revised

14321

Clast-rich, Crystalline Matrix Breccia

8998 grams

Figure 1: Photograph of 14321,0 after cutting illustrating clastic nature. Note crumbly nature which led to many processing fines. NASA# S71-28403. Cube is 1 inch.

Introduction

Based on a stated desire of scientists interested in studies of the interaction of cosmic ray radiation with the lunar surface, the Apollo 14 astronauts collected several "football-sized" rocks, the largest of which was 14321 (which came to be known as Big Bertha). It was collected from near the edge of Cone Crater and is generally interpreted as a piece of the Fra Mauro Formation (Wilshire and Jackson 1972, Swann et al. 1972, 1977).

The "life and times" of Big Bertha were initially discussed in detail in a series of papers by Grieve et al. (1975), Duncan et al. (1975a, 1975b) and Morgan et al. (1975). These studies showed that 14321 was a clastic rock with a variety of lithic and microbreccia clasts (figures 1 - 5). The classification of fragmental breccias from the Fra Mauro Formation was reviewed by Simonds et al. (1977), who found that it was a crystalline matrix breccia (CMB) with about 30% clasts. Warner (1972) placed it in group 4, Chao (1972) group 2b, Wilshire and Jackson (1972) group F4 of their schemes of classification. Wilshire and Jackson suggest that F4 breccias were from the bottom part of the Fra Mauro Formation.

Kohl et al. (1978) showed that the depth profiles in 14321 for ^{53}Mn and ^{26}Al could be explained using the same parameters for cosmic rays as used for 14310 and 68815.

Two breccia guidebooks were prepared (Meyer and King 1979, Shervais et al. 1984), and these led to many studies of the breccia clasts. Shervais et al., in particular, gave an excellent review of what had been learned about this important breccia up to that point.

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note: 14321 has so many studies that they simply can't all be included in this compilation. Sorry!

Figure 2: Photograph of initial saw cut through 14321. This is the west face of 14321,37. The white clast is W1 (c2). The scale is in cm. NASA photo S78-33119.

The age of the Fra Mauro Formation and Imbrium Event is about 3.85 ± 0.02 b.y. (see review by Stöffler and Ryder 2001). The clasts in Apollo 14 breccias must necessarily be older than the event that created the breccias, and indeed such was found to be the case (see below). Conversely, the age of Imbrium must be younger than the youngest clast found included in the breccias, if these breccias were indeed formed by this event (Stadermann et al. 1991)!

The trace siderophile composition of the various lithologies of 14321 indicate that the last lithification event did not contribute significant additional meteoritic material.

Petrography

The breccia matrix was studied by SEM petrography by Lally et al. (1972) and Phinney et al. (1977). The matrix is mostly crystalline with grain size 1-5 microns and microvoid space 15-20% (figure 5). Phinney et al. describe the matrix as crystalline, moderately coherent and the result of sintering in hot ejecta blanket

Figure 3: Photo of 14321,1408 illustrating light breccia matrix with dark aphanitic breccia clasts. Cube is 1 cm. Photo # S86-26402.

Figure 4: Photo #S85-36423 of 14321,46 illustrating large white troctolite clast (W-101, c1) and large basalt clast (B-102). Cube is about 1 cm.

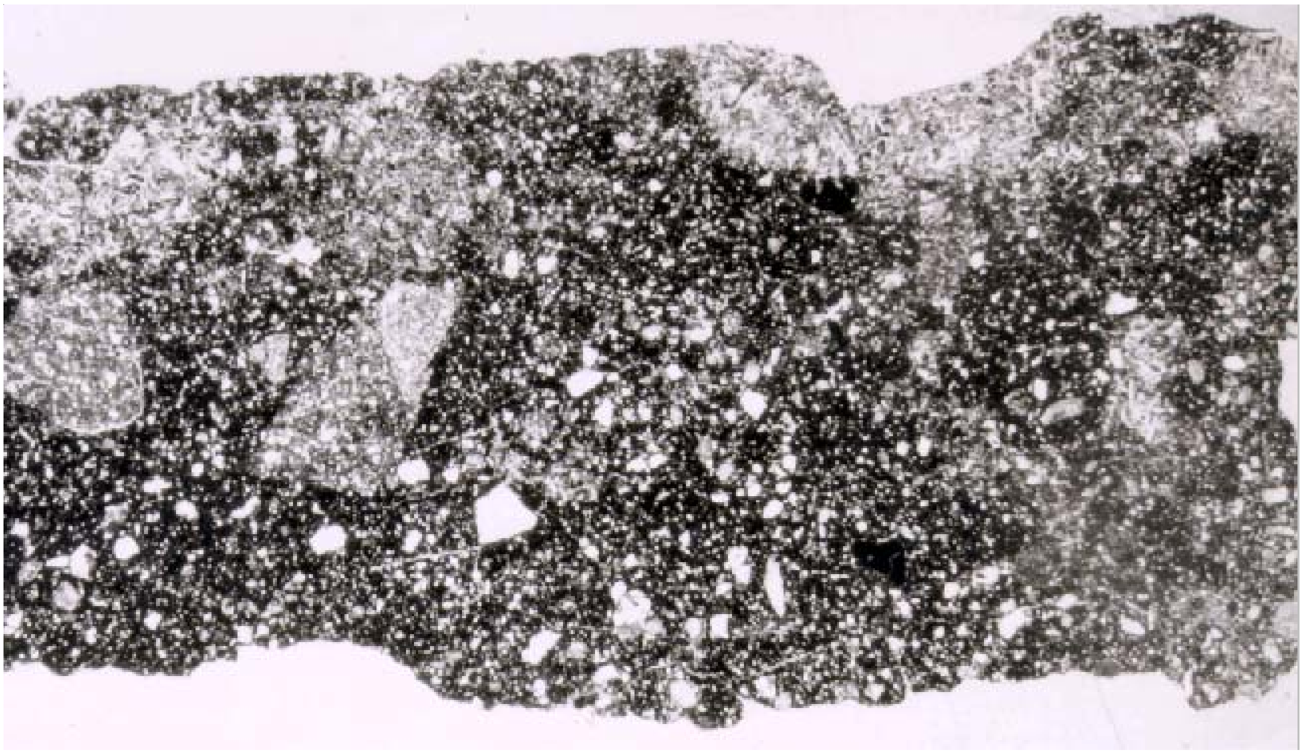

Figure 5: Thin section photomicrograph of breccia matrix of 14321,208. Note breccia-in-breccia texture and serate nature of matrix. Field of view is ~ 1 cm. NASA photo # S71-39078.

without digestion of clasts. On the other hand, Lally et al. attribute the recrystallization of the matrix as due to “shock sintering”. It should be noted that the rock proved to be quite “crumbly” during processing (figure 1).

Wilshire and Jackson (1972) and Grieve et al. (1975) found that 14321 was clast-rich with lithic clasts greater than 1 mm making up more than 30% of the rock. They noted that, in general, the clasts had not reacted with, nor been significantly resorbed by, the matrix. Some clasts are quite large and have received much attention (see below), but most are themselves microbreccias of the approximate same composition as the whole (albeit a darker color). The majority of the non-breccia clasts are aluminous basalts (some quite large). Some are referred to as olivine vitrophyre (Allen et al. 1979). Only a small number of possibly-pristine “plutonic” rock fragments were found (figure 4) and none of these were found to be “norite” nor “ferroan anorthosite” (*sensostricto*).

Lindstrom et al. (1972) and Duncan et al. (1975) found that the dark, microbreccia clasts contained more rare-earth-elements (La = 78 – 112 ppm) than the light matrix material (La = 27 – 51 ppm). The dark microbreccia also was found to contain small clasts of “micro norite” (Grieve et al. 1975), although no large clasts of this material were found.

Significant Clasts

Breccia 14321 has proven to be a treasure chest of important rock clasts from the crust of the moon, but the information for various clasts extracted from 14321 is spread out in the literature. Some clasts were large enough for analysis by several techniques (see table 4

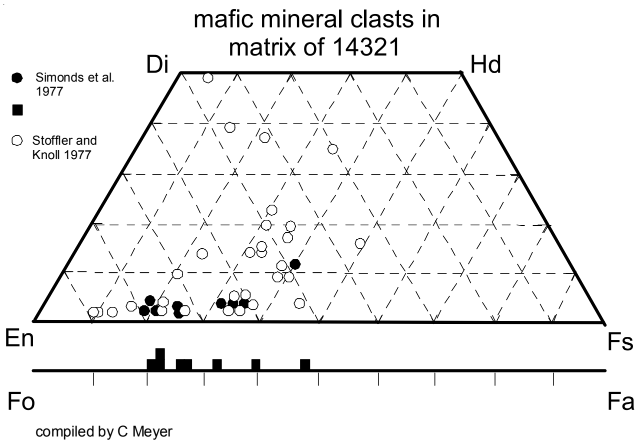

Figure 6: Composition of mafic minerals found as individual fragments in matrix of 14321 (data replotted from Simonds et al. 1977, Stoffler and Knoll 1977).

Figure 7: Photomicrograph of thin section of large basalt clast B-102 from 14321,46 (Meyer and King 1979).

for cross-correlation). Many small clasts are seen in thin section (figure 5).

Taylor et al. (1972) and Ware and Green (1977) reported on a troctolite clast as well as two basalt clasts. Wänke et al. (1972) determined the matrix composition as well as two igneous clasts. Allen et al. (1979) and Shervais et al. (1988) reported on olivine vitrophyre clasts in 14321. Shervais et al. (1983, 1985) analyzed 11 clasts and studied thin sections of them. Lindstrom et al. (1984) studied 7 additional clasts, including magnesian anorthosite, troctolite and "dunite". Dickinson et al. (1985) studied basalts from the processing fines. But Paul Warren made the most fuss, so we shall start with his observations:

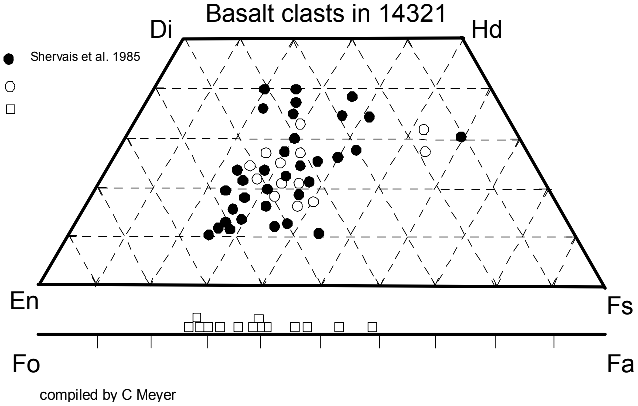

Figure 8: Composition of pyroxene and olivine in basalt fragments in 14321. Data replotted from many sources including Shervais et al. (1985).

Figure 9: Thin section photomicrograph of olivine vitrophyre clast in 14321 (this is figure 1b from Allen et al. 1979). Field of view is 0.5 mm.

c1 (W-101) from ,46 and ,116

Warren et al. (1981) reported that this large (18 x 12 mm) anorthositic troctolite was about 60% plagioclase (An_{96}) and 40% olivine (Fo_{88}), with trace orthopyroxene and diopside (figure 4). Apparently a second piece of this same clast was also studied by Lindstrom et al. (1984) and Shervais and McGee (1998). Warren et al. found it to be pristine (Ir = 0.053 ppb).

c2 (W-1) from ,37

Warren et al. (1981) studied this clast of anorthositic troctolite. It is mostly plagioclase (An_{95}) with some olivine (Fo_{87}) and trace ilmenite and chromite! Ir = 0.031.

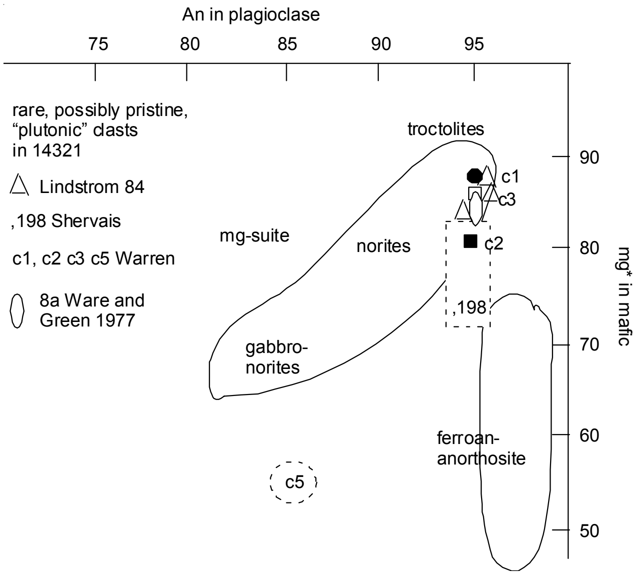

Figure 10: Plagioclase and mafic mineral composition of troctolite and anorthosite clasts in 14321 (data painfully extracted from Warren et al. 1981, 1983a,b, Ware and Green 1977, Lindstrom and Shervais 1984). Note the fields for known lunar plutonic rocks (after James 1980).

