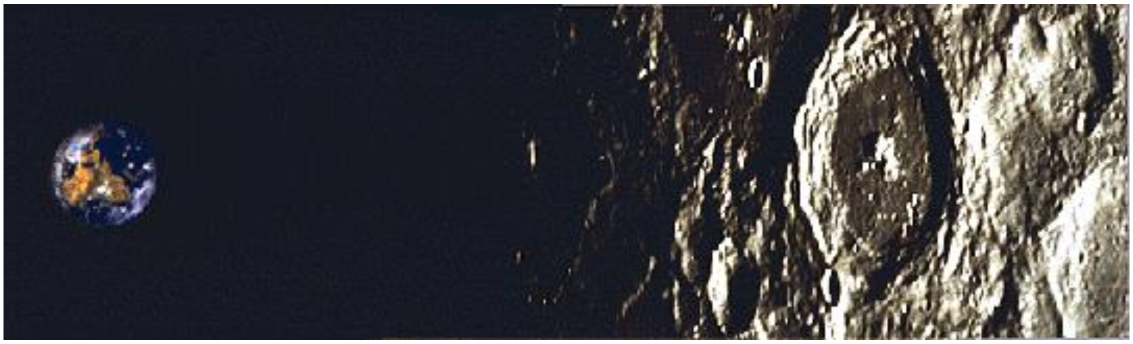
Lunar Meteorite Compendium Introduction Kevin Righter, January 2010



How do lunar meteorites get to Earth? Theory and measurements

The idea that meteorites could be ejected from the Moon and arrive at Earth is not particularly new (e.g., Arnold, 1965; Wetherill, 1968), but evidence was lacking until the discovery of ALH A81005. After initial assessments of Melosh (1984) and cosmic ray exposure age dating (see review of Eugster, 1989), Warren (1994) showed that many of the lunar meteorites could have been ejected from small craters, and that at least six individual craters were involved. Although the number of craters has certainly changed given the multitude of new lunar meteorites reported since then (now 62). Using two different models for ejection dynamics (Earth-Moon-Sun-outer planets) Gladman et al. (1995) showed that fragments of the Moon that were ejected between speeds of 2.4 and 3.6 km/s from the surface of the Moon (just above the escape velocity) would stay in terrestrial orbits only up to approximately 10 Ma. Comparison of the modeling results agrees nicely with the distribution of 4π exposure ages (transition times, which corresponds to exposure as a small object in space) determined on the lunar meteorites (see Figure 1). However, with all of the new lunar meteorites, and additional revisions to impact dynamics (e.g., Head et al., 2002) it is probably worth revisiting this problem in more detail. Nonetheless, it appears that the ages correspond to 4π exposure ages, rather than 2π exposure ages that would result from exposure at the surface of the Moon.

Another aspect of lunar meteorites related to their ejection and launching from the surface of the Moon, is their lower porosity compared to Apollo samples collected at the surface. Warren (2001) showed that eight lunar meteorite breccias have lower porosities (~3%) than 44 analogous Apollo samples (~ 25%). He attributed this difference to two factors: a) stronger and more compact breccias are more likely to have survived the launch to lunar escape velocities, and b) lunar materials are likely to have become compacted and less porous during the impact and shock event that ejected them from the Moon (Warren, 2001). Again, densities should be evaluated in light of the many new meteorites that have been found, including 10 of basaltic composition.

Finally, it has been recognized that some meteorites may be different rock types that were ejected or launched together from the same impact event. These are said to be "launch paired". Some meteorites are suggested to be launched paired based on their For example, Yamato 793169, Asuka 881757, MIL 05035, and MET 01210 are likely launch paired based on their similarity of composition, exposure histories, and crystallization ages (Korotev et al., 2003; Korotev, 2006; Arai et al., 2005, 2009; Zeigler et al., 2007). It has been proposed that NWA 032 is related to the LAP basalts

(Korotev, 2006). And the mingled meteorites, Yamato 793274/981031, QUE 94281, and EET 87521/96008 have all been suggested to be launch paired based on their similar composition, texture, lithology, and exposure history (Korotev et al., 2003; Korotev, 2006, and references therein). However, no other meteorites have been definitively launch paired, although evidence to the contrary may be presented in the future. As a result it seems clear that the lunar meteorites represent a large number of source craters, and thus represent samples from a large and random portion of the lunar surface.

