STRENGTH/POROSITY/PETROLOGIC SCREENING DURING DELIVERY OF LUNAR METEORITES

Paul H. Warren, Institute of Geophysics, UCLA, Los Angeles, CA 90095-1567 (pwarren@ucla.edu)

The degree to which meteorites are representative of the near-surface portions of their parent bodies is among the major unresolved issues of planetary science. The trip from point of origin to Earth's surface begins with a violent impact-propelled launch off the parent body, and ends with a stressful passage through Earth's atmosphere. Large chunks of rock presumably do not survive these processes unless they are tough and coherent. Weaker materials break into fragments too small to become meteorites.

Asteroids commonly appear to have low densities that imply much higher porosity than typical meteorites [1]. But petrologic ground truth is only available for two or three meteorite parent bodies: the Moon, Mars (SNCs), and Vesta (HEDs?). Only the Moon has been sampled in a documented way. Lunar meteorites (lunaites) come from positions that are thoroughly random (aside from being shallow) within the Moon [2]. Their number has reached about 12, depending on how pairing is reckoned. This sample population is suitable for statistical comparison with the 382 kg of rock and soil acquired within 9 widely separated regions by the Apollo and Luna programs.

Most (at least 9/12) of the lunaites were launched from shallow depth, less than about 3 m [3-6], and most (8/12 or 9/12, depending upon classification of Y8xxx) are regolith breccias. Regolith breccia forms by compaction and minor intergranular shock-melting of material derived mainly from the topmost few meters, as evidenced by high concentrations of solar wind noble gases (e.g., ^{36}Ar), presence of quenched melt spherules, etc. The degree to which this rock type is overrepresented among lunaites is unclear. Most of the rocks collected by the first Apollo mission are regolith breccias. Later missions acquired relatively few regolith breccias, but this easily recognizable rock type may have been shunned by the later Apollo astronauts. Being ultra-polymict, regolith breccias are usually, *at any given point on the Moon*, highly uniform; collecting many tens of such samples probably became a low priority.

Ideally, we should know the tensile strength of each lunaite, plus comparable data for other meteorite types and Apollo rocks. Unfortunately, no strength measurement seems available for any Apollo rock, nor for any lunaite, except in the form of qualitative observations. Some Apollo regolith breccias were so loosely consolidated that they completely disaggregated into soil during gentle handling by NASA curatorial personnel, others seem about as cohesive as fresh igneous rock. The vast majority are intermediate: coherent, but obviously not as strong as fresh, unbrecciated igneous rock, such as mare basalt.

Lacking direct measurements of strength, we can gauge strength indirectly, by measuring a property that probably closely correlates with strength. The process that lithifies a lunar regolith breccia is the same process that determines its final porosity. The mechanism is impact-shock. As the fine-grained, highly porous (~ 50%) starting material is shock-compressed, intense stress concentrations develop at colliding grain boundaries. Among the results are compaction, plus a minor but strategically distributed component of glass, which welds the material into a rock [7]. In general, the more intense the compaction, the more glass will form, and stronger the final rock will be. Of course, the correlation between strength and compaction will not be perfect. More than one major shock episode may affect the material (even in a single event, compression and rarefaction waves may interfere near the free surface of the Moon), and in cases/areas where the shock is too intense, production of vesicular glass may enhance the final porosity [8]. Nonetheless, among Apollo regolith breccias there appears to be a significant anticorrelation between porosity and qualitatively measured strength.

Until this study, no direct quantitative measurements had been reported for porosity of lunaites. However, it was already apparent from petrographic descriptions that lunaite regolith breccias typically feature relatively low porosity [9], and that most seem unusually tough and cohesive compared to typical Apollo regolith breccias [3]. Also, bulk densities had been reported for three lunaite regolith breccias [10-11]. Given the relatively simple, predictable mineralogy of lunar materials, a measurement of bulk density combined with a mode or bulk analysis is tantamount to a determination of porosity. The reported bulk densities imply porosity = just 1-4% for the three lunaite regolith breccias studied. I have used a point-counting technique very similar to that of McKay and coworkers [12-13] to measure porosity of 5 additional lunaite regolith breccias, along with 8 Apollo analogs.