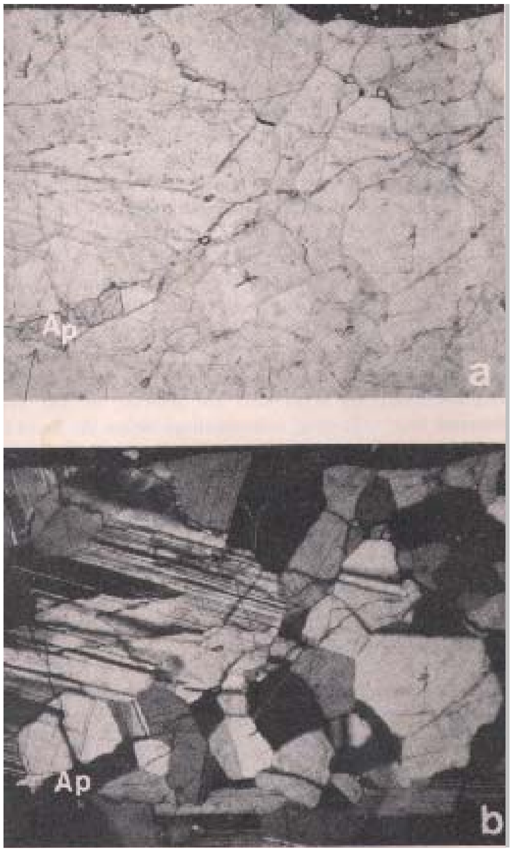

Figure 12: Thin section photomicrograph of magnesian anorthosite clast in 14321,1273 (figure 1 from Lindstrom et al. 1984). Scale is 2.3 mm across.

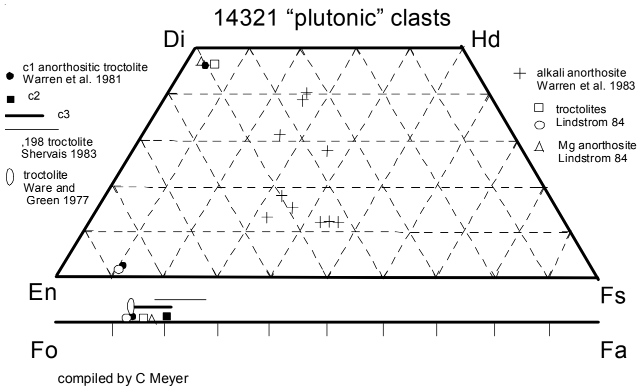

Figure 11: Pyroxene and olivine composition diagram for rare, possibly-pristine, "plutonic" clasts in 14321 (replotted from Warren et al. 1981, 1983a,b, Shervais et al. 1983 and Lindstrom et al. 1984).

c3 ,1035

Warren et al. (1983a) analyzed this small clast and found it was a Mg-rich anorthositic troctolite with about 70% plagioclase (An_{95}), 30% olivine (Fo_{85}) and trace pyroxene and opaque. Ir = 0.58.

c4 ,1027

Warren et al. (1983a, b) analyzed a granite clast (1.8 g?) in 14321 (table 3). The mineralogical mode of this clast (14321,1027) was reported to be ~60% K-feldspar and 40% quartz with minor Fe-rich pyroxene, ilmenite and yttrobetafite (Meyer and Yang 1988) and zircon (Meyer et al. 1996). The graphic texture is that of intergrown K-spar and silica. Nyquist et al. (1983) and Shih et al. (1985, 1993) dated this clast as 4.09 ± 0.11 by Rb-Sr, 4.11 ± 0.2 by Sm-Nd (figure 27), and 4.06 ± 0.07 by K-Ca (figure 26), while Meyer et al. (1996) dated the U-rich zircon in this granite clast at 3.965 b.y. by U-Pb. Warren et al. found it to be pristine (Ir = 0.047 ppb).

c5 ,1060

Warren et al. (1983b) analyzed a plagioclase-rich clast (6 x 3.5 mm) they termed alkali anorthosite (table 3) that was extracted from 14321,117. This small clast was ~96% plagioclase (An_{77-89}), 1-2% whitlockite, 1-2% pyroxene (scatter) and1% ilmenite, with an annealed cataclastic texture. Warren et al. also give mineral compositions (figure 11). Ir = ?

8A from ,88 (0.5g)

The troctolite clast dated by Compston et al. (1972) at 3.74 ± 0.17 b.y. was analyzed and described by Ware

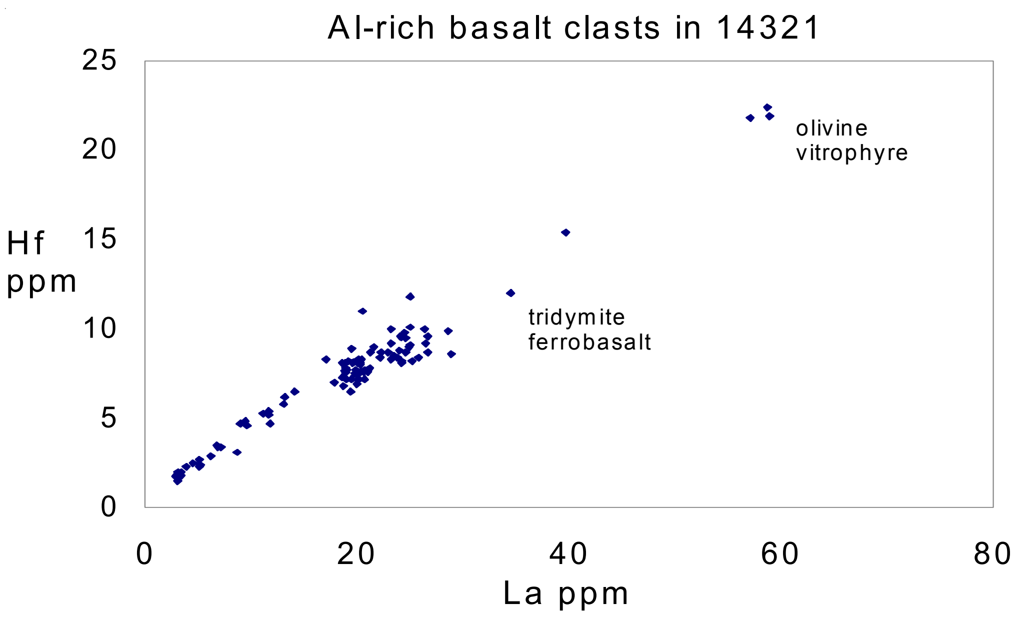

Figure 13: Composition of Al-rich basalt clasts in 14321 (Al2O3 = 11 - 14 %). Data replotted from Duncan et al. 1975, Shervais et al. 1985, Dickinson et al. 1985, Shervais et al. 1988 and Neal et al. 1989.

and Green (1977). It has 35% olivine (Fo$_{86}$), set in ~60% plagioclase (An$_{95}$) with minor whitlockite, ilmenite, chrome spinel and trace armalcolite and K-Ba feldspar. The olivine and plagioclase are unzoned (figure 10). It was also analyzed by Taylor et al. (1972) (table 3).

Sample 14321 contains (as clasts) a rich variety of low-Ti, aluminous mare basalts (Chao et al. 1972, Taylor et al. 1972, Wänke et al. 1972, Duncan et al. 1975a,b, Grieve et al. 1975, Ware and Green 1977, Takeda et al. 1980, Shervais et al. 1984, Dickinson et al. 1985, Neal et al. 1988, 1989). Although these basalt clasts have relatively uniform major-element compositions, they are reported to have an eight-fold variation in "incompatible trace elements" (Dickinson et al. 1985, Neal et al. 1989). The REE patterns vary from KREEP-like (group 1) to low and flat (group 5). Basalt clast groups 2-4 are intermediate, but all lack the bow-shaped pattern characteristic of mare basalts (Shervais et al. 1985). Group 3 basalts are roughly similar to sample 14053 (which may itself have been a clast in the Fra Mauro Formation). Neal et al. (1989b) provide a model for the origin of these aluminous basalts. Dickinson et al. (1985) analyzed 36 fragments of basalt from the processing fines (Meyer and King 1979) and found that they were all high alumina (HA). Neal et al. (1989) provided data for 26 additional fragments of HA basalt

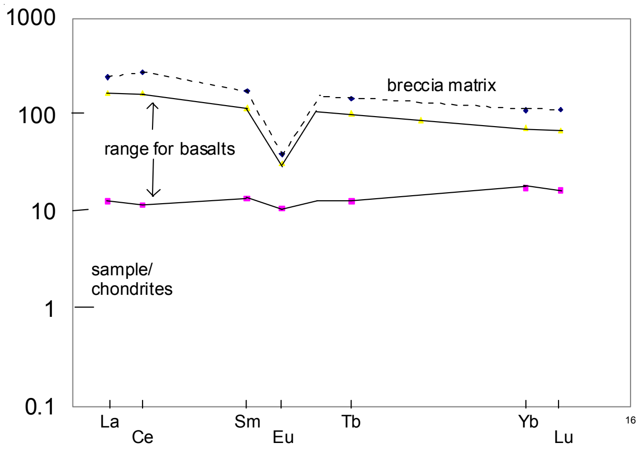

Figure 14: Noramlized rare-earth-element diagram for basalt clasts and matrix of 14321. Data from Neal et al. 1988, table 1 and 2.

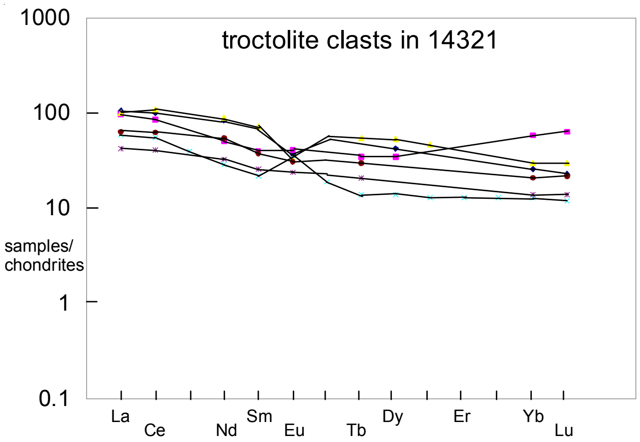

Figure 15: Normalized rare-earth-element patterns for troctolite clasts from 14321 (data from table 3).

from 14321. One of the largest basalt clasts in 14321 was B-102 (figure 4), but it is not clear whether it has been analyzed or dated (although it was probably sampled in one of the processing fines studied by Dickinson et al.)

Another group of basalts in 14321 were termed Olivine Vitrophyre Basalts (Allen et al. 1979). These were first seen in thin section only, but later recognized and analyzed by Shervais et al. (1988). The average olivine vitrophyre (AOV) composition is given in table 3A. Note that AOV is ~6 ppb Ir!

6A from ,88 (0.15g)
Basalt clast, similar to 14053, with ~20% olivine and equal quantities of plagioclase and pyroxene with fine grained ilmenite (Ware and Green 1977). Compston et al. (1972) dated this basalt at 4.05 ± 0.08 b.y.

4A from ,88 (0.15g)
Basalt clast with ~3% olivine, 5% opaques and more pyroxene than plagioclase (Ware and Green 1977). Compston et al. (1972) dated this clast – (revised downward to 4.08 ± 0.1 b.y. see de Laeter et al. 1973)

X1
Basalt clast X1 (Gancarz et al. 1971) is a subophitic to intergranular basalt composed of ~70% plagioclase and clinopyroxene (~25%) that was dated by Papanastassiou and Wasserburg (1971). It contained high Ni metal grains (Gancarz et al. 1971).

B1
Basalt clast found by Morgan et al. (1975) and Warren et al. (1979) to have low meteoritic siderophile content – thus pristine.

B-101 from ,46
This large basalt clast (figures 4 and 7) may not have been analyzed or dated yet!

Numerous clasts of troctolite, anorthosite, etc. are described in Lindstrom et al. (1984), Snyder et al. (1995), and Shervais and McGee (1998). Troctolite clast ,1379 was described by Snyder et al. as ~72% plagioclase (An_{94-96}), 27% olivine (Fo_{86-88}) with minor diopside ($Wo_{45-47}En_{49-51}$). See table 4 as a guide to these clasts. Note that norite, and or ferroan anorthosite clasts are absent from this clast collection (except perhaps

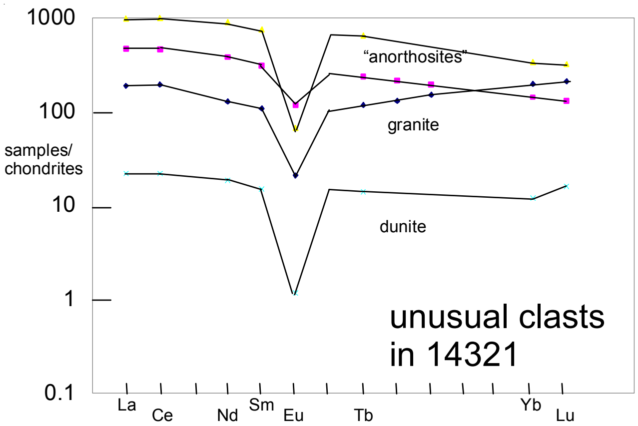

Figure 16: Normalized rare-earth-element patterns for unusual clasts in 14321 (data from table 3).

