8 Apollo 17

Final Objectives

By 1970, three lunar landing missions had been cancelled (Apollos 18, 19, and 20), meaning that Apollo 17 was going to be the last exploration of the lunar surface during the Apollo era. This decision had a profound effect on the selection of the crew and landing site of Apollo 17. Harrison "Jack" Schmitt was scheduled to be the LMP for Apollo 18. With the cancellation of Apollo 18, he was moved to the crew of Apollo 17. The main reason for this switch was that he was a Ph.D. geologist, not a military test pilot; Jack Schmidt would be the only scientist to walk on the Moon. His participation in the Apollo program was the main reason why the other Apollo astronauts became such well-trained field geologists.[88]

88 For a detailed look at the role Jack Schmitt played in the recruiting of geologists to train the Apollo astronauts, see chapter 17 of *To a Rocky Moon* (Wilhelms, 1993).

The landing site of Apollo 17 was chosen in hopes of addressing some of the remaining unanswered geological questions about the history of the lunar surface.[89] Two of the main goals were to find ancient, original crustal material *in situ*, and to find evidence of young, post-mare volcanism. (Ancient crustal material had been found by Apollo 15, and would be found by Apollo 16, but none of it had been found in its original context. The youngest volcanic material returned was from the 3.2-billion-year-old mare surface of Apollo 12.) The landing site chosen to pursue these goals was the Taurus-Littrow valley.

89 When the landing site of Apollo 17 was chosen, the Apollo 16 mission had not yet happened, so the Descartes formation was still assumed to have been formed by ancient volcanism.

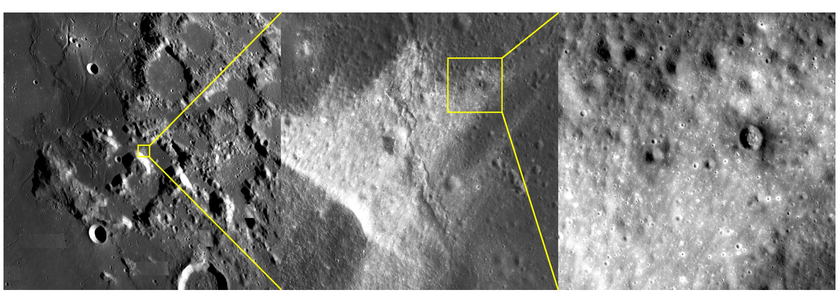

Figure 8.1: Dark halo craters in the Taurus-Littrow valley. (Left) The southeastern rim of the Serenitatis Basin. LROC near side mosaic [NASA/GSFC/Arizona State University]. (Center, Right) Close-up of the landslide in the Taurus-Littrow valley, showing the dark craters reported by Al Worden. LROC NAC image M1098651578RE [NASA/GSFC/Arizona State University].

A strong motivation for the choice of the Taurus-Littrow valley came from site observations by Al Worden, the CMP of Apollo 15. As he had been keeping station in lunar orbit, he had flown over the Taurus-Littrow valley and reported what looked like very recent volcanic activity (Figure 8.1):

> 128:12:46 CMP: Okay. I'm looking right down on Littrow now, and a very interesting thing. I see the whole area around Littrow, particularly - particularly in the area of Littrow where we've noticed the darker deposits, there are a whole series of small, almost irregular shaped cones, and they have a very distinct dark mantling just around those cones. It looks like a whole field of small cinder cones down there. And they look - well, I say - I say cinder cones, because they're somewhat irregular in shape. They're not all - they're not all round - they're positive features - and they have a very dark halo, which is mostly symmetric, but not always, around them individually.

The apparent young volcanism on the floor of the Taurus-Littrow valley pushed it to the top of the list of potential Apollo 17 landing sites. But these dark craters were not the only attraction. Like the Hadley Rille site of Apollo 15, the Taurus-Littrow valley is rich in diverse geological features.

