HAZARDS INVOLVED IN LUNAR PETROGENETIC INTERPRETATION: A SUMMARY OF CRITERIA USED TO ESTABLISH THE PRISTINITY AND MONOMICT NATURE OF MOON ROCKS

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Unravelling the science of returned lunar rocks is a complicated, but it is made even more difficult by meteorite bombardment. As such, each sample must be evaluated for its pristinity and monomict nature. In this discussion, the term *pristine* is used to mean a sample free from meteorite contamination and the term *monomict* is used in the sense that the sample contains only one lunar lithology. In order for any credible petrogenetic interpretation to be made regarding lunar evolution, the pristinity and, more importantly, the monomict nature of the samples must be established. Previous authors [1-8] have outlined criteria that are applied to lunar samples in order to establish pristinity. It is the purpose of this paper to summarize these criteria and to list what we believe are several criteria designed to establish the monomict nature of a given lunar rock. Furthermore, we will highlight the case that just because a sample is pristine does not necessarily mean it is monomict.

PRISTINITY - Warren and Wasson [1] presented 7 criteria for establishing the pristine nature of nonmare (i.e., highland) rocks: 1) low siderophiles ($< 3 \times 10^{-4}$ x chondrites); 2) low incompatibles ($< 5 \times 10^{-3}$ x KREEP); 3) coarse grains (> 3mm); 4) antiquity (> 4.2 Ga); 5) phase homogeneity; 6) low $^{87}Sr/^{86}Sr$ (< 0.6992); 7) "cumulate" character. These authors originally and in their subsequent publications, have intertwined criteria for establishing pristinity with those for establishing a monomict nature. It is obvious that if a sample is non-pristine, it contains two components - lunar and meteoritic - and cannot be monomict. However, a sample can be pristine, in that no meteoritic component is present, but two (or more) lunar lithologies may be present, so this sample is again polymict. Warren and Wasson [1-4] indicate that it is the level of siderophile elements present in a lunar sample which holds the key to demonstrating pristinity. This was also emphasized by Anders [5] who stated that lunar samples containing > 0.1 ppb Ir are non-pristine.

FeNi Metals - Ryder et al. [8] used FeNi metal compositions to define pristine and non-pristine highland lunar rocks. Generally, pristine rocks contain FeNi metals with a Ni/Co ratio of generally < 5, with the Mg-Suite rocks proving the exception. However, non-pristine samples would be expected to contain FeNi metals with Ni/Co ratios of < 5, as well as > 10, as they are mixtures of meteoritic and pristine lunar metal. Goldstein and Yakowitz [9] attempted to define a range of meteoritic FeNi metal Ni/Co ratios which could be used to identify meteoritic contamination. However, this field was based upon *whole-rock* Ni-Co contents of *iron meteorites*, not the FeNi metal of *chondritic meteorites*, which are considered to form the bulk of the extra-lunar contamination on the Moon. In fact, the petrography of the metallic phases can also be useful in identifying a meteoritic component. The presence of schreibesite as well as cohenite is indicative of meteorite contamination [10], as the formation of a carbide in lunar rocks cannot occur without some meteoritic input [11]. Also, if kamacite and taenite exsolution features are present in FeNi metal, this indicates considerable re-equilibration, requiring much slower cooling rates than is normal for lunar igneous rocks (e.g., $10\text{-}100^{o}$ per m.y.) - this can only be achieved within the larger meteorite parent body [12-14]. The morphology of the FeNi metal grains can also give clues to the pristinity of a lunar sample. If large (i.e., > 200u), the grains are usually inherited from the projectile - chemical analysis of the metal is often used in conjunction with this observation [15].