Figure 17: Thin section photomicrograph of troctolite clast in 14321,1241 (figure 5 from Lindstrom et al. 1994). Scale 2.3 mm across.

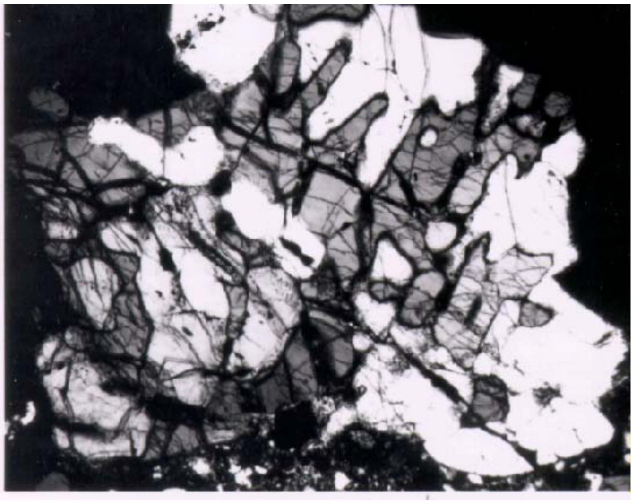

Figure 18: Thin section photomicrograph of granite clast in 14321, 1027 illustrating intergrown silica and K-feldspar (figure 6 from Meyer et al. 1996). Figure is 2.3 mm across.

Summary of Age Data for 14321 (in b.y.)

	Rb/Sr	Sm/Nd	Ar/Ar		
Breccia					
matrix?			3.93 ± 0.04 b.y.		Turner et al. 1971
matrix?			4.06 b.y. (total Ar)		York et al. 1972
Basalt Clasts					
“igneous”			3.92 (total Ar)		Turner et al. 1971
Clast “6A”	4.05 ± 0.08				Compston et al. 1972
Clast “4A”	4.08 ± 0.1				Compston et al. 1971, deLaeter
Clast 191 X1	3.95 ± 0.04				Papanastassiou, Wasserburg 1971
,371	3.99 ± 0.14				Mark et al. 1975
,184,55	4.01 ± 0.12				Mark et al. 1973, 1974
,184,1D			3.84 (total Ar)		York et al. 1972
,184,12B			3.94		York et al. 1972
,184,17B			3.83		York et al. 1972
Group 1	4.12 ± 0.08				Dash et al. 1987
Group 2	4.07 ± 0.03				Dash et al. 1987
Group 3 (14053)	*3.96 ± 0.04*				*Papanastassiou, Wasserburg 1971*
Group 4	4.12 ± 0.15	3.75 ± 0.35			Dash et al. 1987
Group 5	4.33 ± 0.13				Dash et al. 1987
Group 5’	4.24 ± 0.14				Dash et al. 1987
“Tridymite” bas.	4.01 ± 0.04	3.76 ± 0.48			Dash et al. 1987
				U/Pb	
Individual Zircons					
B1				4.010 ± 0.002	Meyer et al. 1996
B2				4.034 ± 0.023	(see also new data in
B8				4.112 ± 0.025	Nemchin et al. 2006)
B10				4.211± 0.008	
B11				4.209 ± 0.009	
B12				4.333 ± 0.005	
B13				4.371 ± 0.010	
B14				4.183 ± 0.010	
Granite	4.09 ± 0.11	4.11 ± 0.2	3.88		Shih et al. 1985, Nyquist et al. 1983
				4.06± 0.07 by K-Ca	Shih et al. 1993
Zircon				3.965 ± 0.005	Meyer et al. 1996
Troctolite “8a”	3.74 ± 0.17				Compston et al. 1972
Anorthosite ,16				~3.91 ± 0.02	Meyer et al. 1996

as minute fragments in the dark microbreccias (see Grieve et al. 1975).

Many more clasts are seen in thin section only (Wilshire and Jackson 1971, Chao et al. 1972). Gay et al. (1972) and Meyer et al. (1988) describe an anorthosite clast with ilmenite and zircon found in thin section 14321,16 and ,17. Steele (1972) and Steele and Smith (1975) describe a unique pink-spinel bearing clast in thin section 14321,76. Wilshire and Jackson pictured a melted and recrystallized granophyre clast.

Mineralogy

Olivine: Olivine compositions range widely (figures 6, 8 and 11). Steele and Smith (1975) and Grieve et al. (1975) determined the trace element contents of olivines.

Pyroxene: Pyroxene compositions of “mineral clasts” in the matrix are given in diagram form in Stöffler and Knöll (1977) and Simonds et al. (1977). Takeda et al. (1980) carefully studied chemical zoning in one of the high-Al basalts. Grieve et al. (1975) report exsolved

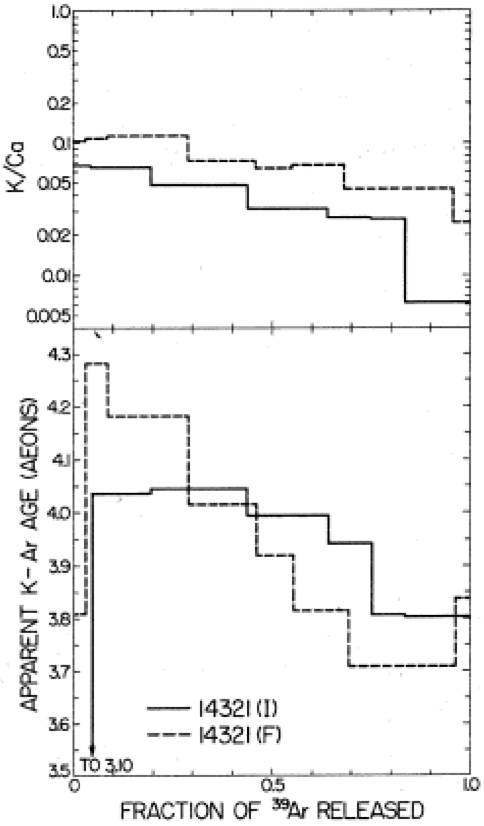

Figure 19: Ar release diagram for 14321 matrix (from Turner et al. 1971).

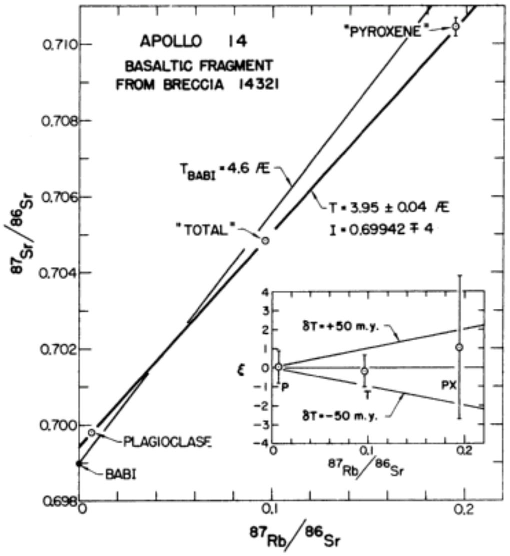

Figure 20: Rb-Sr internal isochron for basalt clast in 14321 (from Papanastassiou and Wasserburg 1971).

pyroxene as well as orthopyroxene. There is a higher proportion of orthopyroxene in the microbreccia lithologies than in the matrix.

Plagioclase: Grieve et al. found plagioclase ranged from An_{72} to An_{96}. Shervais and McGee (1998) studied

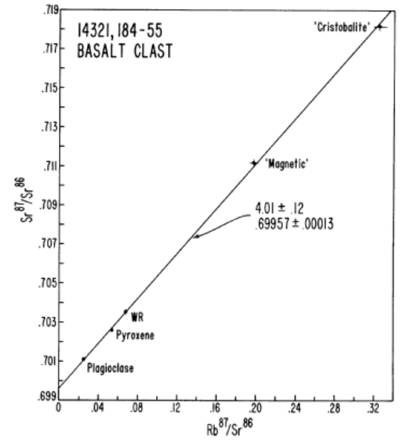

Figure 21: Rb-Sr internal isochron for basalt clast from 14321 (from Mark et al. 1973).

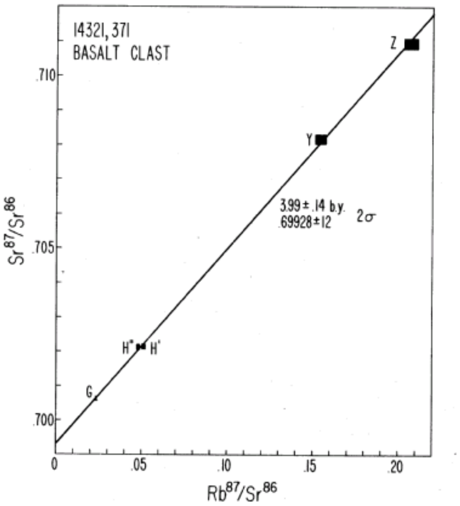

Figure 22: Rb-Sr isochron for basalt clast in 14321 (from Mark et al. 1975).

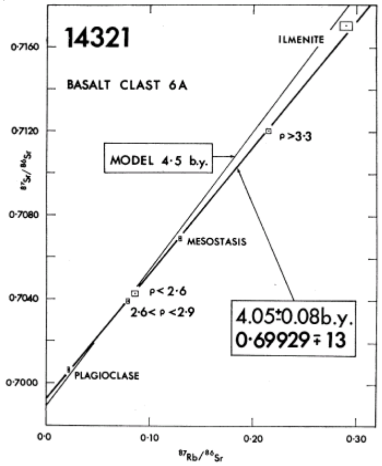

Figure 23: Internal isochron for Rb-Sr dating of basalt clast in 14321 (by Compston et al. 1972).

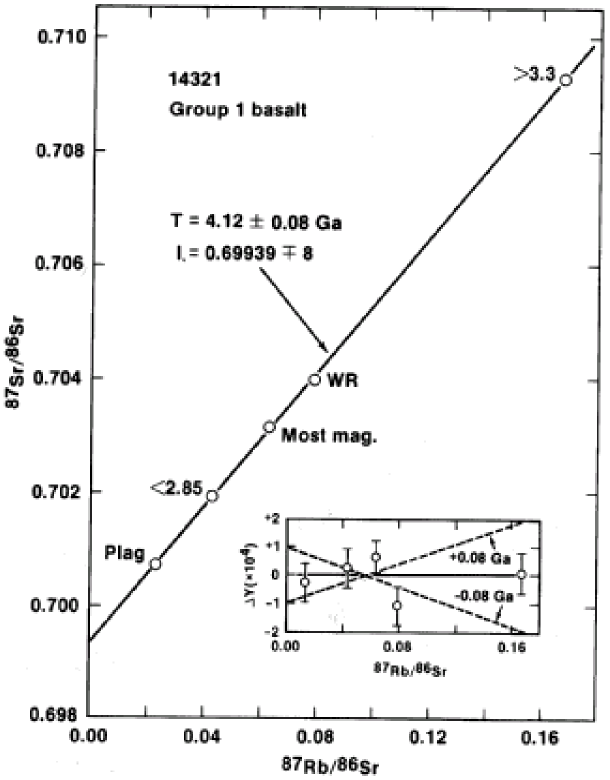

Figure 24: Internal isochron for basalt clast in 14321 (from Dash et al. 1987).

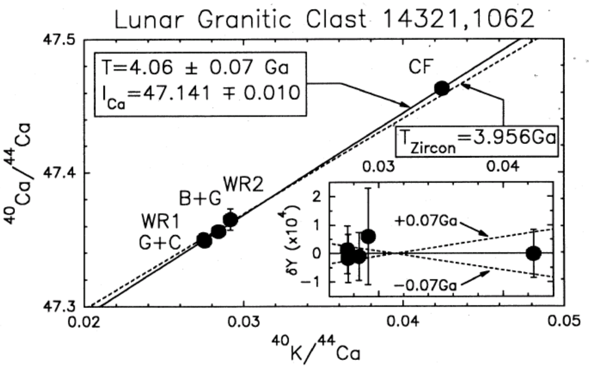

Figure 26: K-Ca internal isochron for granite clast in 14321, also dated by Rb-Sr, Sm-Nd and U/Pb in zircon (from Shih et al. 1993).

the REE patterns of plagioclase in troctolite and anorthosite clasts in 14321.

Phosphates: Grieve et al. reported apatite and whitlockite analyses. Ware and Green (1977) give an analysis of whitlockite in the troctolite clast 8A.

Opaques: Ilmenite is the most important opaque (Grieve et al.), but Ti-Cr spinels are also present. Steele (1972) analyzed the Cr-spinel. Sphene is also reported by Grieve et al.

