PROBLEMS INHERENT IN THE STUDY OF LUNAR HIGHLAND SAMPLES: THE "TYPICAL CASE" AT APOLLO 14 Clive R. Neal* & Lawrence A. Taylor, Dept. Geological Sciences, University of Tennessee, Knoxville, TN 37996; Marilyn M. Lindstrom, Code SN2, NASA Johnson Space Center, Houston, TX 77058. * = Now at: Dept. of Earth Sciences, University of Notre Dame, Notre Dame, IN 46556.

The lunar highland areas are considered to be plagioclase floatation cumulates from a "magma ocean" which formed early in lunar history (e.g., [1,2]). These highlands contain the oldest rocks found on the Moon (e.g., [3]). Three broad suites of these highland rocks have been defined: 1) Ferroan Anorthosites (FANs); 2) Mg-Suite; and 3) Alkali Suite (e.g., [4-6]).

The lunar highlands have suffered much reworking and brecciation through meteorite bombardment. This bombardment presents the lunar petrologist with perhaps an insurmountable challenge - that of determining if highland samples are pristine, and if so, are they monomict? In this paper, *pristine* is used to define a sample free of meteorite contamination, and *monomict* to describe a sample comprised of only one lithological component. We present whole-rock and mineral data from 21 highland samples from the Apollo 14 site which highlight these problems. All samples were taken as clasts from polymict breccias 14303, 14304, 14305, and 14321. Generally, all have granulated textures, or thin sections are comprised of many individual grains due to disaggregation of the clast upon extraction. Also, much of the feldspar has been maskelynitized. In the following discussion, sample numbers in parentheses represent the INA sample, and the first number is that of the thin section. Where only one number is used, it is that of the INA sample.

CLASSIFICATION OF THE APOLLO 14 HIGHLAND SAMPLES - The mineralogy (Table 1) allows the clasts to be classified as FAN, Mg-Anorthosite, or Alkali Anorthosite. Two clasts are part of the FAN suite [14303,171(170) and 14305,490(490)], and the rest fall within the field of the Mg-Suite (Fig. 1). The modal mineralogy (Table 1) was calculated from mineral chemistry and major-element whole-rock chemistry (Table 2). This approach defined 4 dunites, 1 olivine pyroxenite, 3 troctolites, 5 norites, and 8 anorthosites. Two clasts (14305,451 and 14305,539) have no companion thin section and were defined as anorthosites on the basis of whole-rock chemistry.

PROBLEMS OF PETROGENETIC INTERPRETATION - The different rock-types display a wide range of REE compositions (Fig. 2). The dunites should theoretically contain low REE abundances, according to experimentally determined Kd data [7,8]. However, these dunites contain La up to 20 x chondritic abundances (Fig. 2a). Also, the anorthosites show a wide range of La abundances, from 12 to 90 x chondritic. Those anorthosites with the highest overall REE abundances exhibit a marked decrease in the size of the positive Eu anomaly (14304,166) or even a negative Eu anomaly (14303,302) (Fig. 2). The two FANs included in our study are the most REE-rich examples of this suite reported to date, and because of this, their monomict nature is somewhat questionable. These FAN suite samples exhibit brecciated textures and contain relatively high levels of Ir and Au (Table 2). As such, we consider these to be polymict.

In order to obtain any petrogenetic information from these analyses, the pristinity and monomict nature of the clasts must be established. Pristinity in lunar cumulate rocks can be evaluated primarily by the siderophile element content. Warren and Wasson [1,4] suggested that lunar samples containing Ir and Au abundances $<3 \times 10^{-4}$ x C1 chondrite levels could be considered pristine. This would require that lunar samples contain <0.05 ppb Ir or <0.1 ppb Au. Most samples reported here contain >0.1 ppb Ir and Au, suggesting meteoritic contamination. However, analysis of these elements by INA is somewhat difficult, especially at the levels definitive of pristinity. Another criterion that can be used to judge pristinity is the composition and morphology of the FeNi metal phases - presence of cohenite, taenite, and kamacite are interpreted to be a result of meteoritic contamination [9-12]. Also, if the FeNi metal contains up to 50% Ni, and it is present as several large (>200u) grains, these are interpreted as remnants from the projectile [13]. The presence of many small (< 10u) FeNi metal grains is indicative of solar-wind induced auto-reduction of Fe upon meteorite impact. The presence of such grains does not necessarily demonstrate meteorite contamination or mechanical mixing, only that the sample has experienced shock. Such FeNi metal grains were not observed in the Apollo 14 samples.