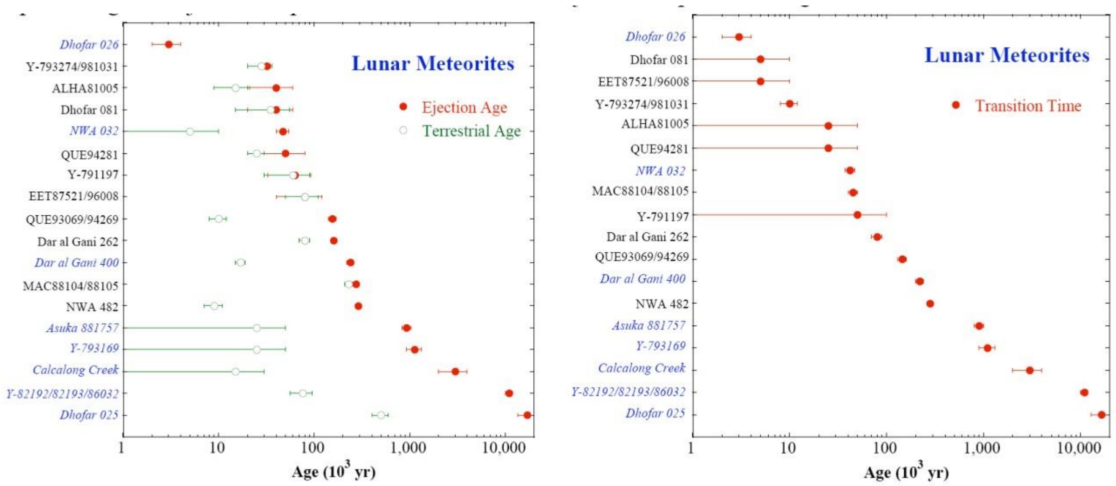
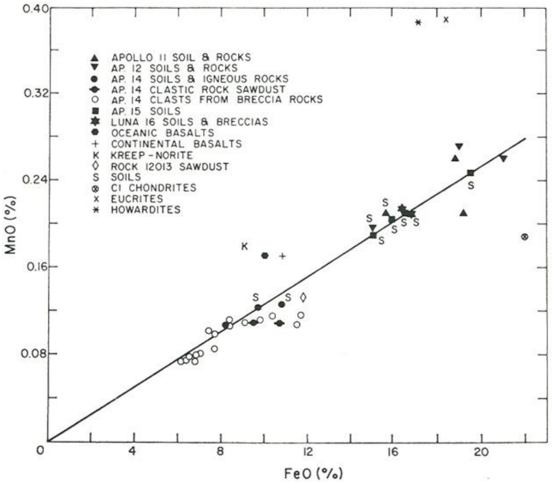


Figure 1: Ejection ages, terrestrial ages, and transition times of lunar meteorites, taken from the most recent work of Nishiizumi et al. (2004).

Identification of lunar material

The first kind of information that can be used to identify a meteorite as lunar is that obtained from either hand samples or thin sections. Lunar meteorites can be feldspathic rocks (and including breccias), basalts (and including breccias), and mixed breccias, and each has its own specific textural characteristics. In addition, lunar materials contain some unique minerals that can help to identify them as lunar. For example, armalcolite is a mineral first found on the Moon ($Mg_{0.5}Fe_{0.5}Ti_2O_5$, with a structure similar to ferropseudobrookite). In addition, some lunar basalts contain > 5 wt% ilmenite, and can also contain FeNi metal.

The second kind of information is compositional data. The Moon is known to be depleted in volatile elements such as Na and Mn. As a result, plagioclase feldspar is highly calcic (anorthitic), and Fe/Mn ratios are higher than many other meteorites and planetary basalts. For example, Fe/Mn ratios for lunar materials are distinct from martian and HED achondrites. This was first observed by Laul et al. (1972) and has been confirmed by many others in subsequent studies of both Apollo and Luna samples, as well as lunar meteorites (Fig. 2). Furthermore, K/La is variable in achondrites and differentiated planets (Fig. 3). The lunar K/La ratio is the lowest, and helps to distinguish lunar samples from others. This characteristic was first reported by Wanke et al. (1972). Chromium concentrations of lunar rocks are typically 100x that of equivalent terrestrial rocks (Korotev, 2005). And finally, oxygen isotopes in material from the Moon are also distinct from other meteoritic basalts, such as eucrites and shergotttites, but identical to terrestrial samples and exhibit homogeneity (Mayeda et al., 1983, and Fig. 4).