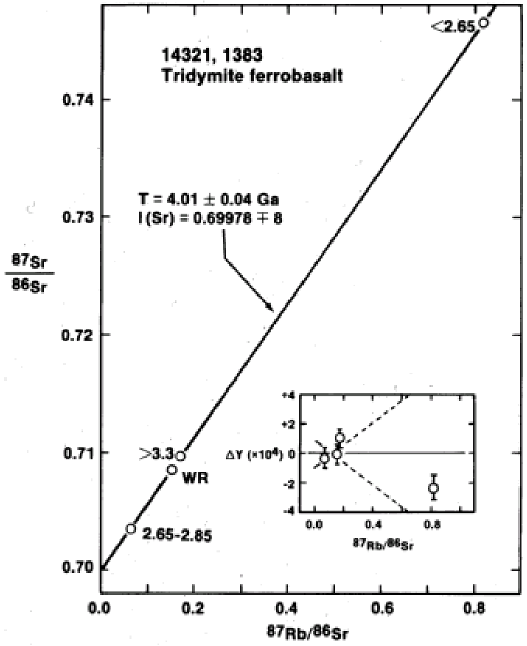

Figure 25: Internal isochron for basalt clast in 14321 (from Dash et al. 1987).

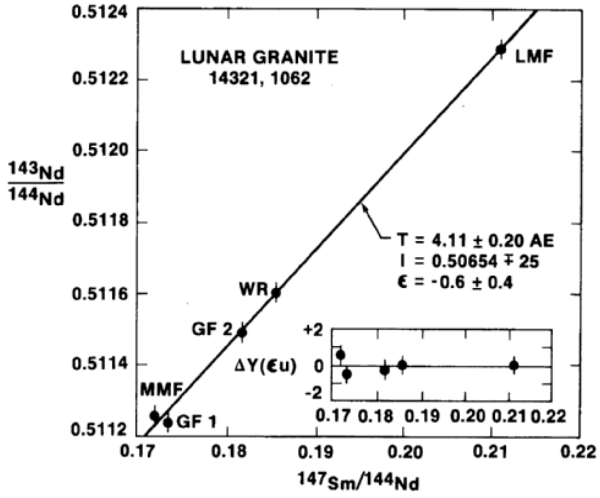

Figure 27: Sm-Nd internal mineral isochron for lunar granite clast 14321,1062 (from Shih et al. 1985).

Zircon: Braddy et al. (1975) determined the U content of 93 zircons extracted from 14321 (U = 15 – 400 ppm) . Meyer et al. (1996) and Nemchin et al. (2006, 2008) dated large zircons extracted from 14321 sawdust by ion microprobe (U = 8 – 900 ppm). Also see analysis of zircon in Grieve et al. (1975).

Yttrobetafite: Meyer and Yang (1988) found that this metamict mineral contained significant Nb and W.

Table 1a. Chemical composition of 14321 (matrix).

											Morgan 72					Scoon 72		Wanke 72	
reference	Eldridge 72			Kieth 72		Rancitelli72		LSPET 71	LSPET 71		Duncan 72					Masuda 72		Baedecker	
weight	*1.1kg*	*200 g*		*1.1 kg*		*72 g*					9A	9B	10A	13				184-25	
SiO2 %								48	50							47.78		47.7	
TiO2								2.4	1.5		2.27	2.28	2.01	2.08	(c)	2.06		1.3	
Al2O3								14	18		13.3	14.1	12.38	14.74	(c)	15.2		16.44	
FeO								13	9		15.4	13	15.05	12.86	(c)	12.25		10.7	
MnO								0.26	0.15		0.21	0.2	0.21	0.19	(c)	0.17		0.13	
MgO								12	11							10.73		11.27	
CaO								8.5	8.2							9.94		9.37	
Na2O								0.4	0.58		0.6	0.71	0.62	0.7	(c)	0.78		0.79	
K2O	0.48	0.47	(a)	0.48	(a)	0.49	(a)	0.33	0.56		0.17	0.24		0.31	(c)	0.62		0.56	
P2O5																0.41			
S %																0.07			
sum																			
Sc ppm								43	16	(b)	52.8	34.9	44.7	38.9	(c)			20	(c)
V								85	32	(b)	104	69	85	86	(c)				
Cr								2900	110	(b)	2920	1630	2800	2160	(c)			1070	(c)
Co								33	32	(b)	33.2	28.1	50.1	33.4	(c)			39	(c)
Ni								180	240	(b)								200	(c)
Cu								13	7	(b)									
Zn											2.8							35	(c)
Ga																		5.2	(c)
Ge ppb											240							160	(c)
As																			
Se											0.16								
Rb								7	14	(b)	3.6								
Sr								140	180	(b)									
Y								160	220	(b)									
Zr								670	860	(b)									
Nb								22	46	(b)									
Mo																			
Ru																			
Rh																			
Pd ppb																			
Ag ppb											1.1								
Cd ppb																		84	(c)
In ppb											7.3							3.4	(c)
Sn ppb																			
Sb ppb											15.3								
Te ppb																			
Cs ppm											0.23								
Ba								380	730	(b)		590	560	600	(c)				
La								40	65	(b)	27.3	58.2	35.6	51	(c)	70.6	(d)	99	(c)
Ce											82	172	119	138	(c)	193.4	(d)	230	(c)
Pr																			
Nd														55	(c)	114.2	(d)		
Sm											14.7	26.4	16.8	23.7	(c)	31.75	(d)		
Eu											1.55	2.23	1.74	1.96	(c)	2.647	(d)	3.03	(c)
Gd																37.01	(d)		
Tb											3.1	5.5	3.7	4.6	(c)			8.9	(c)
Dy																41.7	(d)	48	(c)
Ho																			
Er																25.63	(d)		
Tm																			
Yb								20	28	(b)	9.3	18.5	10.5	15.8	(c)	22.78	(d)	28	(c)
Lu											1.6	2.82	1.85	2.3	(c)	3.32	(d)	3.9	(c)
Hf											9.8	18	12.5	18.1	(c)			31	(c)
Ta												2.6	1.9	3.4	(c)			4	(c)
W ppb																			
Re ppb											0.06								
Os ppb																			
Ir ppb											0.71							5.2	(c)
Pt ppb																			
Au ppb											0.7								
Th ppm	12.7	10.8	(a)	12.7	(a)	13.3	(a)				3.6	12.2	6.2	9.2	(c)				
U ppm	3.9	2.9	(a)	3.6	(a)	3.42	(a)												

technique: (a) radiation counting, (b) emis. spec., (c) INAA, (d) IDMS

Table 1b. Chemical composition of 14321 (matrix and microbreccia clasts).

					Morgan 75		
reference	Strasheim 72	Boynton 75		Palme 78	Lindstrom 72		
weight	5 g				microbreccia clasts		
SiO2 %	48.1			48.01	184,15	184,14A	184,19A
TiO2	2.03			1.75	1.73	1.58	2.07
Al2O3	14.62	14.7		15.4	15.25	16.8	15.15
FeO	12.9	10.9		11.4	10.55	10.68	12.35
MnO	0.17			0.16	0.14	0.11	0.16
MgO	11			11.54			
CaO	10	9.24		9.44			
Na2O	0.69	0.73		0.78	0.88	0.81	0.81
K2O	0.42			0.56	0.96	0.52	0.46
P2O5	0.38			0.69			
S %				0.04			
sum							
Sc ppm		24.4	25	23.6	21.4	20.3	29.6
V	77				38	39	56
Cr	1642	1510	1540	1380	1180	1280	1620
Co	39	32	40	42.2	31.4	39	37.9
Ni	132	314		390			
Cu	9.9			4.55			
Zn		3.8		3.54	3.8	6.6	3.3
Ga		5.86		5.25			
Ge ppb		430		1100			
As				0.119			
Se				0.039	139	128	92
Rb	12			14.8	30.8	12.9	9.3
Sr	185			188			
Y	187			261			
Zr	708			1210	1070	720	820
Nb	59			75			
Mo							
Ru							
Rh							
Pd ppb							
Ag ppb					1.49	0.88	0.83
Cd ppb		18		300	17	298	52
In ppb		1.5			1.69	3.4	1.45
Sn ppb							
Sb ppb					2.1	2.2	2.4
Te ppb					8	11	6
Cs ppm				0.692	1.29	0.54	0.42
Ba	628	900	800	940	1140	1070	730
La		85	79	88	97.1	88.6	77.7
Ce		230	210	237	260	260	211
Pr				29.4			
Nd				142	150	125	147
Sm		38	35	34.3	46.9	42.2	37.6
Eu		2.51	2.59	2.69	3.34	3.42	2.7
Gd				43.6			
Tb		6.6	7	7.71	9.4	9.6	7.6
Dy		40		48.3			
Ho				10.4			
Er				29.3			
Tm				4.25			
Yb		26	26	28.3	32.6	30.5	25.5
Lu		3.5	3.6	3.89	4.35	4.3	3.5
Hf		23	22	29.2	32.1	29.5	24.1
Ta				3.9	7.3	6	6
W ppb				1800			
Re ppb				0.7	0.64	0.7	0.55
Os ppb							
Ir ppb		6.4		8	6.9	7.8	6.1
Pt ppb							
Au ppb		5.9		7.8	8.08	6.06	6.41
Th ppm		3.9		13.8			
U ppm				4.04			

Table 1c. Light and/or volatile elements for 14321.

	Eisenstraut 72				LSPET	LSPET 71	Morgan 72	Palme 78
Li ppm					18	19		35
Be	6.99	4.23	1.77	4.84	5.28	3.31	6.09	
B								
C					28			
S								
F ppm								
Cl								51
Br ppb							85	150
I								
Pb ppm								
Hg ppb								
Tl ppb							1.7	
Bi ppb							0.55	

Chemistry

Eldridge et al. (1972) determined bulk K, Th and U contents of large pieces by “radiation counting” (table 1) and these analyses probably give the best idea of the “whole rock” composition (compare with Palme et al. 1978). Scoon (1972) and Strasheim et al. (1972) give bulk analyses of the “whole rock”. Wänke et al. (1972), Boynton et al. (1975) and Palme et al. (1978) appears to have analyzed the matrix, while others may have analyzed only very small, unrepresentative portions of this massive breccia (table 1). Lindstrom et al. (1972), Duncan et al. (1975) and Morgan et al. (1975) showed that there were more rare-earth-elements and more meteoritic contamination (Ir, Au etc.) in the dark microbreccia clasts than in the light matrix of 14321. The parental rock type that provides the high REE content of the microbreccia, remains a mystery.

Table 2 tabulates only a few of the basalt analyses. They were all found to have uniformly high Al_2O_3. Duncan et al. (1975) analyzed 15 basalts, but did not match them with thin sections. Dickinson et al. (1985) analyzed 36 fragments of basalt, and found five (5) different groups. However, since their fragments were from the processing fines, presumably at least some were from the same broken basalt clast, yielding artificial groupings. Shervais et al. (1985) analyzed 13 more and Neal et al. (1988) an additional 26. When all the data are plotted, there appears to be a continuum of these basalts (figure 11). Figure 12 shows the REE patterns for some of the basalts.

Shervais et al. (1988) report the average composition of olivine vitrophyre clasts (AOV) – see table 3A. However, note that there is about 6 ppb Ir (non-pristine?)

Analyses of possibly-pristine, plutonic, rock clasts are given in table 3.

Radiogenic age dating

The age of the breccia matrix has not been well determined. Both Turner et al. (1971) and York et al. (1972) determined stair-step Ar release patterns for the matrix – yielding total K-Ar ages of 3.93 and 4.06 b.y. (but this can’t be right!). Clearly the matrix sample includes minerals of various old ages, which have not all been degassed of old Ar (figure 19).

Mark et al. (1973, 1974, 1975) dated several basalt and microbreccia clasts in 14321 by Rb-Sr (figures 21, 22). Compston et al. (1972), Papanastassiou and Wasserburg (1971), York et al. (1972) and Dash et al. (1987) have also dated the basalt fragments in 14321 (figures 20, 23, 24 and 25).

Compston et al. (1972) dated a “troctolite clast” (see table).

Meyer et al. (1996) dated zircons, including one in the granite clast analysed by Warren et al. (1983) and dated by Nyquist et al. (1983) and Shih et al. (1985) (figure 27). Nemchin et al. (2006, 2008) dated additional zircons from 14321, finding a wide range of ages.

Mark et al. (1975) first noted that the initial Sr ratios for basalt isochrons were distinctly different, such that they must be from different basalt flows and were not equilibrated when incorporated into the crystalline

Table 2. Chemical composition of some basalt clasts in 14321.