While it may be true that the samples contain a degree of meteorite contamination, this will be << 1% if all the Ir and Au in the sample is attributable to meteorites. Such low levels of contamination will not radically alter the REE contents of these samples. However, it must be demonstrated that these clasts do not represent mixtures of two (or more) lunar lithologies. If these clasts are mixtures, then any conclusions regarding petrogenesis are limited to end-member mixing models, but this may be important in recognizing as yet unsampled highland components (e.g., [14]). Most of the Apollo 14 clasts are brecciated, suggesting an environment ripe for "lithological mixing". If so, a range in mineral chemistry (between rather than within grains) should be observed, inconsistent with a plutonic origin. However, Lindstrom and Lindstrom [14] described granulites which were clearly polymict, yet had generally homogeneous mineral compositions due to re-equilibration. A range of mineral compositions is observed in two samples: dunite 14305,305(306) - Fo_{76-88}; and norite 14305,489(489) = An_{85-95} and Fo_{64-68}. The variation in the dunite is core-to-rim, but in the norite it is binter-grain. Furthermore, the major element whole-rock chemistry (Table 2) could not be reconstructed using the observed mineral compositions. This suggests different component(s) have been included in the INA sample of this clast or not all components are present in the thin section. The major element chemistry of troctolite 14305,538(537) also could not be reconstructed from mineral analyses, and this sample also contains a brown impact glass. Furthermore, if pigeonite is used to plot this sample on Fig. 1, it falls in the alkali anorthosite field; if olivine is used, it plots in the Mg-Anorthosite field. These observations, with the brecciated nature of these samples, suggest that norite 14304,489(489) and troctolite 14305,538(537) are polymict samples. The remaining clasts exhibit relatively homogeneous mineral chemistries (Table 1) and all whole-rock major-element data can be reconstructed using the analyzed mineral compositions. Therefore, *we suggest that while these samples may not be strictly pristine, they are essentially monomict in that they contain only* ***one lunar lithology***. If the whole-rock major-element data could be reconstructed, yet there was inter-grain heterogeneity, such a statement could not be made.

Another problem in the study of these Apollo 14 clasts is that of sample size. The INA sample weights range from 10 to 106 mg, and as the highland samples are coarse-grained cumulates, the problem of representative sampling is a major consideration. It is this which has led us to only broadly classify these clasts into 5 groups. Any further subdivision would be ridiculous and even this broad grouping may be misleading, but gives us a basis for describing these clasts. Also, the modal variations of olivine, pyroxene, and plagiolcase cannot account for the range of REE profiles noted in Fig. 2. However, inclusion or exclusion of trace-element rich minor phases, such as zircon [which may account for the high Hf and HREE content of dunite 14304,160(161)] and phosphate, could account for these compositional ranges. While our samples are almost certainly subject to sampling errors, the development of the minor phases which produce these compositional ranges, presents an exciting new avenue in lunar research. Neal et al. [15-19] proposed that the phosphates, and possibly other minor phases, are metasomatic in origin and could not have crystallized from *in-situ* intercumulus liquid. Are the compositional ranges in Fig. 2 generated by different degrees of metasomatism or by mechanical mixing of different lithologies? Certainly, the addition of meteoritic components could not generate such a range, and present evidence suggests that the majority of our samples are *essentially monomict* in that they contain only one **lunar** lithology. Furthermore, it takes only a small amount (0.1%) of whitlockite to dramatically increase the REE content of an anorthosite and overprint an inherent positive Eu anomaly with a negative one (Fig. 2c) [20]. However, if we had a larger sample size, would each clast have the same amount of minor phases and the compositional range be narrowed? Such questions cannot be answered, and this seriously hampers research into the lunar highlands. Indeed, if these considerations are not addressed, the conclusions that can be made may be detrimental to our understanding of early lunar crustal evolution.