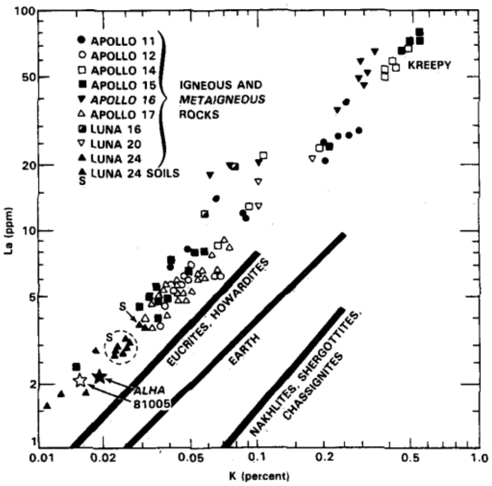


Figure 2: FeO vs. MnO correlation in Apollo samples from Laul et al. (1972); compared to eucrites, howardites, and chondrites. Figure 3: K vs. La correlation in Apollo samples from Wanke et al. (1972) compared to eucrites, terrestrial and martian meteorites.

Rock types and terminology

Lunar meteorites have been discussed in three different groupings – basalts, anorthosites, KREEP-rich samples, and brecciated mixtures of these three end members. The latter type has also been referred to as "mingled". There is some precedence for terminology from the extensive work on Apollo and Luna rocks returned from the Moon. The classification scheme of Le Bas (2001) is used for the eight unbrecciated basaltic lunar meteorites. The rest of the lunar meteorites are breccias, and the terminology recommended by Stöffler et al. (1980) on highlands rocks is used here. Because this terminology is less than simple, it will be reviewed here for clarity. There are three different subgroups of breccias – monomict, dimict, and polymict. Monomict breccias exhibit intergranular in-situ brecciation of a single lithology; they can also be recrystallized. Dimict breccias exhibit intrusive-like veined textures of fine grained melt breccias within coarse grained plutonic or metamorphic rock types. And polymict breccias can come in five different forms. Regolith breccias contain clastic regolith constituents including glass spherules and brown vesiculated matrix glass. Fragmental breccias contain rocks clasts in a porous clastic matrix of fine grained rock debris. Crystalline melt or impact melt breccias contain rock and mineral clasts in an igneous textured matrix (can be granular, ophitic, sub-ophitic, porphyritic, poikilitic, dendritic, fibrous, sheaf-like, etc.). Impact glass or glassy melt breccias contain rock and mineral clasts in a coherent glassy or partially devitrified matrix. And finally, granulitic breccias contain rock and mineral clasts in a granoblastic to poikiloblastic matrix. Wherever possible, these terms will be applied to the lunar meteorite breccias in this compendium, but it should be emphasized that all brecciated lunar meteorites are polymict breccias.

Regolith breccias from the Apollo collections have been studied extensively, and three characteristics allow their maturity (length of exposure near the lunar surface) to be estimated. Implantation of noble gases by solar wind leads to higher levels in more mature regolith (e.g., Eugster, 1989). Siderophile elements (e.g., Ni, Ir, Co) become higher and more uniform in mature regolith, approaching levels of that of the impacting materials such as chondrites (e.g., Korotev, 1994). Finally, the ferromagnetic resonance analysis (FMR) maturity index, or I_s/FeO, is correlated with other indicators of maturity and has been measured on many lunar soils and regolith samples (e.g., Morris, 1978; McKay et al., 1986). All three of these parameters have been used to characterize maturity of breccias in lunar feldspathic meteorites and will be part of the discussions for individual meteorites.

Finally, bulk compositional data are being used to make initial classifications of many lunar meteorites, and often times before careful petrography has been done. As a result many lunar meteorites have been classified based on their trace element content by inference from previously studied and classified samples. Although the first few decades of lunar meteorite research led to an understanding of compositional variation that can be explained in terms of three end member components – anorthosite/FHT – KREEP/PKT – mare basalts (Fig. 5), the many additional meteorite samples that have become available have led to recognition of a fourth component, which is mafic anorthositic and noritic lithologies (Korotev et al., 2009b). The compositional variation required by this fourth component is clear, and has fundamental implications for interpreting geological and petrologic data for lunar samples (Figure 5). As with KREEP component, it is not clear if this fourth component can be recognized in thin section or petrographically.