				Baedecker 72										
reference	Taylor 72		Duncan 75	Wanke 72	Neal 88		Dickenson 85					Shervais 85		
weight			Morgan 75	184-1E	low	high	group 1	group 2	group 3	group 4	group 5	tridymite	MB-4	
SiO2 %				47.7	42.8	48.9								
TiO2			2.02	1.78	2.56	2.41	2.2	2.1	2.7	2.3	2.6	6.49	2.57	(b)
Al2O3			11.96	12.28	11.1	13.7	12.7	12.3	12.5	12.1	11.8	9	13.4	(b)
FeO			16.34	16.7	20.1	14.2	16.2	16.8	16.9	16.8	17.5	22.8	15.9	(b)
MnO			0.22	0.23	0.24	0.19	0.22	0.23	0.24	0.24	0.24	0.3105	0.24	(b)
MgO				8.95	12.1	9.1	7.9	9.3	8.2	10.6	10.3	6.47	10.8	(b)
CaO				10.35	10.1	10.3	11.2	10.9	10.8	10.6	10.8	9	10.9	(b)
Na2O			0.54	0.55	0.46	0.6	0.6	0.51	0.42	0.36	0.39	0.294	0.52	(b)
K2O			0.13	0.17	0.07	0.36	0.16	0.13	0.009	0.007	0.007	0.5	0.14	(b)
P2O5														
S %														
sum														
Sc ppm			54.6	61	65.2	48.9	59	59	56	59	62	75.8	60.3	(b)
V			92		132	81	102	115	116	124	121	98	117	(b)
Cr			3200	3070	3270	2040	2531	3079	2326	3010	3147	2550	3350	(b)
Co			34.3	30	33.6	35.9	29	31	27	30	29	24.6	31.9	(b)
Ni				36	80							10	90	(b)
Cu														
Zn			2.9	3.7										
Ga				4										
Ge ppb			640	880										
As														
Se			0.338											
Rb	5.7	(a)	2.7									21	8	(b)
Sr	120	(a)										60	60	(b)
Y	74	(a)												
Zr	440	(a)					320	270	170	170	70	500	280	(b)
Nb	22	(a)												
Mo														
Ru														
Rh														
Pd ppb														
Ag ppb			0.6											
Cd ppb			24	7.9										
In ppb			1.84	3.7										
Sn ppb	200	(a)												
Sb ppb			0.78											
Te ppb			6											
Cs ppm	0.38	(a)	0.17									0.3	0.19	(b)
Ba	280	(a)					159	131	112	101	53	340	165	(b)
La	28	(a)	19	21	3.06	39.7	25	19.7	11.3	6.4	3.4	34.5	18.9	(b)
Ce	84	(a)	56	65	7	105	65	53	30	18	8	91.9	52.3	(b)
Pr	12	(a)												
Nd	46	(a)			5.2	62	40	34	21	10.8	6.3	56	35	(b)
Sm	14	(a)	10.8		2.14	17.6	12.5	10	6.6	3.7	2.3	16.9	9.92	(b)
Eu	1.5	(a)	1.34	1.4	0.6	1.78	1.45	1.3	1.24	0.88	0.71	1.05	1.19	(b)
Gd	17	(a)												
Tb	2.5	(a)	2.34	2.5	0.46	3.8	2.5	2.1	1.49	0.88	0.67	3.68	2.21	(b)
Dy	15	(a)		13			14.9	12.6	10.2	5.5	0.45			(b)
Ho	3.7	(a)												
Er	9.8	(a)												
Tm	1.5	(a)												
Yb	7.7	(a)	6.5	7.5	2.9	12.2	8.3	7	6	3.9	3.2	13.4	6.72	(b)
Lu			1.15	1.2	0.42	1.59	1.21	1.04	0.89	0.6	0.61	2.02	1.02	(b)
Hf	7.5	(a)	7.7	8	1.5	15.4	8.7	7.3	4.7	2.9	1.9	12	7.67	(b)
Ta			1.2	1.2	0.37	2.02	1.3	1.1	0.9	0.6	0.5	1.79	0.89	(b)
W ppb	200	(a)												
Re ppb			0.0051											
Os ppb														
Ir ppb			0.044	0.4										
Pt ppb														
Au ppb			0.3											
Th ppm	2.9	(a)	2.3			7.3	2.3	1.9	0.9	0.8	0.4	4.6	1.81	(b)
U ppm	0.71	(a)				2.6						1.2	0.46	(b)

***technique** (a) emiss. spec., (b) INAA*

Table 3a. Chemical composition of other clasts in 14321.

	troct.		igneous		troct.	troct	troct.	granite	alkali anor.		AOV
reference	Taylor 72		Wanke 72		Warren 81		Warren 82	Warren 83	Warren 83		Shervais 87
weight	8a		223		c1	c2	c3	c4	c5		
SiO2 %	43.5	(a)	47.5		42.8	41.94	42.8	74.2			46.5
TiO2	0.19	(a)	1.8		0.05	0.68	0.09	0.33			1.3
Al2O3	23.3	(a)	12.09		28.7	26.46	26.08	12.5			12.4
FeO	4.56	(a)	15.8	(b)	2.59	5.07	3.72	2.32	0.95		9.86
MnO	0.6	(a)	0.22		0.02	0.05	0.04	0.02			0.13
MgO	15.82	(a)	8.79		9.46	12.45	11.79	0.07			19.2
CaO	12.27	(a)	11.33		15.12	13.86	13.86	1.25	19.6		7.9
Na2O	0.28	(a)	0.5		0.38	0.32	0.37	0.52	1.39		0.8
K2O	0.06	(a)	0.13		0.075	0.054	0.07	8.6	0.17		0.51
P2O5	0.03	(a)									
S %											
sum											
Sc ppm			55	(b)	1.69	4.5	2.4	3	3.5	(b)	17.8
V											41
Cr			2800	(b)	1000	643	730	17	61	(b)	1566
Co			28	(b)	9.2	14.8	16.9	0.94	1.1	(b)	35.5
Ni			39	(b)	32	24	72	4.9	<17	(b)	297
Cu			8.2	(b)							
Zn			5.1	(b)	2.4	3.5	2.2	1.9		(b)	
Ga			4	(b)			5.6	9	8.6	(b)	
Ge ppb			470	(b)	26.8	18.1	31	87		(b)	
As			0.077	(b)							
Se											
Rb	0.9	(a)	6.7	(b)				210		(b)	22
Sr	150	(a)	100	(b)				55	430	(b)	156
Y	22	(a)									
Zr	110	(a)			38	350	560	660	850	(b)	815
Nb	3.2	(a)									
Mo											
Ru											
Rh											
Pd ppb			0.001	(b)							
Ag ppb											
Cd ppb							129	34		(b)	
In ppb											
Sn ppb											
Sb ppb											
Te ppb											
Cs ppm	0.08	(a)	0.32	(b)			0.21	5.7		(b)	0.69
Ba	300	(a)	100	(b)	250	280	320	2160	610	(b)	767
La	14	(a)	22	(b)	25	22.9	24.2	44.3	111	(b)	58.2
Ce	34	(a)	60	(b)	61	52	67	117	280	(b)	158
Pr	3.6	(a)	7.4	(b)							
Nd	13	(a)			38	23	41	58	173	(b)	93
Sm	3.2	(a)	8.6	(b)	10.5	5.9	10.8	15.9	46	(b)	25.3
Eu	2	(a)	1.17	(b)	2.07	2.3	1.88	1.17	6.6	(b)	2.01
Gd	3.8	(a)	14.4	(b)							
Tb	0.5	(a)	2.5	(b)	1.9	1.27	1.99	4.3	8.6	(b)	6.05
Dy	3.6	(a)	13	(b)	10.4	8.5	13.2	31.5	52	(b)	
Ho	0.73	(a)	2.2	(b)			2.6	8.4	10.8	(b)	
Er	2.3	(a)	9.3	(b)							
Tm	0.43	(a)									
Yb	2.2	(a)	6.8	(b)	4.2	9.6	4.9	32.2	23.2	(b)	19.8
Lu			0.94	(b)	0.56	1.56	0.73	5.1	3.15	(b)	2.64
Hf	2.8	(a)	7.1	(b)	0.15	8.8	10.3	13.9	17.5	(b)	22
Ta			1	(b)	0.037	1.77	0.18	8.3	0.46	(b)	2.56
W ppb	100	(a)	0.55	(b)							
Re ppb					0.02	0.02	<.13	<0.018		(b)	
Os ppb											
Ir ppb			1.1	(b)	0.053	0.031	0.58	0.047	<5	(b)	6.57
Pt ppb			0.6	(b)							
Au ppb					0.17	0.031	0.058	0.035		(b)	
Th ppm	0.56	(a)	2.6	(b)	2	2.6	2.27	65	11.5	(b)	11.53
U ppm	0.16	(a)	0.54	(b)	0.4	1.6	0.27	23.4	2.1	(b)	2.94

technique (a) emiss. spec., (b) INAA

Table 3b. Chemical composition of other clasts in 14321.

	Mg-Anorthosites			Troctolites			Dunite?	troct.
reference	Lindstrom 84			Lindstrom 84				Snyder 95
weight	,1211	,1205-1	,1205-2	,1140	,1142	,1154	,1141	,1331
SiO2 %								43
TiO2		0.07	0.21	0.06	0.16		0.08	
Al2O3	35.2	32.2	31.4	15.02	21.6		0.56	26
FeO	0.43	0.097	1.37	8.55	4.67	2.78	11.55	3.3
MnO								0.02
MgO	2.08	0.89	2.78	30.5	17.7		53.7	13.3
CaO	19.1	19.2	18.6	9.2	12.5	15.2		13.3
Na2O	0.5	0.475	0.53	0.198	0.372	0.378	0.023	0.33
K2O					0.072			
P2O5								
S %								
sum								
Sc ppm	1.42	0.433	2.61	3.46	3.79	1.47	5	2
V								
Cr	71	34	209	397	933	225	522	268
Co	1.22	0.53	5.46	22.2	21	8.29	61	11.8
Ni			50	44	<55	<22	70	21
Cu								
Zn								
Ga								
Ge ppb								
As								
Se								
Rb								
Sr	240	240	220	127	161	195	<30	
Y								
Zr			150	<40	135	<25	<70	
Nb								
Mo								
Ru								
Rh								
Pd ppb								
Ag ppb								
Cd ppb								
In ppb								
Sn ppb								
Sb ppb								
Te ppb								
Cs ppm								
Ba	460	375	410	152	238	274	24	248
La	231	57.7	21.5	10.16	15.14	14.8	5.14	8.04
Ce	620	152	53.4	24.8	38	35.2	13.5	17
Pr								
Nd	410	97	26	14.8	25	22.4	8.4	
Sm	110	28.7	8.33	3.8	5.58	5.07	2.255	1.66
Eu	3.73	2.48	2.5	1.31	1.76	2.05	0.065	1.94
Gd								
Tb	23.6	6.75	1.82	0.76	1.11	1.01	0.5	0.213
Dy								
Ho								
Er								
Tm								
Yb	55.3	11.7	4.65	2.2	3.35	2.08	1.98	1.13
Lu	7.84	1.53	0.681	0.356	0.549	0.299	0.39	0.16
Hf	0.68	0.24	3.84	0.198	3.38	0.058	0.93	0.197
Ta	0.1	0.108	0.47	0.055	0.31	0.024	0.1	0.062
W ppb								
Re ppb								
Os ppb								
Ir ppb								
Pt ppb								
Au ppb								
Th ppm	30	6.5	2.6	0.75	1.23	0.89	0.71	0.064
U ppm	2.8	0.61	0.71	0.21	0.29	0.069	0.09	0.03
technique	*(a) emiss. spec., (b) INAA*							

Table 4. Cross-correlation of sub-sample numbers (14321).

clast	parent	type	size in mm	Ir ppb	analyzed	TS	dated	other desig.	references
c1	,46	anor. troc.	18 x 12	0.053		,1019		W-101	Warren 81, Meyer 79, Lindstrom 84
						,1241			Shervais and McGee 98
c2				0.031					Warren 81, Meyer 79, Lindstrom 84
c3	,46	anor. troc.	7 x 5	0.58	,1037	,994		W-5	Warren 83a
c4	,46	granite	16 x 7	0.047	,1027	,1047	,1062	W-3	Warren 83a, Shih 93, Shih 85
		w. zircon				,1613			Meyer 96
c5		mg anorth							Warren 83b
8A		troctolite							Compston 72, Taylor 72, Ware 77
6A		basalt							Ware 77
4A		basalt							Ware 77
B-102	,46	basalt	38 x 20		????	,970	????	MB-1	Meyer 79, Shervais 84
DA-3	,37	ol. vitrophyre	65 x 35	~ 6		,1243			Allen 79
		ol. vit.			,1159				Snyder
		ol. vit.			,1180				Snyder
		troctolite			,1331	,1379			Snyder 95
	,46	dunite	6 x 5		,1141	,1236			Lindstrom 84, Shervais 84
	,116	troctolite			,1154	,1241			Lindstrom 84, c1 of Warren 81
	,46	troctolite	10 x 10		,1140	,1235		w-4	Lindstrom 84, Shervais 84
									Shervais and McGee 98
	,46	troctolite			,1142	,1237		w-2	Lindstrom 84, Shervais 84
	,90	mg anor.	4 x 2		,1211	,1273		w-1	Lindstrom 84, Shervais and McGee 98
	,601	mg anor.	8 x 5		,1205	,1269		w-1	Lindstrom 84
DV-1	,1082	basalt			,1184	,1261			Shervais 84b
DV-3	,1082	basalt			,1185	,1262			Shervais 84b
MB-8	,1082	basalt			,1179	,1256			Shervais 84b
MB-10	,37	basalt			,1157	,1242			Shervais 84b
MB-4	,46	basalt	6 x 5		,1143	,1238			Shervais 84b
DV-6	,1082	vitrophyre			,1183	,1260			Shervais 84b
DV-7	,90	vitrophyre			,1210	,1271			Shervais 84b
DV-2	,37	14053 type			,1160	,1245			Shervais 84b
MB-1	,112	14053 type			,1149	,1151	,1394	group 4	Shervais 85, Dash 87
DV-4	,37	olivine b.			,1161	,1246	,1384	group 5	Shervais 85, Dash 87
DV-5	,37	tridymite ferro. Bas.				,1162	,1247	,1383	Shervais 85, Dash 87
		olivine bas.			,198				Shervais
		ol. Bas.			,199				
		ol. Bas.			,970				
		high Al bas.			,1445				Neal 1989
					,1448	,1482			
					,1449	,1483			
					,1451	,1484			
	fines	HA basalt			,9056		,9056	group 2	Dash 87, Dickinson 85
	fines	HA basalt			,9059		,9059	group 5	Dash 87, Dickinson 85

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matrix breccia. This has also been discussed by Dash et al. (1987) and Neal and Taylor (1990).