The Taurus-Littrow Valley

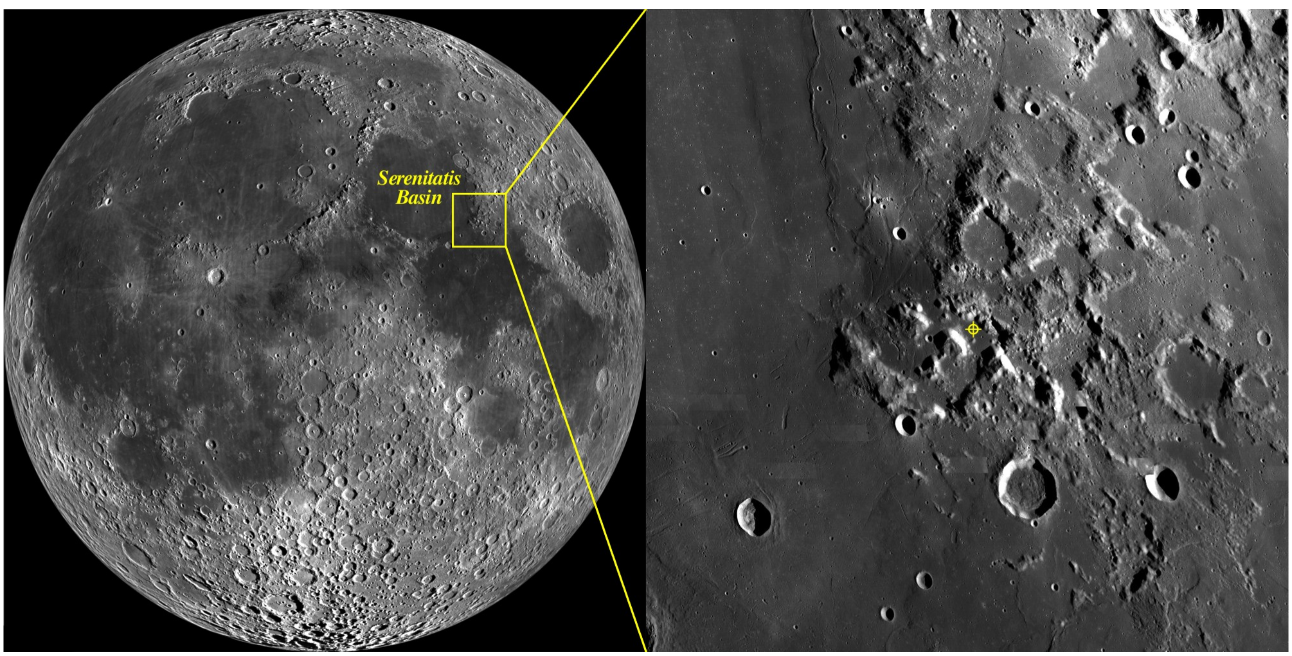

Figure 8.2: The location of the Serenitatis Basin and the landing site of Apollo 17 on the southeastern rim of the Serenitatis Basin in the Taurus-Littrow valley. LROC WAC near side mosaic [NASA/GSFC/Arizona State University].

The Apollo 17 landing site shares many characteristics with the Apollo 15 landing site. Both are feature-rich sites that are located where a mare surface laps up against the rim of a large impact basin. The Taurus-Littrow valley is located on the southeastern rim of the Serenitatis impact basin (Figure 8.2), and is the eastern-most of the Apollo landing sites. The mare material near the rim of the Serenitatis basin has a lower albedo than the mare in the center. At the time, this darker mare was assumed to be younger than the brighter mare. In fact, the association of dark material with young age was major theme in the planning for the Apollo 17 mission.