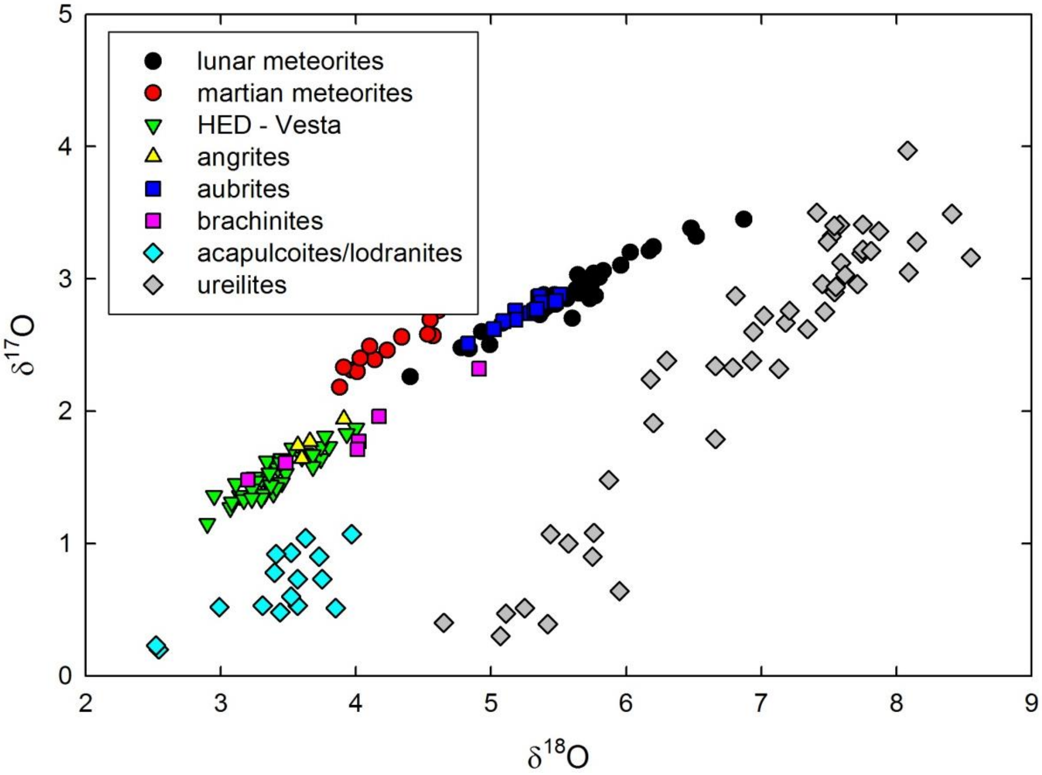


Figure 4: Three oxygen isotope diagram for lunar meteorites and other achondrites (data from Clayton and Mayeda, 1996).