MONOMICT NATURE - Criteria used to define whether one or more lunar lithologies have been mixed in during meteorite impact are less well defined. These rocks may be pristine with regard to meteorite contamination, but still polymict. The initial criterion is that of texture. If a sample is brecciated or granulitic, the sample is more likely to be polymict than if it possessed a cumulate or ophitic to sub-ophitic texture. However, as was the case of 14310, meteorite-induced impact melts can produce "monomict" textures upon cooling. The key to understanding 14310 was the "straw-like" and "cross-hatched" nature of the feldspars [16,17]. This texture is produced by melting to just below or, very briefly, above the liquidus. Another textural criterion in defining impact melts and rocks affected by impacts is the presence of many minute, interstitial metal grains, distributed in cracks. This is indicative of "auto-reduction" (caused by solar-wind implanted H) of a lunar rock or soil upon meteorite impact and may not contain any meteoritic contamination. This may not necessarily indicate the mixing of several components, but denotes brecciation and other criteria should be applied to make sure of a monomict nature. Warren and Wasson [1-4] stated that inter-phase homogeneity is indicative of pristinity. We agree with Warren and Wasson [1] that phase homogeneity is indicative of a monomict nature in plutonic lunar rocks. However, Lindstrom and Lindstrom [18] noted that Apollo 16 granulites, clearly polymict from textural evidence, had essentially re-equilibrated to almost homogeneous mineral compositions. Also, this criterion is not applicable to extrusive lunar rocks, where phase inhomogeneity is the rule rather than the exception. Also, for plutonic rocks, attempting to recalculate the whole-rock major-element chemistry from analyzed mineral compositions can be used to test for a monomict sample. If the whole-rock chemistry cannot be reproduced, this suggests another component has been included in the whole-rock (INA) sample. However, this must be used in conjunction with texture and mineral homogeneity in order to be definitive - the whole-rock major-element could be reconstructed from the mineral chemistry of a polymict rock if all components are present in both the thin section and INA samples. This problem of representative sampling is critical in the examination of the coarse-grained highland rocks. Ideally, a thin section should be made from the INA sample after analysis.

Many lunar breccias have "KREEPy" incompatible element abundances and ratios and are polymict rocks. This suggests that KREEP forms an important constituent of lunar soils (e.g., [19,20]). Therefore, if a lunar sample contains high incompatible element abundances, other criteria outlined above must be used to establish a monomict nature. Warren and Wasson [1-4] stated that plutonic rocks containing incompatible elements $> 5 \times 10^{-3}$ x KREEP were not pristine - this criterion is used here to mean monomict as meteorites would not elevate the incompatible elements to KREEPy levels. This may be true for some plutonic samples, but cannot be used as a generalization because the presence of minor phases, such as whitlockite, apatite, and zircon, may be of metasomatic origin (e.g., [21]) rather than from mechanical mixing. Hence this criterion must be used in conjunction with others to establish the polymict/monomict nature of a given lunar sample. Furthermore, Salpas et al. [22] described breccia 72275 as containing clasts compositionally indistinguishable from the breccia matrix. This breccia was derived from one or a series of closely related KREEP basalt flows, as were the included clasts. There is very little contamination of this breccia by meteorite or other lunar lithology, and as such, this breccia may be considered pristine and monomict!

LUNAR GLASSES - So far, this discussion has centered upon rock samples. However, the lunar glass beads have also produced significant petrogenetic advances in our understanding of the Moon (e.g., [23,24]). The problems involved in distinguishing pristine, primary glass beads from impact melts and non-pristine glasses is slightly different. Pristine, volcanic glasses must be of basaltic composition, possess intra-sample homogeneity, contain no bubbles, have a surficial coating of volatile material, and high Mg/Al ratios, but contain no schlieren or exotic inclusions. Stone et al. [25] used FMR analysis to determine the volcanic or impact origin of glass beads. This criterion was presented in terms of I_s and glass beads containing high values of I_s are consistent with an impact origin. This is in response to the solar-wind induced auto-reduction of metallic Fe in the lunar soil upon meteorite impact. Therefore, glass beads of volcanic origin possess low I_s values. Furthermore, only those glasses with CaO/Al_2O_3 (weight) ratios of greater than 0.75 are considered to have mare parentage. Those with CaO/Al_2O_3 ratios < 0.75 are considered to be of highland parentage and formed by meteorite impact. Delano [24] concluded that in a lunar magma, Ni will act as a lithophile element and form a positive correlation with MgO. If glass beads have been "doped" with Ni from meteorite impact, they will form horizontal extensions from this positive correlation on a Ni (ppm) vs. MgO (wt%) plot.

