PIGEONHOLING PLANETARY METEORITES: THE LESSONS OF MISCLASSIFICATION OF EET87521 AND ALH84001.

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The last few years have provided two noteworthy examples of misclassifications of achondritic meteorites because the samples were **new kinds** of meteorites from **planetary** rather than asteroidal parent bodies. Basaltic lunar meteorite EET87521 was misclassified as a eucrite [1,2] and SNC (martian) orthopyroxenite ALH84001 was misclassified as a diogenite [3]. (Here a *planetary body* is one that remained internally active for a significant period of geologic time. The term *planetary bodies* includes the Moon, while *the planets* does not.) In classifying meteorites **we find what we expect:** we pigeonhole meteorites into known categories most of which were derived from the more common asteroidal meteorites. But the examples of EET87521 and ALH84001 remind us that planets are more complex than asteroids and exhibit a wider variety of rock types. We should **expect variety** in planetary meteorites and we need to know how to **recognize them when we have them.**

Lunar meteorites were unknown and unexpected in 1982 when ALHA81005 was found in Antarctica. But the comparison of this anorthositic breccia with returned lunar samples left no doubt as to its parent body. As the number of lunar meteorites grew to 7, our knowledge that 17% of the lunar surface was covered by mare basalts should have led us to anticipate a basaltic lunar meteorite. Nonetheless EET87521 was classified as a eucrite because it almost fit in that pigeonhole. Its real parentage was soon discovered by investigators [1,2] and within a year three more basaltic lunar meteorites were identified (two reclassified and one a new meteorite). In 1991, with the lunar highlands and mare well represented by meteorites, the discovery of Calcalong Creek, a KREEP-rich lunar breccia [4], was surprising only as the first non-Antarctic lunar meteorite. Table 1 lists generalized lithologies of meteorite parent bodies and planets. The lithologic types and abundances for Earth and Moon were determined by studies of surface rocks, while those of the asteroids and other planets were inferred from meteorites and remote geology. The current suite of lunar meteorites represents the three most common lithologies on the lunar surface.

The study of martian meteorites has also been hampered by pigeonholing. ALHA77005 was originally classified as a unique achondrite with similarities to several types of achondrites. Research established a petrogenetic link to shergottites and subsequently ALHA77005 (and later LEW88516) was classified as a shergottite, a basalt pigeonhole that does not really fit its ultramafic character (10 % plagioclase). ALH84001 was also pigeonholed, as a diogenite, where it remained little-studied for 8 years before its SNC affinities were revealed [3]. By the mid-1980s SNC achondrites were assumed to be martian meteorites [5, 6] by all but the most diehard skeptics. Should we not have expected a wider variety in basalts and ultramafic rocks from the planet Mars than are seen in the HED meteorite suite from an asteroid? Yet we continued to try to squeeze all martian meteorites into one of the three S-N-C pigeonholes. If we had opened our minds to a wider variety of martian igneous rocks, might we have discovered ALH84001 sooner?

Our intent here is to show that our asteroidal perspective is inappropriate for planetary meteorites, not to criticize curators for misclassifications. The initial descriptions and classifications are deliberately cursory so as not to impinge on detailed research, yet they noted unusual features in both EET87521 and ALH84001 which should have been clues that further study was needed. Table 2 lists some characteristics of basalts (and ultramafic rocks) from various bodies in the solar system. Some are determined in the initial classification, but others should be measured in the first round of scientific analysis. Many of these characteristics have been used before to distinguish planetary from asteroidal meteorites, especially Fe/Mn and oxygen isotopes, but they are tabulated together here for the whole suite of basalts. Many other characteristics are also useful. No single characteristic can clearly identify the parent body because the values overlap (Fe/Mn HED=Mars, Earth~Moon; O isotopes: HED=Angrites, Earth=Moon), but two or more characteristics together may be definitive, even without the canonical oxygen isotope analysis. Use of these characteristics should make it possible to identify planetary igneous rocks within the first year of study and prevent the recurrence of the long delay in discovery of ALH84001.

Several of the characteristics in Table 2 appear to be dependent on the size of the parent body: oxidation state, volatile content, and ages of volcanism. The smaller bodies, the Moon and the differentiated asteroids, are volatile-poor and more reduced than the planets which are volatile-rich and oxidized. Duration of volcanism is shorter on smaller bodies. Other correlations with the size of the parent body include the variety and fractionation of igneous rocks [7, 8]. The differences in volatiles, duration, variety and fractionation are reflected in Table 1.