Cosmogenic isotopes and exposure ages

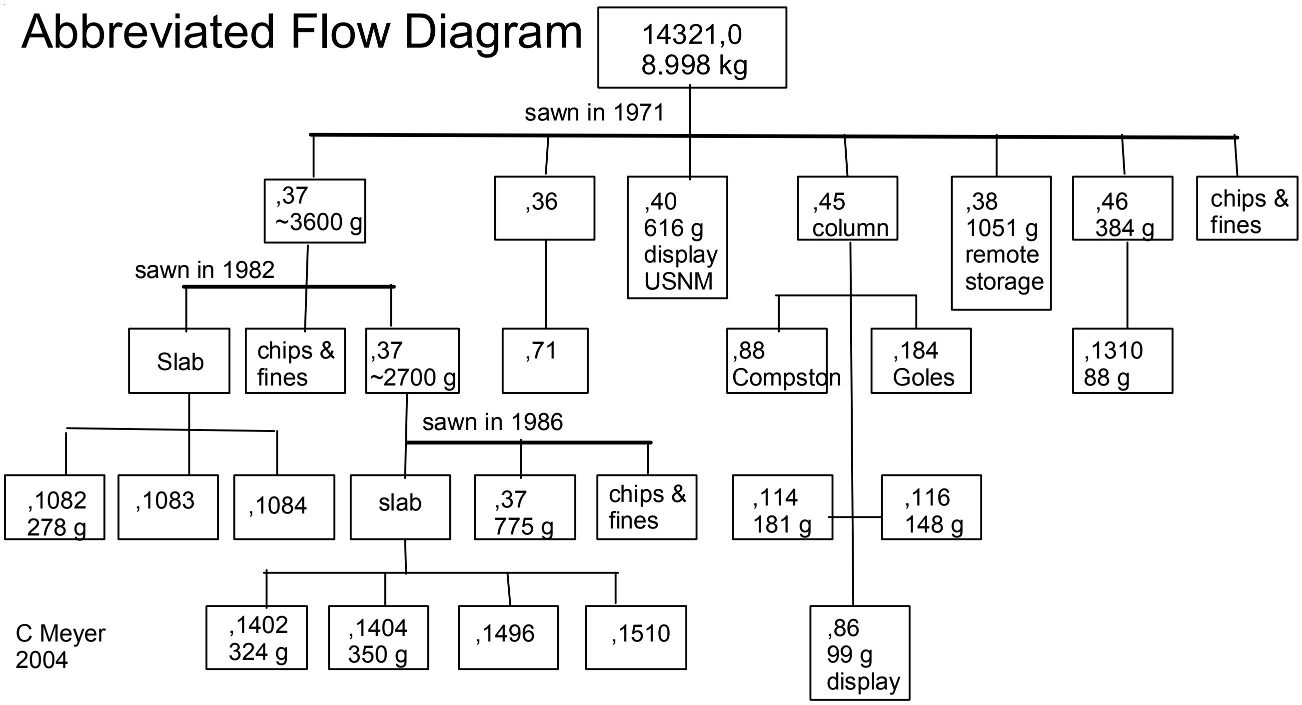
Eldridge et al. (1972), Rancitelli et al. (1972) and Kieth et al. (1972) reported ^{22}Na, ^{26}Al, ^{54}Mn, ^{56}Co and ^{48}Sc activity for large pieces of 14321. Wahlen et al. (1972) reported ^{56}Co, ^{54}Mn, ^{55}Fe, ^{22}Na, ^{26}Al, ^{53}Mn, ^{36}Cl and ^{10}Be activity in smaller samples, including surface samples with high activity of ^{56}Co (77 day half life). 14321 was used for ^{53}Mn and ^{26}Al depth profiles (Wahlen et al. 1972, Imamura et al. 1974, Kohl et al. 1978) (see figure 30).

Burnett et al. (1972) reported an ^{38}Ar exposure age of 24 ± 2 m.y. Lugmair and Marti (1972) determined an exposure age for 14321 of 23.8 m.y. by the ^{81}Kr method. This is interpreted to be the age of cone crater (Burnett et al., Arvidson et al. 1975). Burnett et al. also found that 14321 must have been buried about 4 meters during part of its history.

Other Studies

Morrison et al. (1972) counted the micrometeorite craters on various surfaces of 14321. Remanent magnetization was studied by Gose et al. (1972), Pearce et al. (1972) and Hargraves and Dorety (1972). Pearce et al. found that the thermoremanent magnetization was

Abbreviated Flow Diagram



directionally consistent in three different fragments of 14321.

Crozaz et al. (1972) and Hutcheon et al. (1972) etched fossil fission tracks in phosphates in 14321 in an attempt to search for evidence of extinct ^{244}Pu.

Nemchin et al. (2006) determined the oxygen isotope composition of zircons.

Processing

14321 was oriented by photography to establish its top lunar surface (Swann 1971). Warner and Heiken (1972) made a map of the surface of 14321 before it was subdivided. It was originally cut in half, and a thick column (,45) was prepared from one half (figure 27) for initial allocations. A large piece (,40) is on public display at the Smithsonian and another large piece (,38) is in remote storage. In 1982, the largest remaining piece (,37) was slabbed parallel to its west face (the original saw cut, figure 2), creating pieces ,1082 ,1083 and ,1084 (Shervais et al. 1984)(see flow diagram). In 1986, the remains of ,37 were again sawn to reveal interior clasts.

Gordon Goles led the first consortium study of 14321 (preliminary results reported in Lindstrom et al. 1972, Duncan et al. 1975). Located in their 70 gram piece (,184) were three basalts (one of which was estimated at 20 grams). Unfortunately, in this initial study "it was not possible to match specific clasts between thin sections and the fragment surfaces which were to be sampled because of the way in which the thin sections were prepared."

A consortium of Bill Compston, John Lovering, Ted Ringwood and Ross Taylor studied sample 14321,88 (84 grams), which also had three basaltic pebbles (clasts) (Ware and Green 1977).

Two breccia guidebooks were prepared to guide in the selection of clasts for further study: Meyer and King (1979) and Shervais, Knapp and Taylor (1984). The data packs describing the allocations of 14321 occupy a full shelf in the data center at JSC.

The large piece (,88) that was initially studied by Compston et al., has been returned, and is now available for experiments in the PI Experiment laboratory at JSC.

There are more than 100 thin sections of 14321!

Figure 28: Mug shot of 14321 after dusting. Scale in cm. NASA photo # S71-28416.

Partial List of Photo #s for 14321

S71-28416	Best mug shot whole rock B&W
S71-28403	,0 dusted (after fist cut)
S71-40118	exploded part diagram
S71-40119	cutting plan, column
S76-24004-9	,40 display sample with white clast
S78-32831	close-up of white clast and basalt clast in ,46
S78-32834	2 cm white clast in ,46
S78-26758	the model
S78-33116-9	,37 with white clast
S83-25954	slab
S83-43737	,1082
S84-33329	,37
S84-33333	,116 white clast
S85-36423	,46
S85-38260	,46?
S86-26402	,1408 showing light matrix

The Final Word

Grieve et al. (1975) state *"Analysis and interpretation of a complex rock like 14321 is rewarded with few categorical conclusions, but we believe that the elucidation of its compositional character and assembly history leads to a very probably evolutionary picture for this area of the Moon"*. They suggest a partial schematic history in their paper.

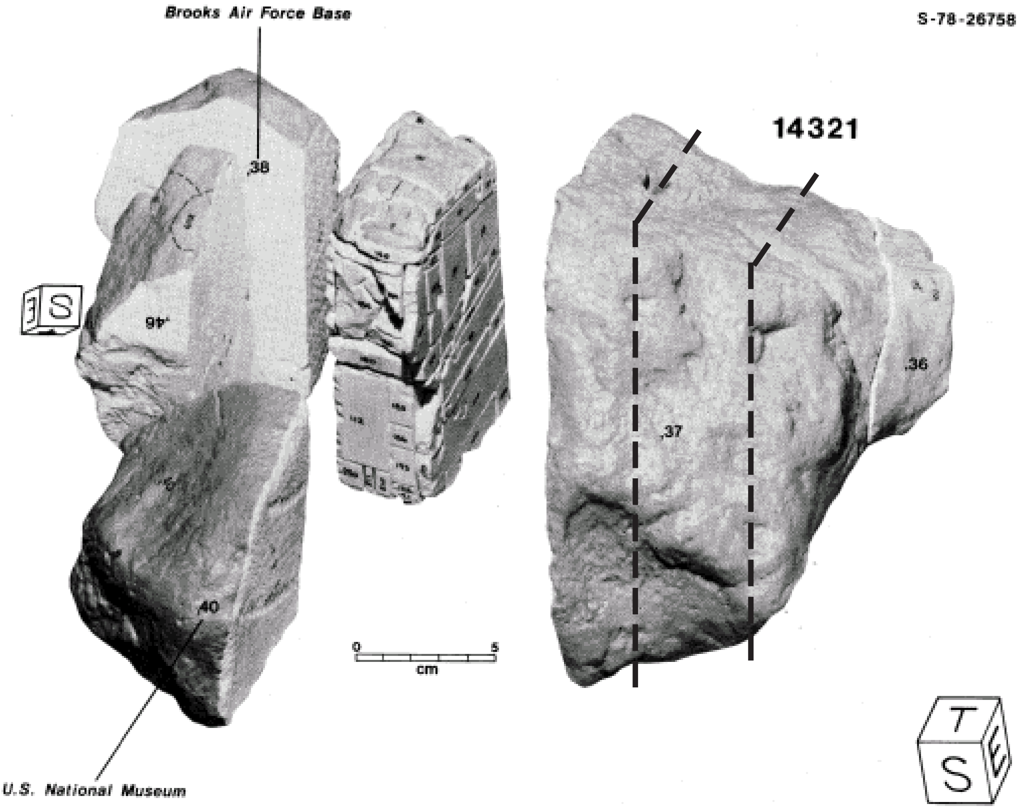


Figure 29: Photo of model of 14321 illustrating the initial processing in 1971. The dotted black lines indiate the relative positions of saw cuts in 1982 (Shervais et al. 1984) and again in 1986.

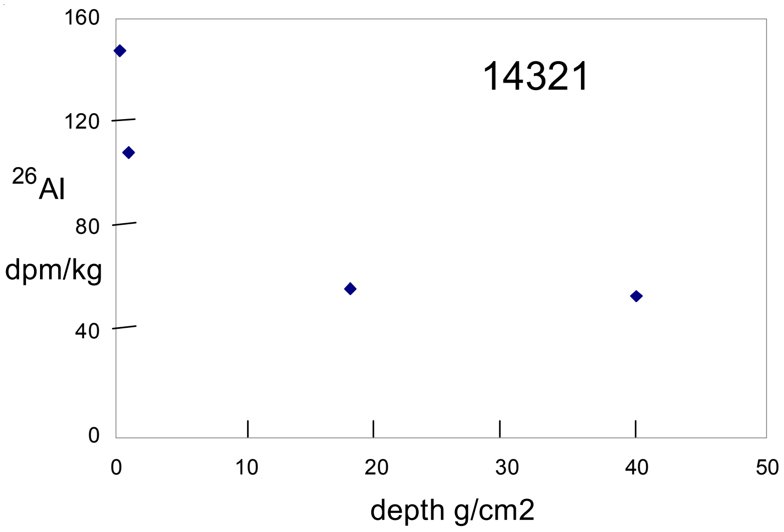


Figure 30: Depth profile of 26Al in 14321 (data from Wahlen et al. 1972).

References for 14321

Allen F.M., Bence A.E. and Grove T.L. (1979) Olivine vitrophyres in Apollo 14 breccia 14321: Samples of the high-Mg component of the lunar highlands. Proc. 10th Lunar Planet. Sci. Conf. 695-712.

