	1. 31	1. 37	1. 35	1. 32	0. 37	0. 30
Al_2O_3	27. 81	17. 18	19. 82	17. 44	16. 89	17. 75	14. 32	13. 98
MgO	7. 96	12. 66	11. 78	13. 16	12. 93	12. 74	13. 23	14. 31
CaO	15. 09	10. 91	11. 74	10. 88	10. 76	10. 94	9. 08	8. 65
Na_2O	0. 41	0. 66	0. 56	0. 65	0. 68	0. 68	0. 55	0. 39
FeO	4. 19	9. 01	8. 28	9. 39	9. 36	9. 04	10. 32	10. 38
MnO	0. 05	0. 11	0. 10	0. 12	0. 12	0. 11	0. 17	0. 17
P_2O_5	0. 03	0. 29	0. 21	0. 28	0. 27	0. 26	0. 10	0. 14
Cr_2O_3	0. 09	0. 18	0. 16	0. 19	0. 20	0. 14	0. 36	0. 36
K_2O	0. 07	0. 41	0. 21	0. 24	0. 23	0. 24	0. 15	0. 18
Total	100. 34	100. 36	100. 47	100. 52	99. 99	99. 22	99. 75	99. 96

*All data in weight percent

TABLE 2

Large-Ion-Lithophile Trace Elements in Phases From 77215*

	77215, 152 Opx	77215, 152 Plag	77215, 152 Matrix	77215 $D_{opx/plag}$	78235 $D_{opx/plag}$	77215, 115 B.D. Black Dike
Li	11.4	13.6	12.4	.92	-	21.0
K	208	2240	1180	.18	-	2230
Rb	0.624	4.60	3.21	.19	-	6.51
Sr	20.1	238	102	.20	-	171
Ba	29.3	305	154	.10	.24	350
Ce	4.92	15.9	24.6	.31	.38	84.4
Nd	3.54	9.03	15.5	.39	.50	51.9
Sm	1.50	2.14	4.40	.70	.79	14.4
Eu	0.200	2.28	1.03	.09	.09	1.93
Gd	-	-	5.21	-	-	--
Dy	4.93	2.21	6.64	2.2	3.3	19.6
Er	4.04	1.15	4.57	3.5	6.1	10.0
Yb	5.10	0.973	4.88	5.2	8.5	8.59
Lu	0.775	0.115	0.592	6.7	-	1.76
Zr	91.4	51.8	-	1.8	-	419
Hf						

	77215, 119 Dike	77215, 121 Dike	77215, 130 Gray Glass	77215, 115 White Contact Separate	77135, 82 Matrix	77135, 91 Matrix
Li	21.9	26.5				
K	1700	2040				
Rb	6.48	6.26				
Sr	169	174	103	104	177	171
Ba	349	336	154	166	360	294
Ce	73.3	79.1	29.6	39.8	82.8	59.2
Nd	51.7	50.1	18.0	23.4	53.2	41.1
Sm	14.5	13.8	5.05	6.51	14.8	11.2
Eu	1.90	1.97	1.01	1.06	1.97	1.80
Gd	--	--		7.29		
Dy	19.4	18.4	7.31	9.08	18.3	15.1
Er	--	10.7	4.44	5.67	11.4	8.16
Yb	10.5	9.94	4.45	5.80	10.6	8.11
Lu		1.68	.835	.845	1.18	1.17
Zr			147	139		
Hf		3.01 (ave)				

*In PPM

TABLE 3

Ages of Apollo 17 Boulders

Sample	Age ($^{40}Ar/^{39}Ar$), B. Y.	Age Rb/Sr, B. Y.	Reference
Station 7			
77075	3.96 - 3.99	--	(25)
77115	3.85 - 3.91	--	(25)
77135	3.85 - 3.90		(25)
77215		4.42	(26)
73215	3.9 - 4.2		(1)
Boulder 1, Station 2			
72255	3.99	4.4 (mixing)	(28)
72275		4.0	(28)
Station 6			
76015		4.0 - 4.1	(3)