Some of the Apollo samples (10065, 61136, 61195 and 66035) were studied mainly as calibration checks. I studied 12073 because its reported bulk density [14] implied exceptionally low porosity, for an Apollo regolith breccia, and 14076, 14315, and 14318 because these three are compositionally exceptional (e.g., Al-rich, especially 14076) compared to all other Apollo 14 regolith samples. The new data (Table 1) (note: all bulk density and compositional data in this table are from literature sources, e.g., [10-11, 14]) show the porosity of 12073 is actually quite typical, for an Apollo regolith breccia. However, extraordinarily low porosity is confirmed for both 61195 (a compositionally undistinguished Apollo 16 regolith breccia) and 14318. The porosity of 14076 is also low, while 14315 is the least porous among 42 Apollo regolith breccias for which porosity can be constrained (Fig. 1).

The 8 constrained lunaite regolith breccias all feature lower porosity than any Apollo regolith breccia except (by a narrow margin) 14315. Even Calcalong Creek, not yet measured, was described by Hill et al. [15] as "very compact and consolidated, making separation of individual clasts difficult." I have previously cited my impressions of unusual strength during crushing of lunaites prior to INAA [3], and have since made similar observations for QUE9xx69 and QUE94281. It appears that ~11% is the maximum porosity that corresponds with enough strength for a lunaite regolith breccia to become a meteorite.

McKay [9] suggested that lunaite regolith breccias also differ from their Apollo counterparts by having systematically lower regolith maturity. He based this inference partly on an I_s/FeO datum for ALH81005, plus a perceived lack of agglutinates in the lunaites. The systematically greater compaction of the lunaites presumably makes it harder to