Anderson A.T., Braziunas T.F., Jacoby J. and Smith J.V. (1972) Thermal and mechanical history of breccias 14306, 14063, 14270 and 14321. Proc. 3rd Lunar Sci. Conf. 819-835.

Arvidson R., Crozaz G., Drozd R.J., Hohenberg C.M. and Morgan C.J. (1975) Cosmic ray exposure ages of features and events at the Apollo landing sites. The Moon 13, 259-276.

Baedecker P.A., Chou C-L. and Wasson J.T. (1972) The extralunar component in lunar soils and breccias. Proc. 3rd Lunar Sci. Conf. 1343-1359.

Bersch M.G., Taylor G.J., Keil K. and Norman M.D. (1991) Mineral compositions in pristine highlands rocks and the diversity of highland magmatism. Geophys. Res. Lett. 18, 2085-2088.

Boynton W.V., Baedecker P.A., Chou C-L., Robinson K.L. and Wasson J.T. (1975) Mixing and transport of lunar surface materials: Evidence obtained by the determination of lithophile, siderophile and volatile elements. Proc. 6th Lunar Sci. Conf. 2241-2259.

Braddy D., Hutcheon I.D. and Price P.B. (1975a) Crystal chemistry of Pu and U and concordant fission track ages of lunar zircons and whitlockites. Proc. 6th Lunar Sci. Conf. 3581-3600.

Burnett D.S., Huneke J.C., Podosek F.A., Russ G.P., Turner G. and Wasserburg G.J. (1972) The irradiation history of lunar samples. (abs) LS III 105-107.

Carlson I.C. and Walton W.J.A. (1978) **Apollo 14 Rock Samples**. Curators Office. JSC 14240

Chao E.C.T., Minkin J.A. and Best J.B. (1972) Apollo 14 breccias: General characteristics and classification. Proc. 3rd Lunar Sci. Conf. 645-659.

Chao E.C.T. (1973c) Geologic implications of the Apollo 14 Fra Mauro breccias and comparison with ejecta from the Ries Crater, Germany. J. Res. U.S Geol. Survey 1, 1-18.

Christie J.M., Griggs D.T., Heuer A.H., Nord G.L., Radcliffe S.V., Lally J.S. and Fischer R.M. (1973) Electron petrography of Apollo 14 and 15 breccias and shock-produced analogs. Proc. 4th Lunar Sci. Conf. 365-382.

Compston W., Vernon M.J., Berry H. and Rudowski R. (1971) The age of the Fra Mauro Formation: A radiometric older limit. Earth Planet. Sci. Lett. 12, 55-58

Compston W., Vernon M.J., Berry H., Rudowski R., Gray C.M., Ware N., Chappell B.W. and Kaye M. (1972) Apollo 14 mineral ages and the thermal history of the Fra Mauro formation. Proc. 3rd Lunar Sci. Conf. 1487-1501.

Crozaz G., Drozd R., Graf H., Hohenberg C.M., Monnin M., Ragan D., Ralston C., Seitz M., Shirck J., Walker R.M. and Zimmerman J. (1972) Uranium and extinct Pu244 efffects in Apollo 14 materials. Proc. 3rd Lunar Sci. Conf. 1623-1636.

Dash E.J., Shih C-Y., Bansal B.M., Wiesmann H. and Nyquist L.A. (1987) Isotopic analysis of basaltic fragments from lunar breccia 14321: Chronology and petrogenesis of pre-Imbrium mare volcanism. Geochim. Cosmochim. Acta 51, 3241-3254.

de Laeter J.R., Vernon M.J. and Compston W. (1973) Revison of lunar Rb-Sr ages. Geochem. Cosmochim. Acta 37, 700-702.

Dickinson T., Taylor G.J., Keil K., Schmitt R.A., Hughes S.S. and Smith M.R. (1985) Apollo 14 aluminous mare basalts and their possible relationship to KREEP. Proc. 15th Lunar Planet. Sci. Conf. in J. Geophys. Res. 90, C365-C374.

Duncan A.R., McKay S.M., Stoeser J.W., Lindstrom M.M., Lindstrom D.J., Fruchter J.S. and Goles G.G. (1975a) Lunar polymict brecia 14321: a compositional study of its principal components. Geochim. Cosmochim. Acta 39, 247-260.

Duncan A.R., Grieve R.A.F. and Weill D.F. (1975b) The life and times of Big Bertha: lunar breccia 14321. Geochim. Cosmochim. Acta 39, 265-273.

Eisentraut K.J., Black M.S., Hilman F.D., Sievers R.F. and Ross W.D. (1972) Beryllium and chromium abundances in Fra Mauro and Hadley-Apennine lunar samples. Proc. 3rd Lunar Sci. Conf. 1327-1333.

Eldridge J.S., O'Kelley G.D. and Northcutt K.J. (1972) Abundances of primordial and cosmogenic radionuclides in Apollo 14 rocks and fines. Proc. 3rd Lunar Sci. Conf. 1651-1658.

Fireman E.L., D'Amico J., DeFelice J. and Spannagel G. (1972) Radioactivities in returned lunar materials. Proc. 3rd Lunar Sci. Conf. 1747-1762.

Gancarz A.J., Albee A.L. and Chodos A.A. (1971) Petrologic and mineralogic investigation of some crystalline rocks returned by Apollo 14 mission. Earth Planet. Sci. Lett. 12, 1-18.

Gay P., Brown M.G. and Muir I.D. (1972) Mineralogical and petrographic features of two Apollo 14 rocks. Proc. 3rd Lunar Sci. Conf. 351-362.

Gose W.A., Pearce G.W., Strangway D.W. and Larson E.E. (1972) Magnetic properties of Apollo 14 breccias and their correlation with metamorphism. Proc. 3rd Lunar Sci. Conf. 2387-2395.

Grieve R.A., McKay G.A., Smith H.D. and Weill D.F. (1975) Lunar polymict breccia 14321: a petrographic study. Geochim Cosmochim Acta 39, 229-245.

Hargraves R.B. and Dorety N. (1972) Natural remanent magnetization in lunar breccia 14321. Proc. 3rd Lunar Sci. Conf. 2417-2421.

Hohenberg C,M., Marti K., Podosek F.A., Reedy R.C. and Shirck J.R. (1978) Comparison between observed and predicted cosmogenic noble gases in lunar samples. Proc. 9th Lunar Sci. Conf. 2311-2344.

Hunter R.H. and Taylor L.A. (1983) The magma ocean from the Fra Mauro shoreline: An overview of the Apollo 14 crust. Proc. 13th Lunar Planet. Sci. Conf. in J. Geophys. Res. 88, A591-A602.

Hutcheon I.D., Phakey P.P. and Prioce P.B. (1972) Studies bearing on the history of lunar breccias. Proc. 3rd Lunar Sci. Conf. 2845-2866.

Imamura M., Nishiizumi K., Honda M., Finkel R.C., Arnold J.R. and Kohl C.P. (1974) Depth profiles of ^{53}Mn in lunar rocks and soils. Proc. 5th Lunar Sci. Conf. 2093-2103.

James (1980) Rocks of the early lunar crust. Proc. 11th Lunar Planet. Sci. Conf. 365-393.

Keith J.E., Clark R.S. and Richardson K.A. (1972) Gamma-ray measurements of Apollo 12, 14 and 15 lunar samples. Proc. 3rd Lunar Sci. Conf. 1671-1680.

Kohl C.P., Murrell M.T., Russ G.P. and Arnold J.R. (1978) Evidence for the constancy of the solar cosmic ray flux over the past ten million years: ^{53}Mn and ^{26}Al measurements. Proc. 9th Lunar Planet. Sci. Conf. 2299-2310.

Lally J.S., Fischer R.M., Christie J.M., Griggs D.T., Heuer A.H., Nord G.L. and Radcliffe S.V. (1972) Electron petrography of Apollo 14 and 15 rocks. Proc. 3rd Lunar Sci. Conf. 401-422.

Lindstrom M.M., Duncan A.R., Fruchter J.S., McKay S.M., Stoeser J.W., Goles G.G. and Lindstrom D.J. (1972) Compositional characteristics of some Apollo 14 clastic materials. Proc. 3rd Lunar Sci. Conf. 1201-1214.

Lindstrom M.M., Knapp S.A., Shervais J.W. and Taylor L.A. (1984) Magnesian anorthosites and associated troctolites and dunite in Apollo 14 breccias. Proc. 15th Lunar Planet. Sci. Conf. in J. Geophys. Res. 89, C41-C49.

LSPET (1971) Preliminary examination of lunar samples from Apollo 14. Science 173, 681-693.

Lugmair G.W. and Marti K. (1972) Exposure ages and neutron capture record in lunar samples from Fra Mauro. Proc. 3rd Lunar Sci. Conf. 1891-1897.

Mark R.K., Cliff R.A., Lee-Hu C. and Wetherill G.W. (1973) Rb-Sr studies of lunar breccias and soils. Proc. 4th Lunar Sci. Conf. 1785-1795.

Mark R.K., Lee-Hu C-N. and Wetherill G.W. (1974) Equilibration and ages: Rb-Sr studies of breccias 14321 and 15265. Proc. 5th Lunar Sci. Conf. 1477-1485.

Mark R.K., Lee-Hu C. and Wetherill G.W. (1975) More on Rb-Sr in lunar breccia 14321. Proc. 6th Lunar Sci. Conf. 1501-1507.

Matsuda A., Nakamura N., Kurasawa H. and Tanaka T. (1972) Precise determination of rare-earth elements in the Apollo 14 and 15 samples. Proc. 3rd Lunar Sci. Conf. 1307-1313.

Meyer C. and Yang S.V. (1988) Tungsten-bearing yttrobetafite in lunar granophyre. Am. Mineral. 73, 1420-1425.

Meyer C. and King C.D. (1979) Breccia Guidebook #114321. JSC 14753

Meyer C., Compston W. and Williams I.S. (1985) Lunar zircon and the closure age of the lunar crust (abs). LPS XVI, 557-558.

Meyer C., Williams I.S. and Compston W. (1989) ^{207}Pb/^{206}Pb ages of zircon-containing rock fragments indicate continuous magrnatism in the lunar crust from 4350 to 3900 million years (abs). LPS XX, 691-692.

Meyer C., Williams I.S. and Compston W. (1989) Zircon-containing rock fragments within Apollo 14 breccias indicate serial magmatism from 4350 to 4000 million years (abs). *In* Workshop on Moon in Transition: Apollo 14, KREEP, and evolved lunar rocks. LPI Tech Rpt. 89-03, 75-78. Lunar Planet. Inst.

Meyer C., Williams I.S. and Compston W. (1996) Uranium-lead ages for lunar zircons: Evidence for a prolonged period of granophyre formation from 4.32 to 3.88 Ga. Meteoritics & Planet. Sci. 31, 370-387.

Morgan J.W., Ganapathy R. and Krahenbuhl U. (1975a) Meteoritic trace elements in lunar rock 14321,184. Geochim. Cosmochim. Acta 39, 261-264.

Morgan J.W., Laul J.C., Krahenbuhl U., Ganapathy R. and Anders E. (1972) Major impacts on the moon: Characterization from trace elements in Apollo 12 and 14 samples. Proc. 3rd Lunar Sci. Conf. 1377-1395.

Morrison D.A., McKay D.S., Heiken G.H. and Moore H.J. (1972) Microcraters on lunar rocks. Proc. 3rd Lunar Sci. Conf. 2767-2791.

Neal C.R. (2007) Mining the literature for new data: Expanding the Apollo 14 high-alumina basalt isotope database. (abs) Lunar Planet. Sci. XXXVIII #2398

Neal C.R., Taylor L.A. and Lindstrom M.M. (1988a) Importance of lunar granite and KREEP in very high potassium (VHK) basalt petrogenesis. Proc. 18th Lunar Planet. Sci. Conf. 121-137. Lunar Planet. Inst.

Neal C.R., Taylor L.A. and Lindstrom M.M. (1988b) Apollo 14 mare basalt petrogenesis: assimilation of KREEP-like components by a fractionating magma. Proc. 18th Lunar Planet. Sci. Conf. 139-153. Lunar Planet. Inst.

Neal C.R., Taylor L.A., Schmitt R.A., Hughes S.S. and Lindstrom M.M. (1989d) High alumina (HA) and very high potassium (VHK) basalt clasts from Apollo 14 breccia, Part 1: Mineralogy and petrology: Evidence of crystallization from evolving magmas. Proc. 19th Lunar Planet. Sci. Conf. 137-145. Lunar Planet. Inst.

Neal C.R., Taylor L.A., Schmitt R.A., Hughes S.S. and Lindstrom M.M. (1989d) High alumina (HA) and very high potassium (VHK) basalt clasts from Apollo 14 breccia, Part 2 – whole rock geochemistry: Further evidence for combined assimilation and fractional crystallization within the lunar crust. Proc. 19th Lunar Planet. Sci. Conf. 147-161. Lunar Planet. Inst.

Neal C.R. and Taylor L.A. (1991) Evidence for metasomatism of the lunar highlands and the origin of whitlockite. Geochim. Cosmochim. Acta 55, 2965-2980.

