WANTED:

LUNAR DETECTIVES TO UNRAVEL THE MYSTERIES OF THE MOON!

CRIME TO BE SOLVED:

"MASS EXTINCTIONS" ON THE MOON BY METEORITE IMPACT!

Clive R. Neal, Dept. of Earth Sciences, University of Notre Dame, Notre Dame, IN 46556; and **Lawrence A. Taylor**, Dept. of Geological Sciences, University of Tennessee, Knoxville, TN 37996.

EXECUTIVE SUMMARY - Since the return of the first lunar rocks by Apollo 11 astronauts, lunar detectives (scientists) have been attempting to unravel the "crimes" that have affected and created the Moon as we see it today. And the Earth's sister planet is revealing facts about its ancestry which is common both to the Moon and Earth. You see, the Moon's thermal and dynamic nature ended some 3,000,000,000 (3 *billion*) years ago and what we see with the Mare fillings (i.e., the dark "eyes of the Man in the Moon") is the final death throw of the Moon as a living planet. Since then, the Moon has remained effectively dead. Largely because of the lack of an atmosphere and abundant water, the Moon has remained relatively unchanged for the past 3 *billion* years. In contrast, the Earth had a similar early history, starting with its birth some 4.6 *billion* years ago, but has remained in a lively state throughout its history. In fact, the ancient ancestry of the Earth has been largely obliterated by more recent activity, such as plate tectonics, on this frisky and very much alive (and kicking) planet. Therefore, by studying the rocks and soils which make up the "death-mask" of the Moon, we are gaining insight into the early evolution of our own planet Earth.

The only weathering and erosional agent on the Moon is meteorite and micrometeorite bombardment. Due to the lack of water-induced chemical weathering, the composition of the Moon rocks has remained largely unaltered since formation. Or have they?? Meteorites have smashed, melted, metamorphosed, and otherwise affected the lunar rocks. Which rocks are unadulterated?? This is where the "lunar detective" comes in. In order to determine the "*pristinity*" of lunar rocks, we use some of the same logic and chemistry that has permitted us to determine a correlation between Mass Extinctions of life on Earth, such as the Dinosaurs, and giant meteorite impacts. We look for a chemical evidence or signature of meteorite contamination in the element **IRIDIUM**. As on Earth, the lunar rocks contain scarcely any iridium. Therefore, when anomalous iridium contents are observed, the sample has obviously been contaminated by meteoritic matter and the results from our study of the origins of such rocks can be quite misleading.

Therefore, the lunar geologist must not only be a detective in unravelling the mysteries of the Moon, but also judge, jury, and chief executioner in deciding whether or not certain returned samples are *pristine* for analysis. This paper outlines the criteria and clues we look for in identifying contamination as we continue our quest for more knowledge regarding the evolution of the Moon and the early Earth.

PRISTINITY - Warren and Wasson [1] presented 7 criteria for establishing the pristine nature of highland rocks: 1) low elemental abundances of nickel, iridium, and gold - these "siderophile" elements are abundant in meteorites, so the levels in lunar rocks must be very low relative to these meteorites (i.e., $<3 \times 10^{-4}$ x meteorite abundances); 2) low "incompatible" element abundances, i.e., elements which do not like to "fit in" to most mineral structures - these abundances are measured relative to the incompatible-element-rich lunar component "KREEP" ($< 5 \times 10^{-3}$ x KREEP); 3) coarse grains (> 3mm); 4) antiquity (> 4.2 Ga); 5) homogeneous mineral composition; 6) low $^{87}Sr/^{86}Sr$ (< 0.6992) - this ratio is changed by radioactive decay of Rb to Sr at a constant rate and can yield a time constraint in constructing a model for the formation of the rock; 7) "cumulate" character (i.e., the texture appears as if the minerals have settled or cumulated from a liquid). However, Warren and Wasson [1] originally and in their subsequent publications, have intertwined criteria for establishing *pristinity* with those for establishing a *monomict* nature (i.e., is the sample comprised of only one rock type?). 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* (the sample is comprised of more than one rock type). 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 parts per billion Iridium are non-pristine.