REFS: [1] Warren & Wasson 1979 *PLPSC* 10th, 583; [2] Warren 1985 *Ann. Rev. Earth Planet. Sci. 13*, 201; [3] Lugmair et al. 1987 *LPS* XVII, 584; [4] Warren & Wasson 1977 *PLPSC* 8th, 2215; [5] Warren & Wasson 1980 *Proc. Conf. Lunar Highlands Crust*, 81; [6] James 1980 *PLPSC* 11th, pp. 365; [7] Colson et al. 1980 *GCA 52*, 539; [8] Hanson 1980 *Ann. Rev. Earth Planet. Sci., 8*, 371; [9] Gooley et al. 1973 *PLSC* 4th, 799; [10] Axon & Goldstein 1972 *EPSL* 16, 439; [11] Axon & Goldstein 1973 *EPSL* 18, 173; [12] Hewins & Goldstein 1975 *LS* VI, 356; [13] Misra & Taylor 1975 *PLSC* 6th, 615; [14] Lindstrom & Lindstrom 1986 *PLPSC* 16, in *JGR* 91, D263; [15] Neal et al. 1987 *LPS* XVII, 708; [16] Neal et al. 1988 *LPS* XIX, 837; [17] Neal & Taylor 1989 *GCA* 53, 529; [18] Neal et al. 1990 *LPS* XXI, 863; [19] Neal and Taylor (this volume); [20] Eckert et al. (this volume).

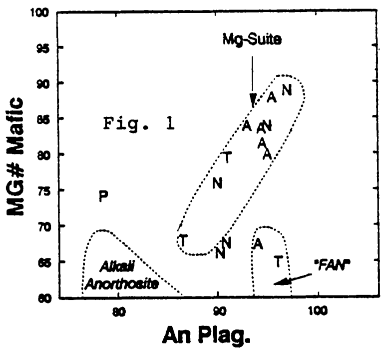

Figure 2

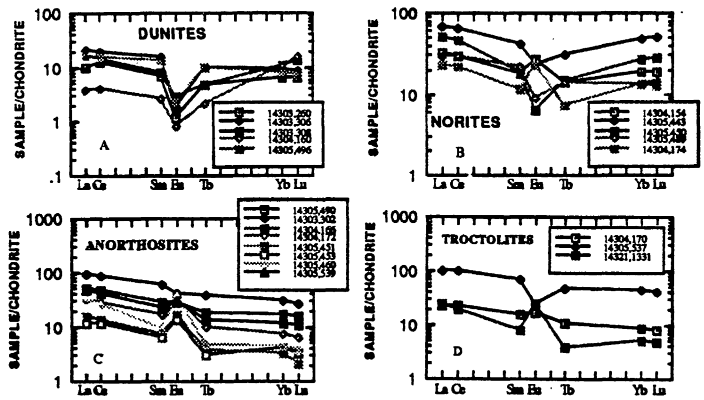

Table 1: Mineral Compositions and Calculated Modal Abundances

	Plagioclase	Low-Ca Px			High-Ca Px			Olivine	Calculated Modes:							
	An	Wo	En	MG#	Wo	En	MG#	Fo	Plag	Ol	Low-Ca Px	High-Ca Px	Cr-Usp	Ilm/Arm	Orth	SiO2
Dunites																
14303,261(260)	–	1-3	73-89	75-90	–	–	–	81-87		81	18.7		0.3			
14303,305(306)	–	–	–	–	–	–	–	76-88		100						
14303,307(308)	–	–	–	–	–	–	–	86-89		100						
14304,161(160)	–	–	–	–	–	–	–	83-89		100						
Olivine Pyroxenite																
14305,496(496)	78-79	<1-2	84-90	85-91	–	–	–	71-75	2	32	66					
Norites																
14304,153(154)	90-92	2-3	77-78	77-80	–	–	–	68-70	71	3	25.9		0.1			
14304,175(174)	94-95	1-3	77-87	78-88	–	–	–	67-70*	68	1	31					
14305,450(450)	96-98	1-3	86-89	86-89	–	–	–	88-90	28	1	71					
14305,489(489)	85-95	2-10	48-76	53-71	38-39	33-34	54-55	64-88	Mode could not be Calculated							
14305,9023(443)	88-92	3-4	64-66	66-68	37-43	43-45	72-76	66-67	56	1.5	30.5	3			3	6
Troctolites																
14304,171(170)	95-97	–	–	–	–	–	–	62-68	72	27.9			0.1			
14304,175(174)									68	1	31					
14305,538(537)	84-89	10-18	56-60	66-69	–	–	–	57-58*	Mode could not be Calculated							
14321,1379(1331)	94-96	–	–	–	45-47	49-51	92-93	86-88	72.5	27		0.5				
Anorthosites																
14303,323/324(302)	94-96	–	–	–	–	–	–	81-88	83	17						
14304,165(166)	95-96	–	–	–	–	–	–	87-89	92	8						
14304,173(172)	93-96	–	–	–	–	–	–	77-84	97	3						
14305,453(453)	94-97	1-2	89-90	90-91	47-48	48-49	93-94	–	81		16	3				
14305,490(490)	93-95	11-15	55-58	64-67	–	–	–	66-68	87	0.2	3.8			9		
14305,9025(460)	92-94	–	–	–	–	–	–	83-85	84	16						

* = Classification based upon pyroxene MG#.