Neal C.R., Shih C-Y., Reese Y., Nyquist L.E. and Kramer G.Y. (2006) Derivation of Apollo 14 high-Al basalts from distinct source regions at discrete times: New constraints. (abs) Lunar Planet. Sci. XXXVII #2003

Neal C.R. and Kramer G.Y. (2006) The petrogenesis of the Apollo 14 high-Al mare basalts. Am. Mineral. 91, 1521-1535.

Nelen J., Noonan A. and Fredriksson K. (1972) Lunar glasses breccias and chondrules. Proc. 3rd Lunar Sci. Conf. 723-737.

Nemchin A.A., Whitehouse M.J., Pidgeon R.T. and Meyer C. (2006) Oxygen isotopic signature of 4.4 – 3.9 Ga zircons as a monitor of differentiation processes on the Moon. Geochim. Cosmochim. Acta 70, 1864-1872.

Nemchin A.A., Pidgeon R.T., Whitehouse M.J., Vaughan J.P. and Meyer C. (2008) SIMS study of zircons from Apollo 14 and 17 breccias: Implications for the evolution of lunar KREEP. *Geochim. Cosmochim. Acta* **72**, 668-689.

Nyquist L.E., Shih C-Y., Bansal B., Wiesmann H. and Wooden J. (1983) Formation of a lunar granite 4.1 AE ago. (abs) Lunar Planet. Sci. XIV 576-577.

Nyquist L.E. and Shih C-Y. (1972) The isotopic record of lunar volcanism. Geochim. Cosmochim. Acta 56, 2213-2234.

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

Palme H., Baddenhausen H., Blum K., Cendales M., Dreibus G., Hofmeister H., Kmse H., Palme C., Spettel B. Vilcsek E. and Wanke H. (1978) New data on lunar samples and achondrites and a comparison of the least fractionated samples from the earth, the moon, and the eucrite parent body. Proc. 9th Lunar Planet. Sci. Conf. 25-57.

Pearce G.W., Strangway D.W. and Gose W.A. (1972) Remanent magnetism of the lunar surface. Proc. 3rd Lunar Sci. Conf. 2449-2464.

Pearce G.W., Gose W.A. and Strangway D.W. (1973) Magnetic studies on Apollo 15 and 16 lunar samples. Proc. 4th Lunar Sci. Conf. 3045-3076.

Phinney W.C., McKay D.S., Simonds C.H. and Warner J.L. (1976) Lithification of vitric- and elastic-matrix breccias: SEM photography. Proc. 7th Lunar Sci. Conf. 2469-2492.

Rancitelli L.A., Perkins R.W., Felix W.D. and Wogman N.A. (1972) Lunar surface processes and cosmic ray characterization from Apollo 12-15 lunar samples analyses. Proc. 3rd Lunar Sci. Conf. 1681-1691.

Scoon J.H. (1972) Chemical analysis of lunar samples 14003, 14311 and 14321. Proc. 3rd Lunar Sci. Conf. 1335-1336.

Shervais J.W., Taylor L.A. and Laul J.C. (1983) Ancient crustal components in the Fra Mauro breccias. Proc. 14th Lunar Planet. Sci. Conf. in J. Geophys. Res. 88, B77-B92.

Shervais J.W., Knapp S. and Taylor L.A. (1984) Breccia Guidebook No.7 14321. JSC 19492.

Shervais J.W., Taylor L.A. and Lindstrom M.M. (1985) Apollo 14 mare basalts: petrology and geochemistry of clasts from consortium breccia 14321. Proc. 15th Lunar Planet. Sci. Conf. in J. Geophys. Res. 89, C375-C395.

Shervais J.W., Taylor L.A., Laul J.C., Shih C.-Y. and Nyquist L.E. (1985) Very high potassium (VHK) basalt: Complications in lunar mare petrogenesis. Proc. 16th Lunar Planet. Sci. Conf. in J. Geophys. Res. 90, D3-D18.

Shervais J.W., Taylor L.A. and Lindstrom M.M. (1988) Olivine vitrophyres: A nonpristine high-Mg component in

Lunar breccia 14321. Proc. 18th Lunar Planet. Sci. Conf. 45-57. Lunar Planet. Inst.

Shervais J.W., Vetter S.K. and Lindstrom M.M. (1990) Chemical differences between small subsamples of Apollo 15 olivine-normative basalts. Proc. 20th Lunar Planet. Sci. Conf. 109-126. Lunar Planet. Inst.

Shervais J.W. and Stuart J.B. (1995) Ion microprobe studies of lunar highland cumulate rocks: New results (abs). LPS XXVI, 1285-1286.

Shervais J.W. and McGee J.J. (1997) KREEP in the western lunar highlands: An ion microprobe study of alkali and Mg suite cumulates from the Apollo 12 and 14 sites. (abs) LPSC XXVIII, 1301-1302.

Shervais J.W. and McGee J.J. (1998a) KREEP in the western lunar highlands: ion and electron microprobe study of alkali suite anorthosites and norites from Apollo 12 and 14. Am. Min.

Shervais J.W. and McGee J.J. (1998b) Ion and electron microprobe study of trctolites, norites and anorthosites from Apollo 14: Evidence for urKREEP assimilation during petrogenesis of Apollo 14 Mg-suite rocks. Geochim. Cosmochim. Acta 62, 3009-3023.

Shih C.-Y., Nyquist L.E. and Wiesmann H. (1993) K-Ca chronology of lunar granites. Geochim. Cosmochim. Acta 57, 4827-4841.

Shih C.-Y., Nyquist L.E., Bogard D.D., Wooden J.L., Bansal B.M. and Wiesmann H. (1985) Chronology and petrogenesis of a 1.8 g lunar granite clast: 14321,1062. Geochim. Cosmochim. Acta 49, 411-426.

Simonds C.H., Phinney W.C., Warner J.L., McGee P.E., Geeslin J., Brown R.W. and Rhodes J.M. (1977) Apollo 14 revisited, or breccias aren't so bad after all. Proc. 8th Lunar Sci. Conf. 1869-1893.

Snyder G.A., Neal C.R., Taylor L.A. and Halliday A.N. (1995b) Processes involved in the formation of magnesian-suite plutonic rocks from the highlands of the Earth's moon. J. Geophys. Res. 100, 9365-9388.

Stadermann F.J., Heusser E., Jessberger E.K., Lingner S. and Stoffler D. (1991) The case for a younger Imbrium basin: New 40Ar-39Ar ages of Apollo 14 rocks. Geochim. Cosmochim. Acta 55, 2339-2349.
14063

Stasheim A., Jackson P.F.S., Coetzee J.H.J., Strelow F.W.E., Wybenga F.T., Gricius A.J., Kokot M.L. and Scott R.H. (1972) Analysis of lunar samples 14163, 14259 and 14321 with isotopic data for 7Li/6Li. Proc. 3rd Lunar Sci. Conf. 1337-1342.

Steele I.M. (1972) Chromian spinels from Apollo 14 rocks. Earth Planet. Sci. Lett. 14, 190-194.

Steele I.M. and Smith J.V. (1975) Minor elements in olivine as a petrologic indicator. Proc. 6th Lunar Sci. Conf. 451-467.

Stoffler D. and Knoll H-D. (1977) Composition and origin of plagioclase, pyroxene and olivine clasts of lunar breccias 14006, 14063, 14066, 14311, 14320 and 14321. Proc. 8th Lunar Sci.Conf. 1849-1867.

Stöffler D. and Ryder G. (2001) Stratigraphy and isotopic ages of lunar geologic units: Chronological standard for the inner solar system. Space Science Rev. 96, 9-54.

Sutton R.L., Hait M.H. and Swann G.A. (1972) Geology of the Apollo 14 landing site. Proc. 3rd Lunar Sci. Conf. 27-38.

Swann G.A., Trask N.J., Hait M.H. and Sutton R.L. (1971a) Geologic setting of the Apollo 14 samples. Science 173, 716-719.

Swann G.A., Bailey N.G., Batson R.M., Eggleton R.E.., Hait M.H., Holt H.E., Larson K.B., Reed V.S., Schaber G.G., Sutton R.L., Trask N.J., Ulrich G.E. and Wilshire H.G. (1977) Geology of the Apollo 14 landing site in the Fra Mauro Highlands. U.S.G.S Prof. Paper 880.

Swann G.A., Bailey N.G., Batson R.M., Eggleton R.E.., Hait M.H., Holt H.E., Larson K.B., McEwen M.C., Mitchell E.D., Schaber G.G., Schafer J.P., Shepard A.B., Sutton R.L., Trask N.J., Ulrich G.E., Wilshire H.G. and Wolfe E.W. (1972) 3. Preliminary Geologic Investigation of the Apollo 14 landing site. *In* Apollo 14 Preliminary Science Rpt. NASA SP-272. pages 39-85.

Taylor D.J., McKeegan K.D., Harrison T.M. and McCulloch M. (2007) 176Lu-176Hf in Lunar Zircon: Identification of an early enriched reservoir on the Moon (abs#2130). Lunar Planet. Sci. 38, Luny Planet. Inst. Houston.

Taylor D.J., McKeegan K.D. and Harrison T.M. (2007) Correlated study og Lu-Hf and REE in lunar zircons, with implication for the differentiation age of KREEP (abs). Meterotical Soc. Tucson

Taylor S.R., Kaye M., Muir P., Nance W., Rudowski R. and Ware N. (1972) Composition of the lunar uplands: Chemistry of Apollo 14 samples from Fra Mauro. Proc. 3rd Lunar Sci. Conf. 1231-1249.

Takeda H., Miyamoto M. and Ishii T. (1980) Composition of basaltic clasts in lunar and eucrite polymict breccias. Proc. 11th Lunar Planet. Sci. Conf. 135-147.

Turner G., Huneke J.C., Podosek F.A. and Wasserburg G.J. (1971) 40Ar-39Ar ages and cosmic ray exposure ages of Apollo 14 samples. Earth Planet. Sci. Lett. 12, 19-35.

Twedell D., Feight S., Carlson I. and Meyer C. (1978) **Lithologic maps of selected Apollo 14 breccia samples.** Curators Office. JSC 13842

Wahlen M., Honda M., Imamura M., Fruchter J.S., Finkel R.C., Kohl C.P., Arnold J.R. and Reedy R.C. (1972) Cosmogenic nuclides in football-sized rocks. Proc. 3rd Lunar Sci. Conf. 1719-1732.

Wanke H., Baddenhausen H., Balacescu A., Teschke F., Spettel B., Dreibus G., Palme H., Quijano-Rico M., Kruse H., Wlotzka F. and Begemann F. (1973) Multielement analysis of lunar samples and some implications of the results. Proc. 3rd Lunar Sci. Conf. 1251-1268.

Ware N.G. and Green D.H. (1977) Troctolitic and basaltic clasts from a Fra Mauro breccia. *In* Lunar Sample Studies. NASA SP-418, 49. JSC

Warner J.L. (1972) Metamophism of Apollo 14 breccias. Proc. 3rd Lunar Sci. Conf. 623-643.

Warner J.L. and Heiken G. (1972) Curators Office

Warren P.H. (1993) A concise compilation of petrologic information on possibly pristine nonmare Moon rocks. Am. Mineral. 78, 360-376.

Warren P.H., Taylor G.J., Keil K., Marshall C. and Wasson J.T. (1981) Foraging westward for pristine nonmare rocks: Complications for petrogenetic models. Proc. 12th Lunar Planet. Sci. Conf. 21-40.

Warren P.H., Taylor G.J., Keil K., Shirley D.N. and Wasson J.T. (1983b) Petrology and chemistry of two large granite clasts from the Moon. Earth Planet. Sci. Lett. 64, 175-185.

Warren P.H., Taylor G.J., Keil K., Kalyemeyn G.W., Rosener P.S. and Wasson J.T. (1983c) Sixth foray for pristine nonmare rocks and an assessment of the diversity of lunar anorthosites. Proc. 13th Lunar Planet. Sci. Conf. in J. Geophys. Res. 88, A615-A630.

Warren P.H., Taylor G.J., Keil K., Kallemeyn G.W., Shirley D. and Wasson J.T. (1983d) Seventh foray: Whitlockite-rich lithologies, a diopside-bearing troctolitic anorthosite, ferroan anorthosite and KREEP. Proc. 14th Lunar Planet. Sci. Conf. in J. Geophys. Res. 88, B151-B164.

Warren P.H., Kallemeyn G.W. and Kyte F.T. (1997) Siderophile element evidence indicates that Apollo 14 high-Al mare basalts are not impact melts. (abs) Lunar Planet. Sci. XXVIII, 1501-1502.

Williams R.J. (1972) The lithification of metamorphism of lunar breccias. Earth Planet. Sci. Lett. 16, 250-256.

Wilshire H.G. and Jackson E.D. (1972) Petrology and stratigraphy of the Fra Mauro Formation at the Apollo 14 site. U.S. Geol. Survey Prof. Paper 785.

York D., Kenyon W.J. and Doyle R.J. (1972) 40Ar-39Ar ages of Apollo 14 and 15 samples. Proc. 3rd Lunar Sci. Conf. 1613-1622.