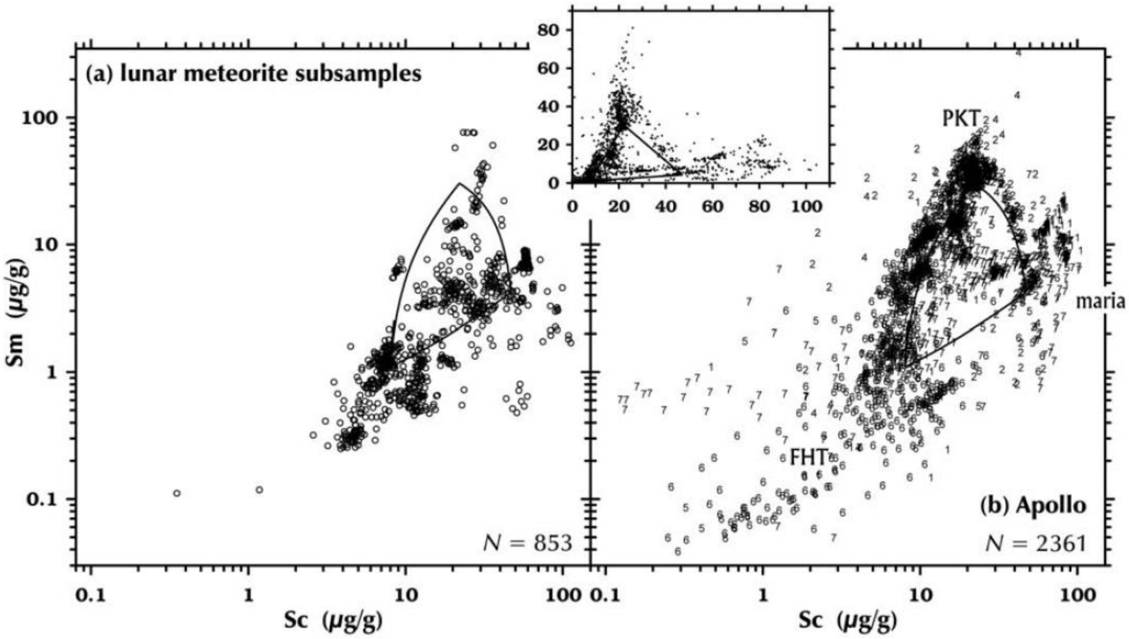


Figure 5: Comparison of lunar meteorite and Apollo sample bulk compositions, from the INAA data and laboratory studies of Haskin/Korotev (from Korotev et al., 2009).

Lunar meteorite source regions and craters

A question and issue of great interest is where do the lunar meteorites come from? Cosmic ray exposure age data, bulk compositional and age dating can be used to determine whether some meteorites may be source or launch paired – that is if hey were derived from the same impact event on the lunar surface. There are a few large groups of meteorites that have been placed in this category. For example, the Yamato 793169 – Asuka 881757 – MET 01210 – MIL 05035 grouping is suggested to be sourced paired (Arai et al., 2009) based on similar REE abundances, crystallization ages (approx. 3.8-3.9 Ga), and isotopic compositions (low U/Pb, low Rb/Sr, and high Sm/Nd). Similarly, the LaPaz Icefield basalts and the NWA 032/479 samples are thought to be launch paired on the basis of bulk composition, age and cosmic ray exposure age data (Ziegler et al., 2006). Finally, the Yamato 981031 – QUE 94281 – NWA 4884 are also thought to be launch or source crater paired on the basis of their unique petrology, geochemistry (Korotev, 2005, Korotev et al., 2009b), and could be from a mare-highlands edge or cryptomare region.

Specific locations have been suggested for some lunar meteorites based on comparison of compositions with available spacecraft data such as Th, FeO, or other elemental parameters.

<u>South polar region:</u>

Dhofar 961 has been proposed to be from the South Pole – Aitken basin (Jolliff et al., 2008, 2009). Two other samples - Calcalong Creek and Y983885 are also proposed to be possibly from SPA (Corrigan et al., 2009).

<u>Farside:</u>

Many lunar meteorites have been proposed to be from the lunar farside based on their low Th contents and feldspathic nature - Dho 489 (Takeda et al., 2007), Dhofar 081, 303 (Corrigan et al., 2009), SaU 300 (Hudgins et al., 2007; Hsu et al., 2008), and Kalahari 008 and 009 (Sokol et al., 2008).

Nearside:

Several samples have been proposed to be from the lunar nearside, based on the magnitude of the incompatible elements such as Th. SaU 169 is REE enriched and seems a good candidate for originating near the PKT on the nearside (Gnos et al., 2005). Dhofar 1180 on the other hand is proposed to be from the nearside, but not close to the PKT (Zhang and Hsu, 2009). A few lunar meteorites are suggested to have originated from the nearside and close to Apollo sites. For examples, the LAP and NWA 032/479 basalts are thought to be related to the Apollo 12 basalt suites (Ziegler et al., 2007; Righter et al., 2005; Joy et al., 2007). And NEA 003 bulk composition is very similar to samples from Mare Serenitatis (Corrigan et al., 2009; Haloda et al., 2006) high Ca/Mg basalt.

Cryptomare:

The source of the YAMM meteorites is likely a terrain of locally high mare-highland mixing within a cryptomare (Arai et al., 2009). Searches for a possible source crater of the YAMM meteorites within the well-defined cryptomare, resulted in an unnamed 1.4 km-diameter crater (53°W, 44.5°S) on the floor of the Schickard crater as a suitable source for the YAMM meteorites (Arai et al., 2009). A different study has identified other potential source areas based on Th, FeO and TiO_2 contents; they identify at least four possibilities that are all outside of the PKT area, and include Mare Crisum, Tsiolkovsky and Humorum (Joy et al., 2008).