DISCUSSION - The above criteria have been outlined in order to demonstrate the complexity of determining whether or not a lunar sample is pristine and monomict. It is evident that *a sample may be pristine, yet may not be monomict*. Also, a sample may be **texturally** monomict, yet non-pristine. After a review of the literature (e.g., [1-8]), it is apparent that confusion can occur when authors use the terms monomict and pristine synominously. Warren and Wasson [1-4] used terms of "possibly" or "probably pristine" to describe some nonmare samples because either the data were lacking or there were conflicting results from the criteria used to define pristinity. We suggest that the study of all lunar samples should first define, using the criteria summarized above, if a sample is pristine (i.e., free of meteorite contamination). Then criteria pertaining to a monomict/polymict sample should be applied. The ideal situation is that we have pristine, monomict samples, but this is not always the case. However, from our studies of Apollo 14 and 17 highland samples [25,26], we propose that pristinity is not the most essential criterion to be met in the study of lunar samples. More important is whether or not more than one ***lunar*** lithology is represented in our sample.

Although a lunar rock is non-pristine, and by definition polymict (i.e., it contains components from 2 or more sources), it may only contain **one** lunar lithology. If this is the case, which can be generally satisfied by applying the above criteria for defining monomict/polymict samples, then such samples may be used for petrogenetic interpretation. This is because a measure of the meteorite contamination can be guaged from Ir and Au abundances, and even in soils, this is generally $< 1\%$. As it is envisaged that many meteoritic projectiles would have vaporized upon impact, this addition was probably due to infiltration of meteoritic material in the vapor phase. Such a mechanism may account for the small amount of meteoritic contamination found in many lunar rocks. Addition of such a small proportion of meteoritic material by whatever means, will have practically no effect on the incompatible trace element abundances or ratios - only the inclusion of other lunar components will radically alter these. Adherence of small amounts of tough matrix to clasts during breccia pull-aparts, such as with Apollo 17 samples [26], will indicate a non-pristine, polymict sample, when in fact the clast in monomict and pristine.

CONCLUSIONS - Pristinity should not be the primary consideration in the study of lunar rocks. The most important criterion to establish is whether or not the lunar sample contains more than one ***lunar*** lithology. Even if a sample is non-pristine, as long as only one lunar lithology is present, petrogenetic interpretation can still be carried out.

REFERENCES: **[1]** Warren & Wasson (1977) PLPSC 8th, 2215; **[2]** Warren & Wasson (1978) PLPSC 9th, 185; **[3]** Warren & Wasson (1979) PLPSC 10th, 583; **[4]** Warren & Wasson (1980) Proc. Conf. Lunar Highlands Crust, 81; **[5]** Anders (1978) PLPSC 9th, 161; **[6]** Norman & Ryder (1979) PLPSC 10th, 531; **[7]** Palme (1980) PLPSC 11th, 481; **[8]** Ryder et al. (1980) PLPSC 11th, 471; **[9]** Goldstein & Yakowitz (1971) PLSC 2nd, 171; **[10]** El Goresy et al. (1972) PLSC 3rd, 333; **[11]** Gooley et al. (1973) PLSC 4th, 799; **[12]** Axon & Goldstein (1972) EPSL 16, 439; **[13]** Axon & Goldstein (1973) EPSL 18, 173; **[14]** Hewins & Goldstein (1975) LS VI, 356; **[15]** Misra & Taylor (1975) PLSC 6th, 615; **[16]** Lofgren (1974) Am. J. Sci. 274, 243; **[17]** Nabelek et al. (1978) PLPSC 9th, 725; **[18]** Lindstrom & Lindstrom (1986) PLPSC 16th, in JGR 91, D263; **[19]** Meyer et al. (1971) PLSC 2nd, 393; **[20]** Warren (1988) Apollo 14 Workshop; **[21]** Neal & Taylor (1989) GCA 53, 529; **[22]** Salpas et al. (1987) PLPSC 17th, in JGR 92, E340; **[23]** Delano & Livi (1981) GCA 45, 2137; **[24]** Delano (1986) PLPSC 16th, in JGR 91, D201; **[25]** Stone et al. (1982) PLPSC 13th, in JGR 87, A182; **[26]** Neal et al. (this volume); **[27]** Eckert et al. (this volume).