Meteorites and the Moon

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1969 was a momentous year for those interested in the Solar System. Rock samples collected during the first Moon landing, and on subsequent missions, contributed enormously to understanding our nearest neighbour, but several meteorite falls that same year also had a profound influence on our wider understanding of the Solar System. Fortuitously, two of these meteorite falls, which by their very nature are unplanned events, also played a significant role in the analysis of samples brought back from the Moon. In this article I will outline how meteorites have contributed to our understanding of the Moon, and how the Moon also has provided information on meteorites.

On 8th February 1969 a huge fireball broke up as it streaked across the northern Mexico sky, showering an area around the village of Pueblito de Allende with more than two tons of a hitherto rare type of meteorite, a Carbonaceous Chondrite called a CV. Later that year, on 28th September, another spectacular meteorite fall showered the town of Murchison, in Victoria, Australia, with more than 100kg of an even rarer type, a CM Carbonaceous Chondrite. These meteorites arrived at a most opportune time. The US government had spent millions of dollars building sophisticated state-of-the-art labs, at the Johnson Manned Spacecraft Center in Houston, to analyse the Lunar samples soon to be returned by the Apollo missions. The Allende and Murchison falls - free gifts from Space - were the ideal material with which to test the new equipment, with enormous benefits both for those running the labs and for others more interested in what the meteorites had to say. It turns out that Allende retains evidence, in abundance, of some of the oldest material and the very earliest events in the Solar System, while Murchison contained amino acids, the building blocks of proteins and, ultimately, life, and so proved that these complex carbon compounds existed elsewhere in the Solar System.

Section through a small Allende meteorite (~3 cm across). The circular objects are chondrules and the irregular whitish patches are Calcium Aluminium Inclusions (CAIs), the oldest dated material in the Solar System.

The laboratories built to analyse the Apollo samples made major contributions to our understanding of Carbonaceous Chondrite meteorites and, in due course, carried out the task for which they were built - analysis of the returned Lunar samples. But these analyses also produced some unexpected results for meteoriticists. Of all the meteorites that fall to earth, more than 75% comprise just three types of stony meteorites called Ordinary Chondrites. In contrast, at least eight different types of Carbonaceous Chondrite have been recognized yet this group comprises less than

5% of meteorite falls. Astronomers have long tried to match up the geochemistry of the various meteorite types with the reflectance spectra of asteroids in the Asteroid Belt but they have found that surprisingly few seem to match the Ordinary Chondrites. Instead it has become apparent is that an awful lot of asteroids are rather dark 'sooty' lumps, much like some of the Carbonaceous Chondrite meteorites. Various possibilities might account for this discrepancy between the abundance of particular meteorite types on Earth and the number of potential parent asteroids for each. The Ordinary Chondrite parent bodies might be more favourably located in the Asteroid Belt than the dark 'carbonaceous' asteroids, perhaps closer to certain Kirkwood Gaps (the orbital resonance regions that 'launch' meteorites out of the Asteroid Belt) so that pieces chipped off in collisions have a better chance of reaching Earth. Perhaps the abundance of particular meteorite types on Earth reflects their toughness, or how likely they are to survive their fiery descent through Earth's atmosphere. Certainly, most Carbonaceous Chondrites are much more crumbly than many Ordinary Chondrites. Remarkably it turns out that the Apollo astronauts inadvertently came back with the answer. Among all the Moon rocks brought back by the Apollo missions were two small meteorites; a CM Carbonaceous Chondrite with Apollo 12 and an EH Enstatite Chondrite (another rare type that accounts for less than 2% of meteorite falls) with Apollo 15. But this is far too small a sample to tell us anything about the relative abundances of the parent bodies from which the more than 100 different types of known meteorite are derived. Instead it was the dusty stuff brought back, the Lunar 'soil', that proved of much greater significance. Analysis revealed that it is not just pulverised Moon rock but is contaminated by the remains of countless meteorites that have pummeled the Moon's surface over billions of years. Without an atmosphere to filter out flimsy meteorites, this 'soil contamination' should represent the average composition of all of the meteorites hitting the Moon. Far from having the Ordinary Chondrite 'signature' that we might predict from meteorite abundances on Earth, the contamination, which amounts to ~2% of the Lunar soil, actually suggests that the dominant meteorites hitting the Moon are type CI Carbonaceous Chondrites. These are among the rarest and most crumbly meteorites to reach Earth, with only five falls known. The chemistry of CI, and the closely similar CM, chondrites matches fairly well with the reflectance spectra of the C-type asteroids which account for around 75% of known asteroids. So, the Apollo, and Luna, missions helped to prove that the 40,000 or so meteorites we have in collections on Earth are seriously skewed towards the tough stuff rather than representing the actual relative abundances of the various types of asteroid out in Space.