Table 2 Whole-Rock Compositions

Rock No.	14304*	14305*	14303	14303	14303	14304	14304	14305*	14305*	14305*	14304
INAA No.	,170	,490	,260	,306	,308	,160	154	,443	,450	,489	,174
PM No.	,171	,490	,261	,305	,307	,161	,153	,9023	,450	,489	,175
Rock-Type	FT	FA	D	D	D	D	N	N	N	N	N
wt (mg)	43.97	10.40	13.43	27.29	27.47	46.32	52.21	13.89	11.90	11.97	57.68
SiO_2	---	—	41	40	40	40	48.1	52	55	—	47.4
TiO_2	---	—	0.09	0.15	0.09	0.06	0.26	0.28	0.16	—	0.16
Al_2O_3	---	—	0.47	0.63	1.97	0.72	23.9	20.2	10.7	—	24.8
Cr_2O_3	---	—	0.24	0.17	0.09	0.09	0.20	0.07	0.18	0.03	0.17
FeO	6.60	1.50	16.5	14.6	11.3	12.1	4.45	7.17	6.01	9.79	3.97
MnO	---	—	0.16	0.16	0.14	0.12	0.10	0.06	0.06	—	0.06
MgO	---	---	40.8	43.4	45.2	46.4	9.21	8.00	22.7	—	9.38
CaO	12.5	17.6	0.45	0.50	1.10	0.52	13.4	11.6	5.70	3.60	13.6
Na_2O	0.29	0.50	0.01	0.02	0.02	0.01	0.32	0.70	0.13	0.14	0.32
K_2O	---	---	0.01	0.01	0.01	—	0.08	0.60	0.03	—	0.07
P_2O_5	---	---	0.14	0.07	0.05	0.07	0.03	---	---	—	0.04
MG#	---	---	81.5	84.2	87.7	87.3	78.7	66.5	87.1	—	80.8
Sc (ppm)	2.1	2.5	2.8	3.4	6.8	5.4	9.8	13.1	16.2	5.4	7.6
Cr	630	192	1680	1110	563	553	1549	1000	2630	511	1328
Co	19.8	4.67	37.5	54.2	58.7	60.0	18.9	16.1	25.7	46.6	18.5
Ni	56	18	170	142	221	143	<29	50	30	90	116
Ba	120	350	28	28	34	11	233	740	72	100	240
Cs	<0.05	0.032	Nd	Nd	Nd	Nd	0.082	0.60	<0.15	<0.07	<0.10
La	7.33	15.2	3.18	6.79	5.47	1.26	10.5	22.5	16.6	9.75	7.31
Ce	19.0	35.5	10.5	17.3	12.9	3.43	24.5	56.5	39.0	25.3	18.8
Sm	3.26	4.68	1.40	3.07	1.66	0.52	3.64	8.33	3.78	4.42	2.31
Eu	1.28	2.42	0.091	0.138	0.217	0.06	2.00	1.72	0.49	0.69	1.71
Tb	0.618	0.77	0.268	0.57	0.275	0.118	0.80	1.76	0.86	0.81	0.423
Yb	1.87	2.50	1.45	2.04	2.31	2.44	4.04	10.5	5.79	2.83	2.93
Lu	0.273	0.36	0.22	0.29	0.463	0.512	0.63	1.67	0.945	0.50	0.431
Zr	115	130	53	72	<40	660	100	410	150	215	109
Hf	3.03	3.11	1.00	1.82	1.12	15.9	2.74	11.3	3.99	4.54	3.17
Ta	0.162	0.33	0.148	0.207	0.141	0.049	0.318	0.83	0.42	0.43	0.226
Th	1.18	1.16	0.70	1.05	0.57	0.36	1.19	5.13	1.35	1.50	0.67
U	0.35	0.22	0.28	0.25	0.11	0.24	0.22	1.65	0.70	0.52	0.30
Ir (ppb)	1.0±0.6	Nd	<2.1	<1.1	<3.2	<1.2	Nd	Nd	Nd	Nd	Nd
Au	17.4±0.5	1.1±1.1	<1	Nd	7.1±0.5	0.9±0.3	1.8±0.4	<3	<4	1.6±0.6	1.8±0.4