Apollo and Luna summary – Lunar geologic history and Apollo era paradigms

Intensive study of the Apollo and Luna sample collections has created a detailed history of the Moon with several specific highlights (e.g., S.R. Taylor, 1982):

- development of an early feldspathic crust that floated on a lunar magma ocean (LMO).
- basaltic magmatism that lasted from 4.4 to 3.2 Ga.
- bimodal high and low Ti volcanism.
- an incompatible element enriched residual liquid from crystallization of the LMO (KREEP)
- a spike in the impact flux, the terminal lunar cataclysm, at 3.9 Ga.

These models and ideas have been summarized in several publications (e.g., BVSP, 1981; Origin of the Moon, 1985; Wilhelms, 1987; Lunar Source Book, 1991; New Views of the Moon, RIMG New Views of the Moon volume, 2006).

However, the Apollo and Luna samples are from only a small region on the Moon (Fig. 6), close to the Procellarum KREEP Terrane (Fig. 7), and it has even been argued that many of the Apollo sites have been affected by the Imbrium impact basin (Korotev et al., 2003). It follows that the samples from these missions have provided only a limited understanding of the origin and evolution of the Moon. The strength of the meteorite collections is that they provide a more random and representative sampling of the lunar surface and thus will be of great value in determining the origin and geologic history of the Moon.

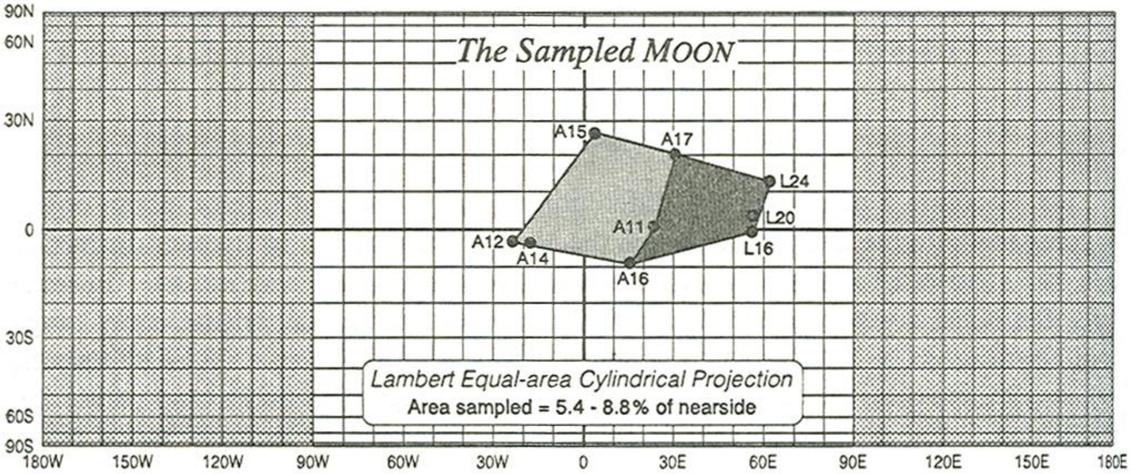


Figure 6: Map of the Moon showing the small region that has been sampled by Apollo (A) and Luna missions (L) (from Warren and Kallemeyn, 1991).