It's now almost 40 years since samples were last brought back from the Moon. These priceless rocks have told us a great deal about the Moon that we could not have learned otherwise, in particular providing a radiometrically dated chronology of Lunar events, but they have their limitations. The Apollo missions were, understandably, confined to 'safe' locations on the Moon's near side and hence the samples brought back were necessarily biased and raised many questions concerning other areas of the Moon. Although there have been no sample return missions to the Moon since 1976 (Luna 24), this is far from the end of the story. Many Lunar samples have since been found on Earth having arrived here for free. These are Lunar meteorites, pieces of rock blasted from the surface of the Moon by the impact of large meteorites, eventually falling to Earth as meteorites themselves. The first was found in Antarctica in 1982 but many more have since been found by scientific expeditions to Antarctica and by commercial collectors in the dry deserts of northern Africa and the Middle East. A single small Lunar meteorite has also been found in Western Australia, and was indeed the first to be found outside of Antarctica, but none have yet been found in Europe, Asia or the Americas. Intriguingly, although four of the Martian meteorites are classified as *falls* (i.e. they were seen to fall), all of the Lunar meteorites are *finds* (i.e. they were not seen to fall but were picked up many decades or even centuries later). Furthermore, the numbers of documented Martian and Lunar meteorites is very similar even though the Moon is an awful lot closer. Counterintuitive though both of these observations might seem, there are sound scientific explanations - but that is another story...

A total of 382 kg of rock, and 2145 individual samples, were brought back by six Apollo missions, with a further 326g of Lunar material returned by three Russian Luna landers. The total weight of Lunar meteorites found so far is more than 60 kg comprising about 140 individual meteorites. This actually represents fewer than 70 meteorite falls as many of these individual stones are ‘paired’ (i.e. were originally part of the same meteoroid that broke up on entry). Of this total, 25kg comprises just two meteorites; the enigmatic Kalahari 009 and the awesome NWA (North West Africa) 5000, while at the other extreme some of the Antarctic Lunar meteorites are tiny and weigh less than a gram. But all Lunar meteorites, from the largest to the smallest, are immensely important for increasing our knowledge of the Moon’s geology because they sample areas, particularly the so-called ‘*highlands’* (these are not necessarily the highest regions but correspond to the paler areas of the Moon, composed of anorthosite, which contrast with the somewhat younger, darker and generally lower areas, known as *maria*, that are composed of basalt), unvisited by any of the Apollo or Luna missions. Interestingly, the Lunar Prospector mission of 1998-99 revealed that all of the Apollo landings were in or near a geochemically ‘anomalous’ region now known as the Procellarum KREEP terrane, where the rocks contain relatively high concentrations of Potassium (K), Phosphorus (P) and various Rare-Earth Elements (REE). Although a few Lunar meteorites are ‘KREEPy’, most come from essentially random locations elsewhere on the Moon and represent lithologies that are rare or unrepresented among the Apollo samples but perhaps more representative of larger areas of the Moon. Each of these Lunar meteorites has a story to tell, but there is space here to talk about just a few of them.

North West Africa, encompassing mainly Morocco, Mauretania, Algeria and Tunisia, has been a major source of meteorites since the mid-1990s. Many thousands of distinct meteorites have been found by locals but few if any of these finds have precise provenance data and so local place names are seldom applied to them. Instead each has been assigned an ‘NWA’ prefix followed by a number. At least 35 of these are Lunar meteorites but, after pairing (where it can be recognized that several meteorites actually represent parts of one original meteoroid), this is reduced to fewer than 20, of which I will mention three here.

7.52g slice of NWA 6355 (paired with NWA 4936 and three others), with chunks of pale anorthosite, darker rock and mineral fragments, and a few vesicles, in a dark matrix of glassy impact melted rock.

One of the effects of more than four billion years of impacts on the Lunar surface is that virtually all of the Lunar samples that we have are intensely brecciated, with the original rock shattered into angular fragments and then welded together by impact-melted rock. A typical example of such a ‘vitric breccia’ is NWA 6355 (and its pairings of NWA 4936, 5406, 6470 and 6470) which shows various mineral and rock fragments, including pale chunks of anorthosite, embedded in a dark glassy matrix of impact-melt. What makes this particular meteorite rather special is that it has an overall composition very similar to the lunar ‘soil’ of the Apollo 16 site and may have originated from near there.