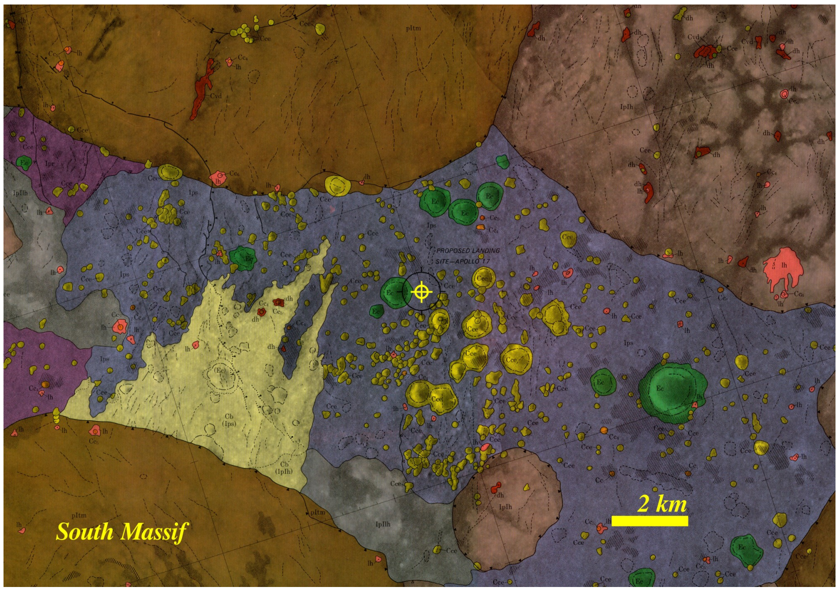

Figure 8.3: Detail from the pre-mission geological map of the Apollo 17 landing site (Lucchitta, 1972).

The pre-mission geological map of the landing site (Figure 8.3) shows a complex site with many distinct features within rover distance. The low albedo mare surface fills in the valley between two large mountains. These two mountains are assumed to be material uplifted during the Serenitatis impact event and they form part of the rim of the Serenitatis Basin. Large, displaced features such as these mountains are referred to as **massifs**. A prominent cluster of Copernican-aged craters covers the mare surface. The southwestern edge of the valley is dominated by a landslide that originated on the South Massif and extends 5 km across the valley floor. Small, dark craters, called *dark halo craters*, sit on top of the landslide and are the features that Al Worden spotted from lunar orbit. All of these features were sampled by the Apollo 17 mission.

One of the more interesting characteristics of the Apollo 17 site is its probable connection to a feature located over 2,000 km away.

Tycho

Tycho is a very young, Copernican-aged, 86-kilometer-diameter, impact crater located in the southern highlands of the near side of the Moon (Figure 8.4). The ejecta from the Tycho Crater can be easily traced all across the near side of the Moon, making it one of the most prominent features on the near side. The Tycho Crater is the youngest feature on the Moon with such a global imprint. The large extent, and young age, of the Tycho ejecta make it a very important time reference for the history of the lunar surface, so determining the age of the Tycho Crater is an important goal in lunar science. The Tycho Crater itself is located well outside of the area of the Moon accessible to the Apollo mission, so a landing at the crater was not possible. However, the large range of the ejecta meant that material from Tycho was sent to distant locations, including the Taurus-Littrow valley over 2,000 km away.

The first suggestion that material from the Tycho Crater is present in the Taurus-Littrow valley was made in the pre-mission geological map of the landing site.[90]. The interpretation of the central cluster of young craters on the floor of Taurus-Littrow was given as:

> "The clusters are most readily explained as of secondary origin. As no primary crater of suitable size or age is found within the vicinity, they must have originated from a young, large, and distant crater in the appropriate direction, possibly the crater Tycho."

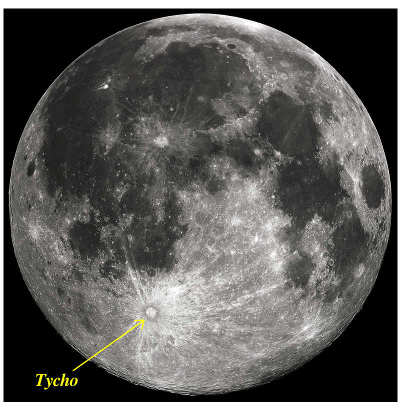

Figure 8.4: Image of the full Moon, showing the location of the Tycho impact crater [Image from Gregory H. Revera].

[90] Lucchitta (1972)

[91] See Muehlberger et al. (1973), Howard (1973), Lucchitta (1977)

Studies published immediately after the Apollo 17 mission added further support to the Tycho connection.[91] These studies noted the alignment of the central cluster of craters, the craters on the top of South Massif, and the landslide with the rays from Tycho Crater (Figure 8.5). The very young relative age of the landslide was further evidence that it had been triggered by the ejecta from Tycho striking the top of South Massif. Collecting samples from the landslide and determining the exposure age of these samples would date the Tycho impact event.