Iron/Nickel Metals - Metallic fragments are ubiquitous in both lunar rocks and meteorites. Criteria must be established to distinguish between lunar and meteoritic metals. Ryder et al. [8] used Iron/Nickel metal compositions to define pristine and non-pristine highland lunar rocks. Generally, pristine rocks contain Iron/Nickel metals with a Nickel/Cobalt ratio of generally < 5, with the Mg-Suite of highland rocks proving the exception. However, non-pristine samples would be expected to contain Iron/Nickel metals with Nickel/Cobalt 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 Iron/Nickel metal Nickel/Cobalt ratios which could be used to identify meteoritic contamination. However, this field was based upon *whole-rock* Nickel-Cobalt contents of *iron meteorites*, not the Iron/Nickel metal of *chondritic meteorites*, which are considered to form the bulk of the meteorite contamination on the Moon. In fact, the petrography of the metallic phases can also be useful in identifying a meteoritic component. The presence of the mineral *schreibesite* as well as *cohenite* is indicative of meteorite contamination [10], as the formation of carbon-bearing minerals in lunar rocks cannot occur without some meteoritic input [11]. Also, if *kamacite* and *taenite* inclusions are present in Iron/Nickel metal, this requires much slower cooling rates than is normal for lunar igneous rocks (e.g., 10-100^o per m.y.) - which can only be achieved within the larger meteorite parent body [12-14]. The shape of the Iron/Nickel metal grains can also give clues to the pristinity of a lunar sample. If large (i.e., > 0.2mm), 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* (see above). The initial criterion is that of texture. If a sample is of widely varying grain size ("brecciated") or granular, the sample is more likely to be polymict. However, as was the case of Apollo 14 sample 14310, meteorite-induced impact melting of existing rocks can produce "monomict" textures upon cooling. The key to understanding 14310 was the "straw-like" and "cross-hatched" nature of the mineral feldspar [16,17]. This texture is produced by melting to just below or, very briefly, above the absolute melting point of the lunar material. 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 hydrogen implanted from the sun by solar-wind) 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 homogeneity between mineral grains of the same species is indicative of pristinity. We agree with Warren and Wasson [1] that such homogeneity is indicative of a monomict nature in lunar rocks formed below the surface (i.e., "deep-seated") of the Moon. However, Lindstrom and Lindstrom [18] noted that rocks from Apollo 16 exhibiting clearly polymict textures, had essentially re-equilibrated to almost homogeneous mineral compositions. Also, this criterion is not applicable to lunar rocks extruded and cooled at the surface of the Moon, where phase inhomogeneity is the rule rather than the exception. Also, for deep-seated rocks, attempting to recalculate the whole-rock composition from analyzed mineral compositions can be used to test for a monomict sample. If the whole-rock composition cannot be reproduced, this suggests another component has been included in the whole-rock sample which is not observed in the sample used to make the determinations of mineral chemistry. However, this must be used in conjunction with texture and mineral homogeneity in order to be definitive - the whole-rock composition could be reconstructed from the mineral chemistry of a polymict rock if all components are present in both the samples used to determine whole-rock and mineral compositions.

Many lunar breccias have "KREEPy" incompatible element abundances and ratios (see above) 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 $> 5 \times 10^{-3} \times$ KREEP were not pristine - this criterion is used here to mean monomict as meteorites would not elevate the incompatible elements to these "KREEPy" levels (remember that KREEP is an incompatible-element-rich lunar component). This may be true for some deep-seated samples, but cannot be used as a generalization because the presence of incompatible-element-rich minor phases (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 Apollo 17 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 meteorite-induced impact melts and non-pristine glasses is slightly different. Pristine, volcanic glasses must be of basaltic composition, possess within-sample homogeneity, contain no bubbles, have a surficial coating of volatile material, and high Magnesium/Aluminium ratios, but contain no exotic inclusions. Stone et al. [25] used a type of "magnetic resonance" 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 (calcium oxide/aluminium oxide) 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, Nickel will act as a lithophile element and form a positive correlation with MgO. If glass beads have been "doped" with Nickel from meteorite impact, they will form horizontal extensions from this positive correlation on a Nickel (parts per million) vs. MgO (magnesium oxide) (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 highland samples because either the data were lacking or there were conflicting results from the various 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* rock type. 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 in the interpretation of lunar evolution in that particular area. This is because a measure of the meteorite contamination can be guaged from Iridium and Gold 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*** rock type. Even if a sample is non-pristine, as long as only one lunar rock type 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).