3.34g slice of NWA 3186 (paired with NWA 773 and six others) a breccia with pale fragments of olivine gabbro and darker clasts of mare basalts. Specimen in the collection of the National Museum of Ireland in Dublin; reproduced with permission.

Another North West African meteorite, NWA 3186 (and its pairings, NWA 773, 2700, 2727, 2977, 3160, 3333 and Anoual), is also a breccia but it contains larger pieces of two very different rock types. The paler breccia fragments are of an olivine gabbro, a coarsely crystalline rock type that cooled slowly deep beneath the Moon’s surface, while the darker clasts are of basalts from the lava flows that flooded some of the vast impact basins. Both the gabbro and the basalt are KREEPy yet they are distinct from any samples collected from the Apollo and Luna sites. What is especially remarkable about the gabbro is its age of around 2.865 billion years old. This is some 250 million years younger than any other lunar sample and around one billion years younger than any other KREEP-rich rock.

Although most Lunar rocks have been brecciated by impacts, some have experienced such massive impact shocks that their original constituents have been metamorphosed into new minerals that form only under extreme shock pressures. Crystalline metamorphic rocks such as these are known as granulites and are not uncommon among Lunar samples. One such example is Dhofar 467 and its various pairings (Dho 026, 457-468) which all come from the same small area of southern Oman, a region that has proven a remarkably rich source of lunar, martian and other meteorites. Dhofar 467 is pretty unprepossessing to look at, being not dissimilar to a blackened piece of melted plastic. Originally it was composed of the pale rock anorthosite but it was hit so hard during its time on the Moon that the shock converted it to a much darker mineral, maskelynite, and even partially melted it. Tiny bubbles in the impact melt of these meteorites indicate that the original rock was very near the lunar surface when the impact occurred. Indeed, the event which brought about the metamorphism may even have been the same one that launched it on its journey to Earth.

27.3g slice of NWA 4881 (paired with NWA 3163), a granulitic breccia formed of shock-metamorphosed anorthosite and dark gabbro clasts. Specimen in the collection of the National Museum of Ireland in Dublin; reproduced with permission.

Kalahari 009 is, at 13.5 kg, the largest of all lunar meteorites and also among the most enigmatic. It was reported to have been found in the Kalahari Desert of Botswana in 1999 but its discovery, and even existence, seemed shrouded in mystery until 2005 when preliminary analyses were published. Kalahari 009 is a mare basalt breccia, but it is no ordinary mare basalt. Most of these were erupted during or soon after a period of intense impact cratering known as the Late Heavy Bombardment, ~3.8-3.9 billion years ago, and hence occupy some of the huge impact basins formed during this event. But scientists were more than a little surprised to find that the basalt of Kalahari 009 (which has a pretty weird chemistry anyway) is 4.35$\pm$0.15 billion years old, indicating that basaltic volcanism started little more than 150 million years after the Moon had formed!

6.39g endcut of Dhofar 467 (paired with Dhofar 026 and eleven others) on display in the Ulster Museum. The tiny holes are bubbles created during the impact shock that transformed the pale anorthosite into dark maskelynite.

Returning to Northwest Africa, and more specifically Mauretania or Algeria, another example of a granulitic breccia is represented by NWA 4881 (paired with NWA 3163). Again, this started out as a largely anorthositic rock which subsequently experienced an extreme impact causing brecciation, recrystallisation and the formation of the shock-indicator mineral maskelynite. However, some of the minerals show evidence for slow cooling from temperatures above 1000°C, which suggests that, in contrast to the near surface impact metamorphism of Dhofar 467, these rocks were metamorphosed at a depth of several tens of kilometers. As such it perhaps represents lithologies from deep beneath the lunar surface that were exposed only as a result of the vast impacts associated with the Late Heavy Bombardment.

There's a huge amount more might be said about Lunar meteorites, covering aspects such as the processes that send them here, possible source locations on the Moon and, of course, the apparent enigma of meteorites from the Moon being as common (or rare!) as those from the very much more distant planet Mars. For anyone particularly interested there is a wealth of information in various meteorite books, of which I would particularly recommend *Meteorites, Ice and Antarctica* by William Cassidy (CUP 2003). However, by far the single most useful and informative source on Lunar meteorites is the astonishingly comprehensive website (http://meteorites.wustl.edu/lunar/moon_meteorites.htm) that has been put together by Randy Korotev, a geochemist who has been working on Lunar rocks since the heady days of the Apollo missions.

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