The Last Landing

The Apollo 17 Lunar Module, *Challenger*, set down on the Taurus-Littrow valley floor on December 11, 1972. Following the well-established pattern, the first EVA was mostly dedicated to setting up the surface experiments. On December 12, 1972, the Apollo 17 astronauts started the second EVA (with a duration of 7h 36m 56s, this was the longest EVA of the Apollo program). The second EVA was a geological traverse to the

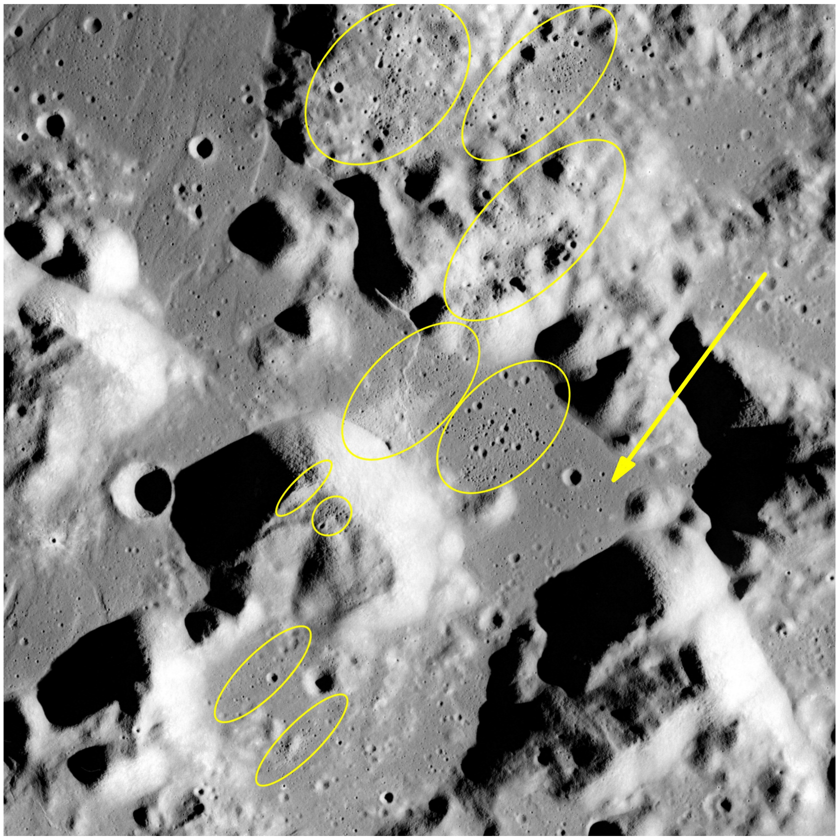

Figure 8.5: Image of the Taurus-Littrow valley [NASA AS17-M-0447]. The yellow ellipses mark recent impact craters on the site (adapted from Lucchitta (1977)). The arrow indicates the direction to the Tycho impact crater.

southwest, to the base of the South Massif and onto the landslide (Figure 8.6). After driving about 8 km across the valley floor, the astronauts arrived at the base of the South Massif, among a field of boulders. The astronauts could observe boulder tracks leading down from the flank of the South Massif to their current position, implying that the boulders had arrived at their current location during a landslide event.

The Apollo astronauts carried with them a wide variety of tools to sample the lunar surface, including scoops to gather regolith, tongs to grab hand-sized rocks, hammers to chip off pieces of larger rocks, and long tubes that they hammered into the surface to collect a deep core of the regolith.[92] Tools for the last three missions included one of the more unusual sample collection tools: a rake (Figure 8.7). The rake was essentially a very coarse sieve that the astronauts would sweep through the lunar regolith. The rake would let the finer regolith pass through, and only collect rocks larger than about a centimeter in diameter. The goal of the rake was to remove any bias in the collection of samples. Instead of collecting only rocks chosen