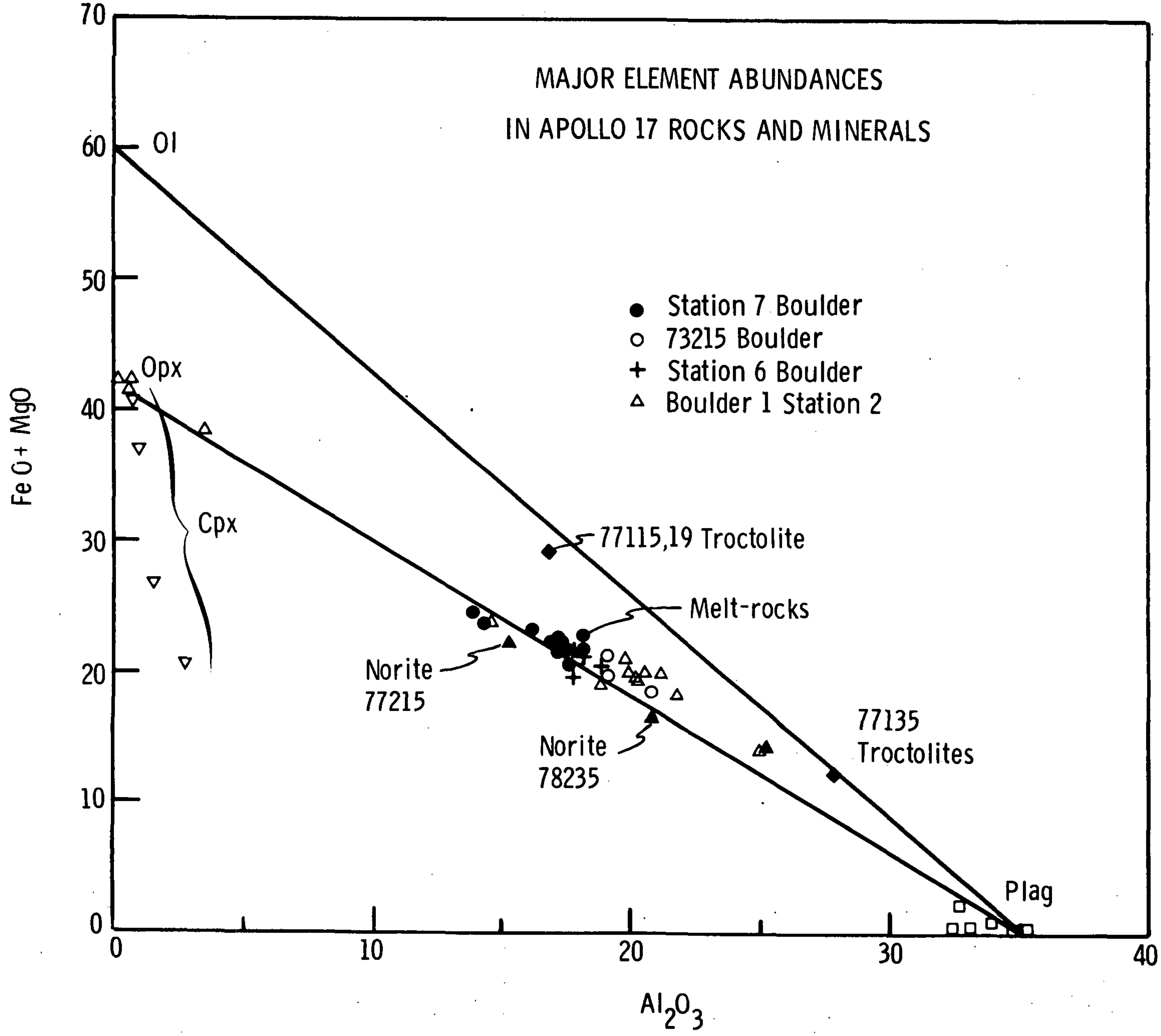
Figure Captions

Figure 1. Major element chemistry of melt rocks, rocks and minerals from the Apollo 17 landing site. See text for data sources.