Rock No.	14305*	14305	14321*	14303	14304	14304*	14305*	14305*	14305*	14305
INAA No.	,496	,537	,1331	,302	,166	,172	,451	,453	,460	,539
PM No.	,496	,538	,1379	,323/324	,165	,173	-----	,453	,9025	-----
Rock-Type	OP	T	T	A	A	A	A	A	A	A
wt (mg)	15.15	14.81	105.9	94.29	56.95	51.84	52.90	11.48	24.08	22.34
SiO_2	---	44.2	43	43.9	44.2	45	44	46	44	44.4
TiO_2	--	0.55	—	0.26	0.29	0.14	—	--	—	0.06
Al_2O_3	—	22.3	26.0	29.0	31.9	34.4	35.0	29.7	29.7	34.9
Cr_2O_3	0.16	0.08	0.02	0.04	0.04	0.03	0.14	0.03	0.01	0.02
FeO	12.5	5.17	3.33	2.44	1.67	0.75	0.21	1.26	2.58	0.24
MnO	—	0.06	0.02	0.03	0.03	0.01	0.002	0.01	0.02	0.01
MgO	—	13.8	13.3	7.76	3.39	1.02	0.68	5.60	7.30	0.37
CaO	0.19	13.1	13.3	16.0	17.9	18.9	20.0	16.9	15.6	19.3
Na_2O	0.38	0.41	0.33	0.45	0.41	0.22	0.31	0.28	0.52	0.53
K_2O	<0.28	0.12	—	0.10	0.12	0.04	<0.15	<0.05	<0.15	0.12
P_2O_5	—	0.19	—	0.06	0.05	0.02	—	---	—	0.03
MG#	---	82.6	87.7	85.0	70.3	70.8	85.2	88.8	83.5	73.3
Sc (ppm)	4.7	7.8	2.0	2.3	3.3	1.2	0.52	1.8	1.7	0.72
Cr	2285	570	268	172	276	237	210	377	114	91
Co	39	22.3	11.8	8.2	7.7	2.3	1.8	8.6	8.8	1.08
Ni	285	109	21	56	66	21	12	37	23	18
Ba	40	429	248	451	301	272	70	54	365	374
Cs	0.028	0.15	0.017	0.075	0.117	0.025	0.03	<0.05	<0.04	0.039
La	5.73	33.6	8.04	30.0	16.5	10.5	5.01	3.96	8.04	11.5
Ce	13.7	85	17.0	77.2	40.5	24.8	12.0	10.0	20.0	22.5
Sm	2.65	14.2	1.66	12.2	5.93	3.49	1.52	1.28	2.34	1.88
Eu	0.17	1.83	1.94	3.09	2.21	2.49	1.25	1.06	3.18	3.03
Tb	0.58	2.68	0.213	2.25	1.02	0.573	0.224	0.18	0.30	0.269
Yb	1.70	9.69	1.13	6.68	3.65	1.69	0.71	0.887	0.96	0.973
Lu	0.26	1.41	0.16	0.88	0.519	0.215	0.073	0.114	0.142	0.125
Zr	63	340	<20	280	104	32	<20	<30	<30	34
Hf	1.59	9.98	0.197	6.57	3.18	1.18	0.285	0.12	0.38	0.979
Ta	0.193	1.11	0.062	0.916	0.456	0.156	0.026	<0.03	0.045	0.073
Th	0.91	5.38	0.064	5.49	1.80	1.06	0.123	---	0.168	0.319
U	0.22	1.66	0.03	2.10	0.57	0.20	0.049	---	0.069	0.18
Ir (ppb)	Nd	1.6±0.7	Nd	0.5±0.2	0.8±0.2	0.28±1.3	Nd	Nd	Nd	Nd
Au	2.0±0.6	<2.5	<3	<1.1	1.1±0.4	Nd	<1	<1	<3	<1.2

FA = Ferroan Anorthosite; FT = Ferroan Troctolite; D = Dunite.; N = Norite; T = Troctolite; OP = Olivine Pyroxenite; A = An orthosite.
Nd = Not detected.