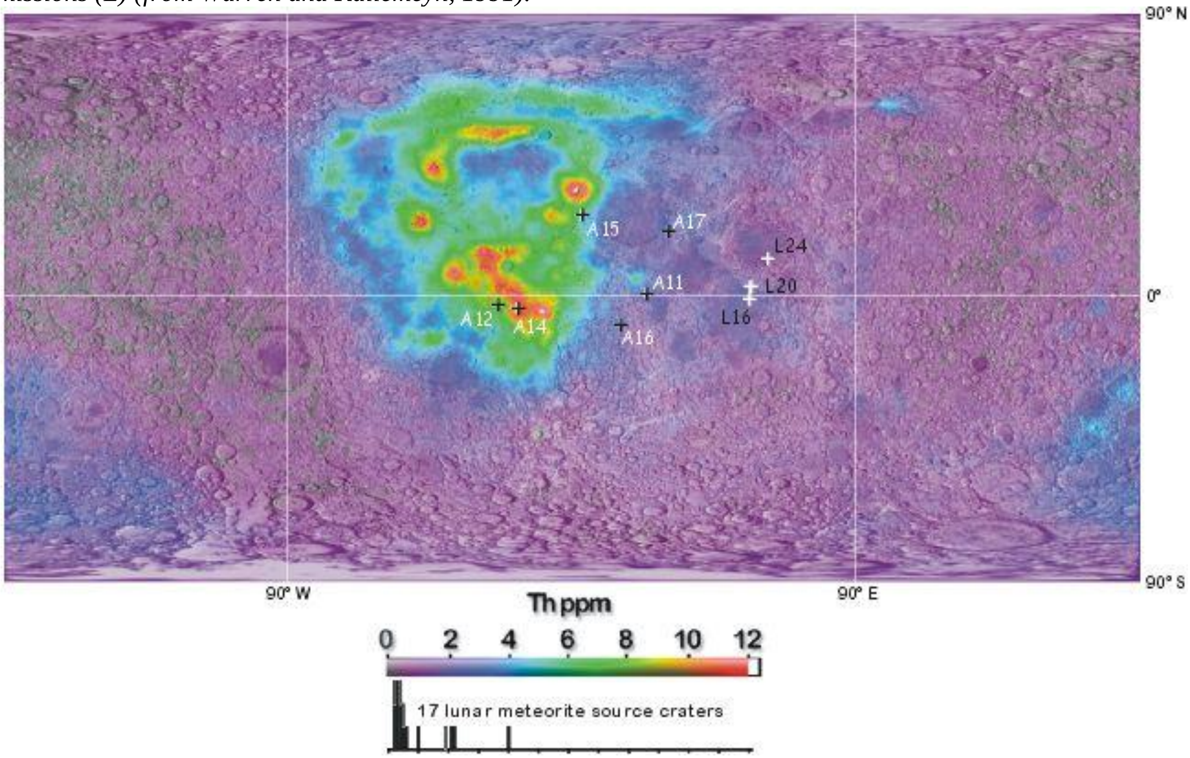


Figure 7: Th map produced from Lunar Prospector data, and also showing the locations of Apollo and Luna sample sites (from Korotev et al., 2003).

Lunar meteorite contribution to lunar science

Lunar meteorites have provided a wealth of new information, requiring revision to some specific scenarios arising out of studies of the Apollo sample collection.

1) Age of basaltic volcanism

Evolved and young low Ti basalts provide evidence that the Moon maintained widespread active magmatism up to ~2.9 Ga (Fig. 8); Fagan et al., 2002; Nyquist et al., 2005; Borg et al., 2004; Rankenburg et al., 2005). Some of the basaltic rocks are highly fractionated and have the lowest MgO contents of corresponding basalt suites among the

Apollo samples (Righter et al., 2005; Anand et al., 2005; Zeigler et al., 2005; Joy et al., 2005). In addition, low Ti basaltic meteorites, Asuka 881757, Yamato793169, MIL 05035 and MET 01210 have yielded the oldest ages for basalt of this composition – 3.8 to 3.9 Ga (Fig. 8; Arai et al., 2008). Basilevsky et al. (2009) emphasize that the gaps in the ages of Apollo basalt groups disappear when the ages of meteoritic basalts are included is assessments.

2) Crustal evolution

Studies of feldspathic lunar meteorites have revealed a rich compositional and petrologic diversity that is inconsistent with a simple picture of a flotation crust of ferroan anorthosite (Korotev et al., 2003). A) The Apollo high magnesium suite of plutonic rocks has not been identified in lunar meteorites, suggesting that this suite is of local, rather than global importance. B) On the other hand feldspathic clasts from highlands breccias yield Sr and Nd isochrons of 4.4 Ga (Fig. 9), providing evidence for an ancient LMO (Nyquist et al., 2002). Clasts in Y-86032 and MAC 88105 are among oldest and also record evidence for magma ocean and differentiation (not just an artifact of Apollo sampling bias). C) a fourth mafic crustal end member is present in highlands breccias (Korotev et al., 2009b).

3) late heavy bombardment – cataclysm or period of decline?

Impact melt clasts from meteoritic breccias have yielded ages that do not confirm or disprove the lunar cataclysm hypothesis, pushing the resolution of this controversial topic to analysis of new lunar meteorites or future sample return missions (Cohen et al., 2000). New high-resolution dating techniques have led to impact ages different from the cataclysmic spike at 3.85 Ga (Gnos et al., 2004). Evidence for the Lunar Cataclysm remains equivocal but many new highlands breccias will help resolve this important problem.

4) Global significance of Apollo defined units

KREEP has been recognized as an important component in only a few lunar meteorites (Korotev, 2005). The idea that KREEP existed only in the early Moon (3.8 to 4.6 Ga) has been challenged by evidence from a new lunar gabbro with a 2.9 Ga age and KREEP connections (Borg et al., 2004). High TiO_2 basalt is part of bi-modal Apollo basaltic volcanism, but has only rarely been observed in a handful of meteorite samples.