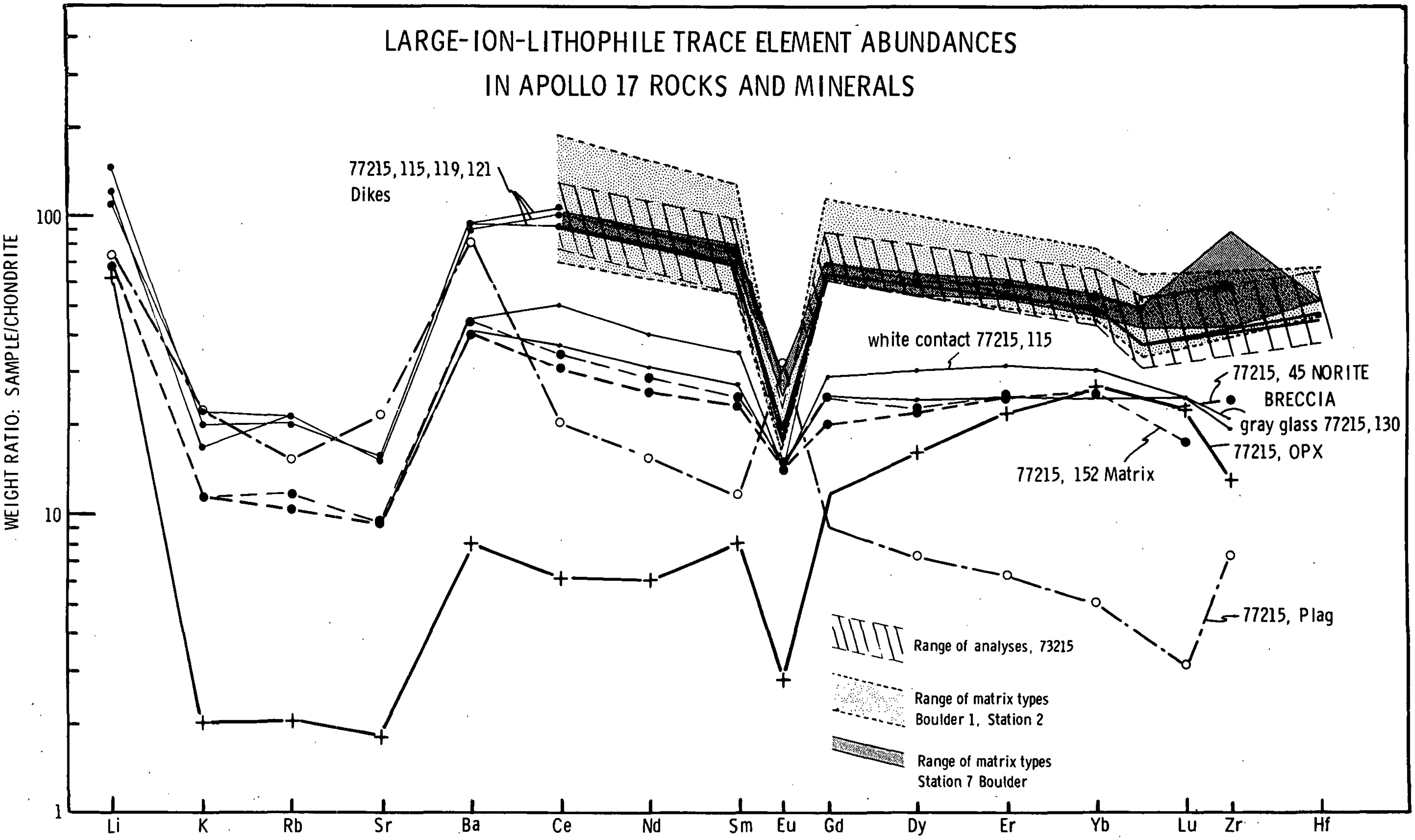
Figure 2. Possible cumulate texture in 77215. Elongated orthopyroxene crystal in plagioclase interstices.