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Sedimentary rocks are not expected on the Moon and asteroids because they are volatile-depleted and lack an atmosphere, but should be common on the terrestrial planets (except Mercury). Fractionation on the Moon was early and global and led to anorthosites, while igneous processes on Earth were complex and produced granites. Mars is likely to be intermediate between Earth and Moon and Venus to be more Earth-like.

In comparing the current suite of martian meteorites to the expected lithologies, we see that they represent only mafic igneous rocks. We have no felsic rocks, sediments or impact breccias. Furthermore, they represent only the young volcanic province, and not the older martian highlands. The characteristics listed in Table 2 may serve as a starting point in evaluating likely mineralogies and compositions of sediments and felsic igneous rocks, but the values will be modified by fractionation and sedimentary processes. However, we must first find the meteorites before we can identify their parent bodies. Would we recognize martian sediments or felsic rocks as meteorites if we found them in Antarctica? Probably not, because they would look too much like Earth rocks. The case is even worse for recognizing possible Earth or Venus meteorites [9]. As long as we look at all meteorites from an asteroidal rather than planetary perspective, we may be missing some of the most interesting meteorites .

TABLE 1. KNOWN AND LIKELY LITHOLOGIES OF DIFFERENTIATED METEORITE PARENT BODIES AND PLANETS. [CAPS: known based on field geology and surface samples. **bold**: known as meteorites. under: very likely, based on remote geology or inferred from collected meteorites. *italics*: likely, based on remote geology or inferred from collected meteorites. Refs. 5-12]

Lithologies	HED	Angrites	Moon	Earth	Mars	Venus
Igneous						
basaltic	**common**	**common**	COMMON	COMMON	**common**	common
ultramafic	**present**	**present**	RARE	RARE	**common**	*rare*
anorthositic	none	none	**COMMON**	RARE	*possible*	*rare*
granitic	none	none	RARE	COMMON	*possible*	*probable*
Sedimentary						
chemical/clastic	none	none	NONE	COMMON	common	common
Impact						
breccias	**common**	*possible*	COMMON	RARE	*possible*	*rare*
Metamorphic						
meta igneous	**present**	*possible*	PRESENT	PRESENT	*possible*	*possible*
meta sediment	none	none	NONE	PRESENT	*rare*	*possible*
meta impact	*possible*	*possible*	PRESENT	RARE	*rare*	*rare*

TABLE 2. CHARACTERISTICS OF SOLAR SYSTEM BASALTS. [normal: approximate measurements in surface samples for Earth & Moon, in meteorites for Mars, HED and Angrites and remote sensing for Venus. *italics*: inferred from remote measurements and geology for Venus. Refs. 5-7, 10-13]

Characteristics	HED	Angrites	Moon	Earth	Mars	Venus
Mineral Composition						
Fe/Mn (px)	35	90	70	60	35	*55*
Plagioclase	An90	An99	An92	An50	An50	--
Oxidation: Fe3+ ox, px	N	Y (ox)	N	Y	Y	Y
iron metal	Y	N	Y	N	N	*N*
sulfide	Troilite	Troilite	Troilite	Pyrrh.	Pyrrh.	*Pyrrh.*
Secondary Alteration Minerals	none	none	none	Hydrous CO_3, SO_4	Hydrous CO_3, SO_4	*Anhydrous* CO_3, SO_4
Bulk Composition						
Fe/Mn	28-40	80-95	60-80	50-70	35-50	55±30
K/U	2,000	150	1,700	12,500	15,000	12,500
K/La (xCI)	0.03	0.002-0.03	0.03	0.15	0.2	*0.1-0.2*
Rb/La (xCI)	0.002-0.02	0.001	0.016	0.09	0.3	*0.1*
Isotopic Composition						
$\Delta^{17}O$	-0.2	-0.2	0.00	0.00	+0.3	*0.0-0.3*
Age of Volcanism	4.6-4.5 Ga	4.6 Ga	4.3 - 3 ? Ga	4 Ga - 0 a	4 ? Ga - 180 ? Ma	*4 Ga- 0 a*

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