92 Allton (1989)

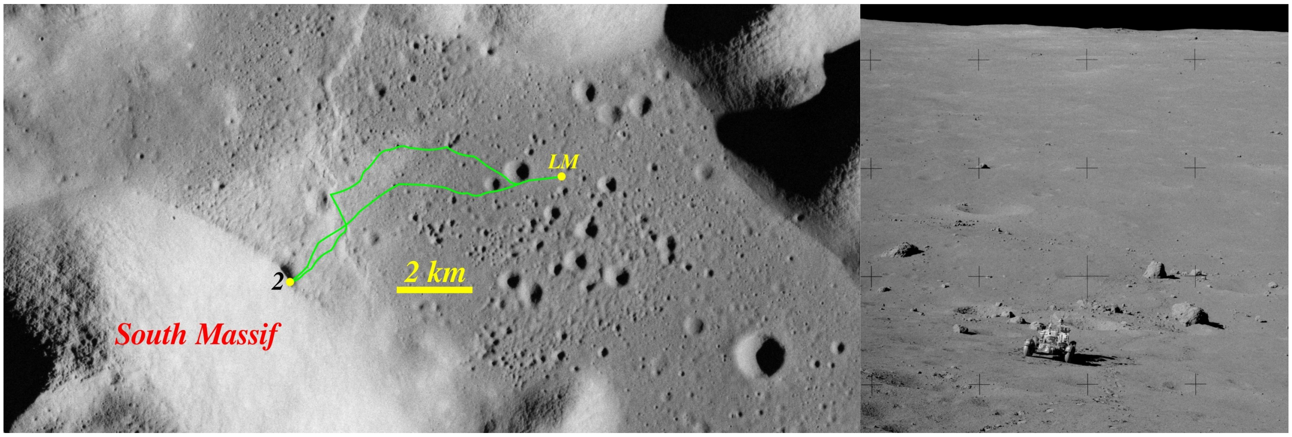

Figure 8.6: The second EVA of Apollo 17. (Left) The route of the second EVA across the Taurus-Littrow valley floor [NASA AS17-M-0447]. The stop at the base of the South Massif is labeled with a **2**. (Right) The Lunar Rover at the base of South Massif [NASA AS17-138-21072]. The view is toward the top of the South Massif. The boulder in the foreground likely originated near the top of the image.

by the astronauts, the rake sample would be a representative sample of all the different types of rocks in the sampling area.

The boulder field at the base of the South Massif yielded many samples (about 38 in all), including about a dozen small rocks swept up in the rake by Jack Schmitt at the base of one of the large boulders. The rake sample at the base of the South Massif was documented (Figure 8.8), collected, and placed in sample bag 501:

> 143:23:19 CDR: I'll be right down there to bag that rake for you.
>
> 143:24:33 LMP: Not many small, walnut-sized fragments in here, Bob. Gotten about seven or eight.
>
> ...
>
> 143:24:57 CDR: Yeah. Bag 501.
>
> 143:25:07 CDR: No, there aren't a lot; but that'll fill up a bag.

Figure 8.7: The rake used to collect an unbiased sample of small rocks in the lunar regolith. (Left) Jack Schmitt with the rake on Apollo 17 [NASA AS17-134-20425]. (Center) The rake in the lunar regolith from Apollo 16 [NASA AS16-116-18690]. (Right) Close-up image of the rake from Allton (1989).

The second EVA continued across the landslide to the north, where the astronauts visited the dark halo craters. These features turned out *not* to be volcanic cinder cones as they had appeared to be from orbit; rather, they were the result of a small impact event that had dug up older darker material and deposited it around the resulting crater. (Here is yet another misinterpretation of an impact process as volcanic.) The dark material was not young, but old, titanium-rich mare volcanic material, much like the basalt collected at the Apollo 11 site. No young volcanic material was found by Apollo 17, leaving that goal for future lunar explorations.

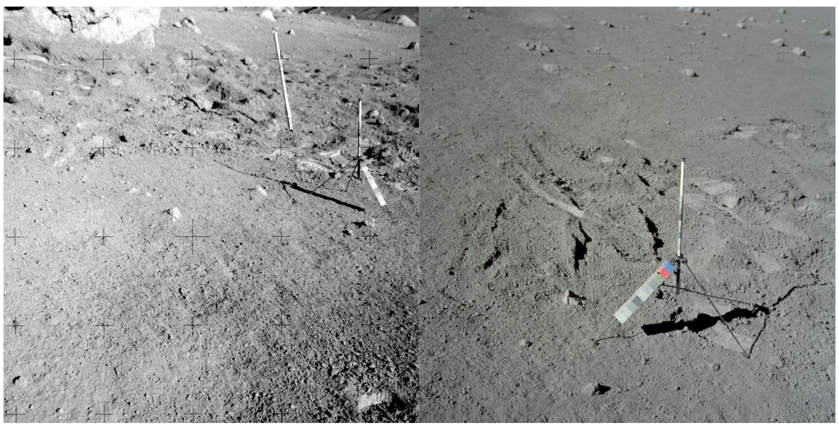

Figure 8.8: The before and after images of the rake sample collection site at the base of the South Massif [NASA AS17-138-21046 (left), AS17-137-20962 (right)].