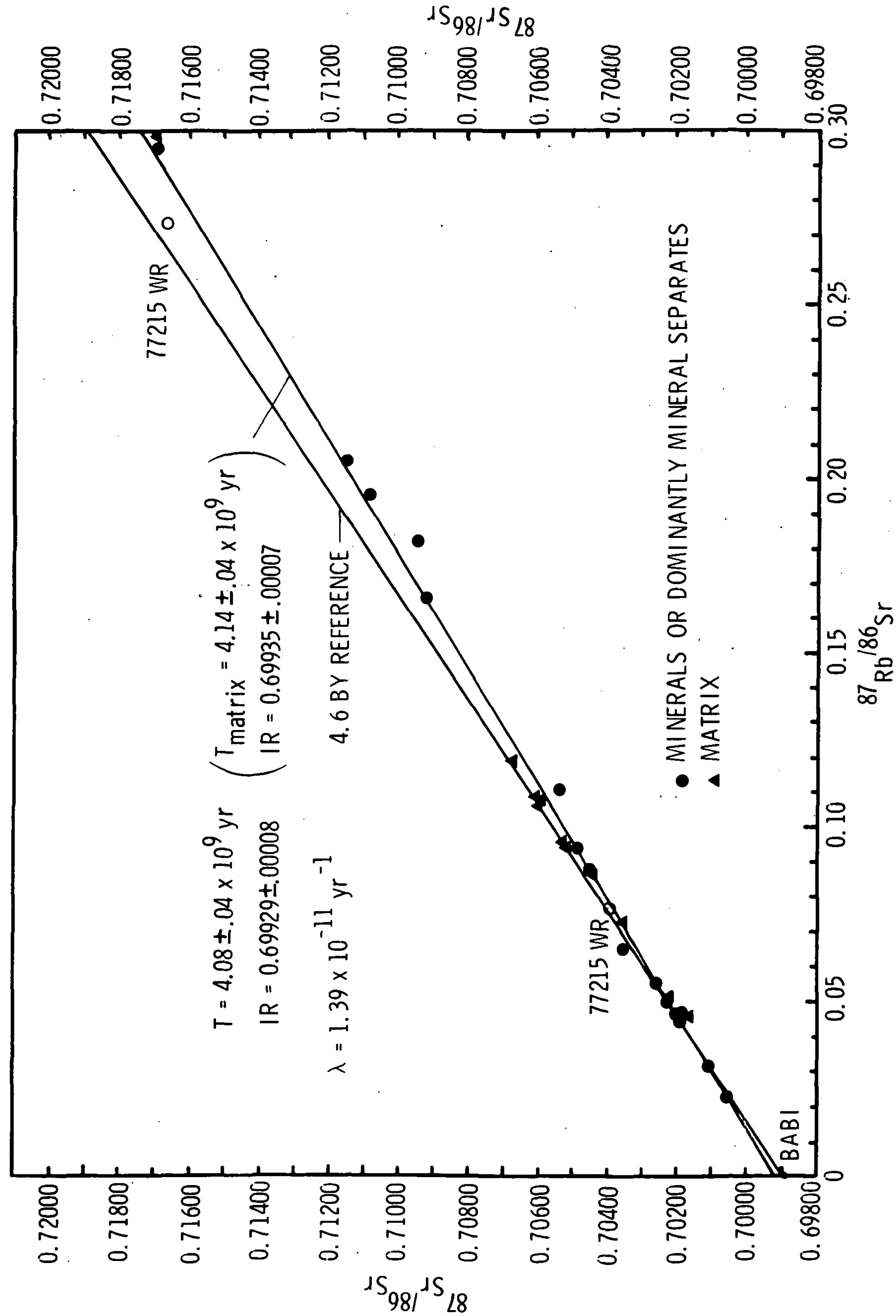
Figure 3. Large-ion-lithophile trace element abundances in rocks and minerals from the Apollo 17 landing site. See text for data sources.

Figure 4. Rb/Sr evolution diagram for Apollo 17 melt rocks and selected minerals. See text for data sources.


MAJOR ELEMENT ABUNDANCES
IN APOLLO 17 ROCKS AND MINERALS
Station 7 Boulder
73215 Boulder
Station 6 Boulder
Boulder 1 Station 2
Ol
Opx
Cpx
77115,19 Troctolite
Melt-rocks
Norite
77215
Norite
78235
77135
Troctolites
Plag
Fe O + MgO
Al_2O_3
70
60
50
40
30
20
10
0
0
10
20
30
40


0.2 mm


LARGE-ION-LITHOPHILE TRACE ELEMENT ABUNDANCES
IN APOLLO 17 ROCKS AND MINERALS
77215, 115, 119, 121
Dikes
white contact 77215, 115
77215, 45 NORITE
BRECCIA
gray glass 77215, 130
77215, OPX
77215, 152 Matrix
77215, Plag
Range of analyses, 73215
Range of matrix types
Boulder 1, Station 2
Range of matrix types
Station 7 Boulder
WEIGHT RATIO: SAMPLE/CHONDRITE
100
10
1
Li
K
Rb
Sr
Ba
Ce
Nd
Sm
Eu
Gd
Dy
Er
Yb
Lu
Zr
Hf



$^{87}Sr/^{86}Sr$
0.72000
0.71800
0.71600
0.71400
0.71200
0.71000
0.70800
0.70600
0.70400
0.70200
0.70000
0.69800
0
0.05
0.10
0.15
0.20
0.25
0.30
$^{87}Rb/^{86}Sr$
77215 WR
77215 WR
BABI
$T = 4.08 \pm .04 \times 10^9$ yr
$IR = 0.69929 \pm .00008$
$\lambda = 1.39 \times 10^{-11}$ yr^{-1}
$T_{matrix} = 4.14 \pm .04 \times 10^9$ yr
$IR = 0.69935 \pm .00007$
4.6 BY REFERENCE
● MINERALS OR DOMINANTLY MINERAL SEPARATES
▲ MATRIX