POROSITY AND STRENGTH SCREENING OF LUNAR METEORITES: P. H. Warren

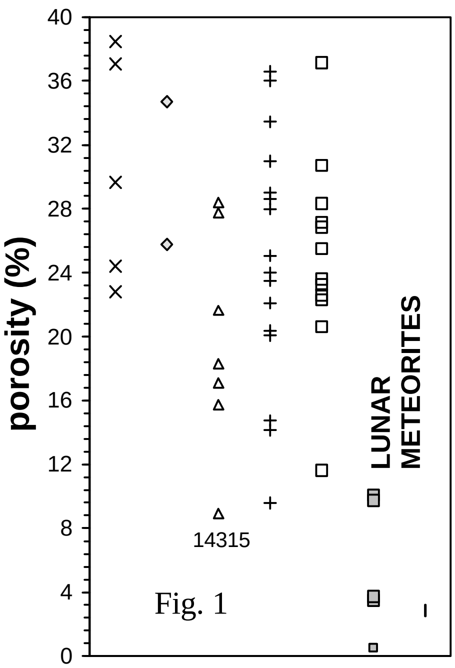

Fig. 1

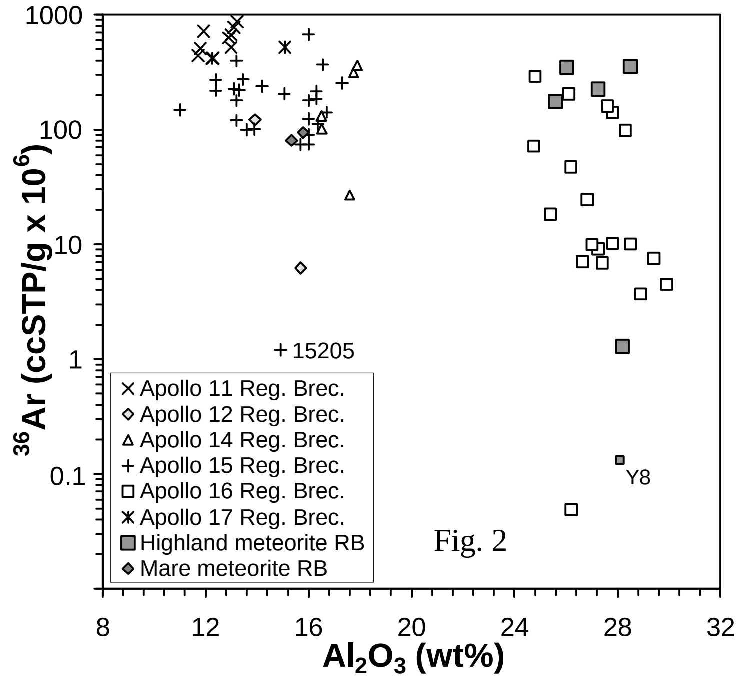

Fig. 2

recognize crushed agglutinates in them — yet ALH81005 was observed to be fairly rich in squashed agglutinitic matter [16]. Because I_s/FeO measures abundance of sub-microscopic metallic Fe, it is unsuitable for application to even mildly weathered meteoritic finds. Literature noble gas data (Fig. 2) indicate that, considering that most of the lunaite regolith breccias are from older highland (Al_2O_3-rich) regions, they show no significant difference in average maturity vs. Apollo regolith breccias.

Table 1. Results (measured porosity) and other relevant data.

Sample	$[Al_2O_3]$ (wt%)	density (g/cm^3) bulk	Intrinsic	porosity (%) calc.	meas.*
Selected Apollo regolith breccias					
10065	12.6	2.37	3.12	24	24
12073	13.9	2.9	3.18	9	26
14076	30.4	no data			17
14315	21.7	no data			9
14318	17.6	2.56	3.09	17	16
61135	29.4	1.96	2.84	31	28
61195	26.8	2.46	2.90	15	12
66035	28.5	2.13	2.84	25	27*
Lunar meteorite regolith breccias					
ALH81005	25.6				3.5
Dar al Gani	27.2			*NB: weathered*	*10*
MAC88105	28.2				11
QUE93069	28.6	Note: QUE93069 and			9
QUE94269	28.3	QUE94269 are paired			9
Y8XXXX	28.1	2.86	2.87	0.5	
Y793274	15.3	3.07	3.16	3	
Y791197	26.0	2.84	2.95	4	

* for comparison, [12] measured 26% for 66035.

Unfortunately, it is difficult to say whether the main cause of the dearth of weak, high-porosity regolith breccias among lunaites is fragmentation during launch, or fragmentation during atmospheric entry. Lunaites generally enter at much lower velocity than most other meteorites (which derive from more eccentric orbits). Also, the vast majority of Apollo regolith breccias are compositionally indistinguishable from local soils at the point of sample acquisition. Compositionally "exotic" regolith breccias are very rare [e.g., 12-13]. The greatest exceptions, 14076 and 14315, are extraordinarily compact. Thus, it appears that the launch process, even just to transport an intact rock for a distance of order 100 km across the surface of the Moon, may generally require greater strength than a typical regolith breccia possesses.

The lesson from the lunaites is that meteorites may be a strongly biased sampling of the actual range of materials on their parent bodies. The bias may be particularly acute for launches off Mars (v_{esc} = 2.1x that of the Moon). For example, the scarcity of hydrated secondary minerals in the carbonate-bearing ALH84001 is puzzling. But conceivably this particular chunk of the parent material only survived the launch off Mars by virtue of being atypically strong, and thus atypically poor in hydrated minerals.

References: [1] Consolmagno C. J. & Britt D. T. (1996) *MPS* 31, A31. [2] Warren P. H. (1994) *Icarus* 111, 338-363. [3] Nishiizumi K. et al. (1996) *MPS* 31, 893-896. [4] Thalmann C. et al. (1996) *MPS* 31, 857-868. [5] Swindle T. D. et al. (1995) *MPS* 30, 584-585. [6] Bischoff A. et al. (1998) *MPS*, submitted. [7] Christie J. M. et al. (1973) *PLSC* 4, 365-382. [8] Ahrens T. J. & Cole D. M. (1974) *PLSC* 5, 2333-2345. [9] McKay D. (1991) *Abstr. 16th Symp. Ant. Met.*, p. 96-99. [10] Yanai K. & Kojima H. (1985) *Abstr. 10th Symp. Ant. Met.*, p. 87-89. [11] Yanai K. & Kojima H. (1985) *Abstr. 12th Symp. Ant. Met.*, p. 17-18. [12] McKay D. et al. *PLPSC* 16, D277-D303. [13] McKay D. et al. *PLPSC* 19, 19-41. [14] Talwani M. et al. (1973) In *Apollo 17 Prelim. Sci. Rpt.*, p. 13.1. [15] Hill D. et al. (1991) *Nature* 352, 614-617. [16] Warren P. H. et al. (1983) *GRL* 10, 779-782.