In summary, lunar meteorites have so far provided new information that has led to a better understanding of fundamental issues such as the age, evolution, bulk composition and origin of the Moon. It is clear that Apollo-based models for lunar differentiation and magmatism must be revisited. Limited Apollo sample datasets, on which global models have been based, are of a more localized nature, and have likely led to erroneous models that cannot explain more global features observed in the meteorite and spacecraft datasets.

Summary

Terranes defined by the Apollo GRS (Arnold and Reedy), and Lunar Prospector and Clementine missions are very different from those surmised from only Apollo/Luna sites. Integration of meteorite, Apollo/Luna and mission data has lead to a more robust and comprehensive understanding of the Moon. Many of the lunar meteorites require much more extensive studies. This compendium is meant to facilitate comparisons of meteorite and Apollo samples, and interpretation of lunar geology by integration of information about rocks with spacecraft data.

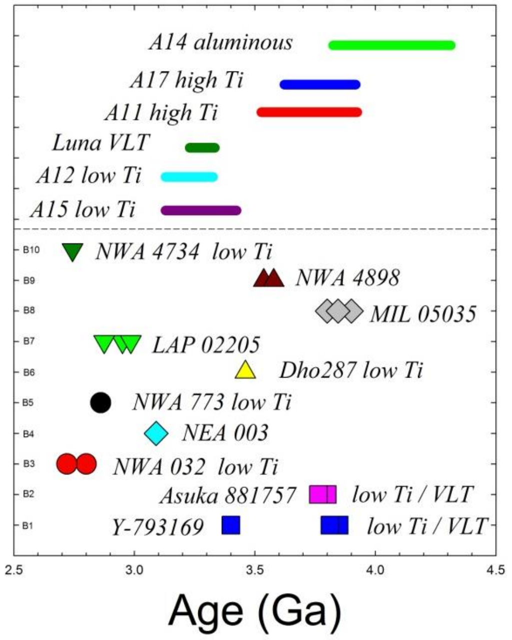


Figure 8: Compilation of ages for basaltic lunar meteorite, with chapter number (B#) along left edge of figure. References are B1 (Yamato 793169): Misawa et al. (1991); Fernandes et al. (2009); B2 (Asuka 881757): Kita-Torigoye et al. (1993); Fernandes et al. (2009); B3 (NWA032/479): Fagan et al. (2002); Borg et al. (2009); Fernandes et al. (2009); B4 (NEA 003): Haloda et al. (2009); B5 (NWA 773 and pairs): Borg et al. (2004); B6 (Dhofar 287): Shih et al. (2002); B7 (LAP 02205 and pairs): Rankenburg et al. (2005); Nyquist et al. (2005); Fernandes et al. (2009); B8 (MIL 05035): Nyquist et al. (2007); Fernandes et al. (2009); B9 (NWA 4898): Fernandes et al. (2009b), Gaffney et al. (2008); B10 (NWA 4734) Fernandes et al. (2009b).

Apollo age summary is taken from Nyquist et al. (2001).

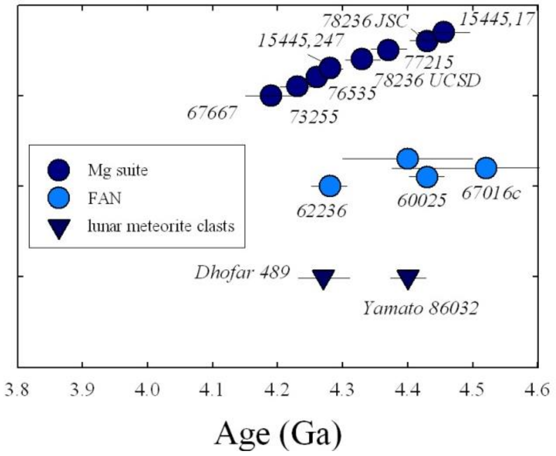


Figure 9: Comparison of ages obtained from anorthositic and troctolitic clasts from feldspathic lunar meteorites: Yamato 86032 is from Nyquist et al. (2006) and Dhofar 489 data is from Takeda et al. (2006). Apollo FAN and Mg suite samples are from the compilation of Snyder et al. (2000) and Norman et al. (2003)