On December 14, 1972, at 2:55 pm PST, the Apollo 17 astronauts lifted off the surface of Moon, ending the direct exploration of the lunar surface. The Apollo lunar program ended five days later on December 19, 1972, at 11:25 am PST, when the Apollo Command Module *America* splashed down in the Pacific Ocean. While the Apollo lunar missions ended as 1972 closed, the scientific investigation of the lunar samples was just starting to reach its prime.

Bag 501

Sample bag 501 contained 436 grams (about a pound) of rake samples from the base of the South Massif. When the bag was processed in the Lunar Receiving Laboratory, it was found to contain 15 small pieces of breccia composed almost entirely of impact melts (Figure 8.9)[93]. The largest of these impact-melt breccias was the 221-gram, baseball-sized rock 72535.

[93] Butler (1973)

All of the samples were chemically similar to the nearby boulders,[94] suggesting that the small, rake-sample rocks had once

[94] Laul and Schmitt (1975)

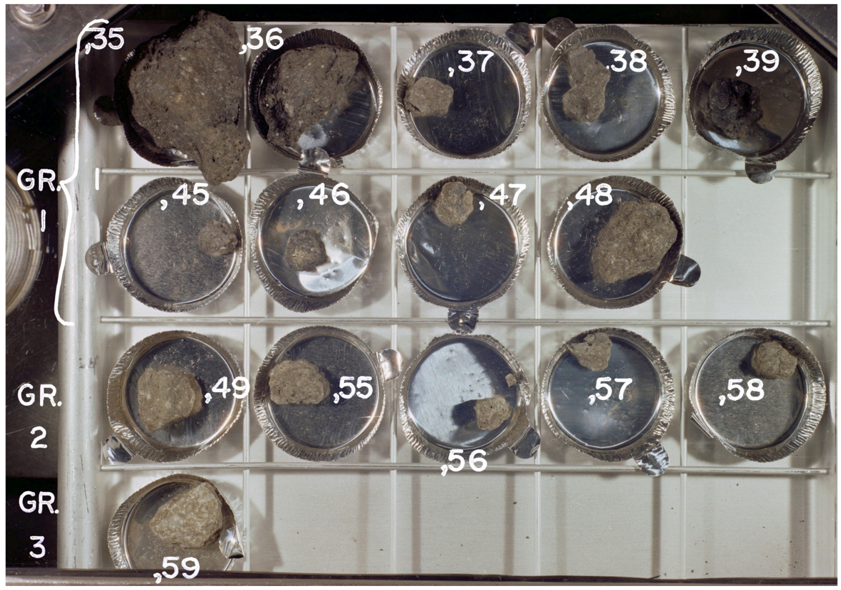

Figure 8.9: The larger rocks from the rake sample collected in bag 501 [NASA S73-19605]. The sample 72535 is the largest sample, in the upper left corner. The round aluminum sample trays are about 2 inches across.

been part of the South Massif and that they likely had broken off the larger boulders as they tumbled down the South Massif during the landslide event.

Like the impact-melt clasts in 67015, the sample 72535 looks like a sample of volcanic basalt: dark and fine-grained (Figure 8.10). As we saw in Chapter 7, impact melts are melted by the energy of an impact event, so the radiogenic age of an impact melt is an indication of the age of the related impact event. The radiogenic age of 72535 was found to be 3.887 ± 0.016 billion years old.[95]

[95] Dalrymple and Ryder (1996)

The same study that determined the age of 72535 found that many of the impact melts collected by Apollo 17 share a very similar age, and the authors of this study suggest that these samples were melted by the formation of the Serenitatis impact basin. If the age of the Serenitatis Basin is 3.887 billion years old, that would add another giant impact basin that was formed in the short interval between the formation of the Nectaris Basin (3.92 b.y) and the Imbrium Basin (3.87 b.y).

Of course there are other interpretations. There is recent evidence that suggests that the impact melts from the base of the South Massif were *not* formed by the Serenitatis impact event. High-resolution images of the Taurus-Littrow region taken by the Lunar Reconnaissance Orbiter in 2011 have shown that the entire region may be covered by melt from the Imbrium event.[96] This would imply that the age of 72535 does not date

[96] Spudis et al. (2011)

Figure 8.10: The sample 72535 at the Lunar Receiving Laboratory. The cube is 1 cm across [NASA S73-19581].

the Serenitatis event, but rather the Imbrium event. That would put the age of 72535 very close to the age of the impact melts in 14321.

Another recent study used high-resolution crater counts in order to determine the sequence of giant basin formation.[97] This study found that the Serenitatis Basin probably formed *before* the Nectaris Basin. If this is true, then the 3.887-billion-year age of 72535 cannot be related to the Serenitatis Basin, but must date from — and tell us the date *of* – a later impact, most likely Imbrium. The wide-ranging influence of the Imbrium event may mean that the samples from Apollo 17 are so contaminated by Imbrium material that finding material that is unambiguously from Serenitatis may be very difficult.

[97] Fassett et al. (2012)

Exposure Age

The sample 72535 formed during an impact event and solidified into a rock 3.887 billion years ago. However, this is not the only interesting age that can be teased from a lunar sample. Another important bit of temporal datum is called the **exposure age**. As its name implies, the exposure age is a measure of how long the sample has been exposed to space. In other words, it is a indication of how long the sample has sat, exposed, on the surface of the Moon, before it was collected. The exposure age and radiogenic age of a sample are almost always very different; the exposure age is usually much younger.

A sample that is exposed on the surface of the Moon is subject to the continual bombardment of **cosmic rays**.

Cosmic rays are high-energy particles (not rays) that originate mostly far beyond our solar system. These particles are pieces of atoms (protons, helium nuclei, and electrons) with very high energies that continually bathe all the objects in our solar system. When cosmic rays collide with a rock on the surface of the Moon, they can break up the nuclei of elements in a sample into smaller pieces, creating lighter elements. This process is a naturally occurring form of nuclear fission called *cosmic ray spallation*.

There are many isotopes of elements that are primarily created this way. For example, argon-38, an isotope of argon, is mostly formed by cosmic rays smashing into calcium atoms. Since calcium is a common rock-building element, argon-38 is common in rock samples that have been exposed to cosmic rays. The longer a rock is exposed to cosmic rays, the more argon-38 is produced. Therefore, by measuring the amount of argon-38 in a rock's sample, you can determine how long the rock has been exposed to cosmic rays. argon-38 is only one of many different isotopes that can be used to measure a sample's exposure to cosmic rays.

Cosmic rays can only penetrate centimeters into the lunar surface. This means that only rocks very near the surface are exposed to cosmic rays. By measuring how long a rock has been exposed to cosmic rays, you are essentially measuring how long it has been sitting on the lunar surface. Of course, a single lunar sample may have been buried and exposed many different times over its lifetime, so it can have a very complicated exposure history.

Age of Tycho

The exposure age of many of the Apollo 17 samples has been determined using this technique.[98] Many of the samples (including 72353) were found to have simple exposure histories, meaning that they were exposed to cosmic rays for the first time by the event that evacuated them. The exposure age of 72535 was found to be 107 million ± 4 million years old.

98 Arvidson et al. (1976)

The exposure age of 72535 was found to be very close to the exposure ages of samples collected 8 km away in the central cluster of craters near the Lunar Module. The average exposure age of all of these samples is 96 ± 5 million years. This strongly implies that the same event exposed samples at both locations at the same time. If the landslide off the South Massif, and the formation of the central cluster of craters were both due to ejecta arriving from the Tycho Crater, then the 96 million year old exposure age of these samples date the Tycho impact event.

96 million years ago was near the end of the Cretaceous period of the history of the Earth, about 30 million years before the extinction event that ended the reign of the dinosaurs on the surface of the Earth. These animals would have been the last to witness the surface of the Moon change. The formation of the Tycho Crater is the latest event in the history of the lunar surface that could have easily been observed with the unaided eye from the surface of the Earth. This is in stark contrast to the ever-changing surface of the Earth: a long-lived observer on the Moon would have seen a great deal of change on the Earth's surface over the last 96 million years, just with the unaided eye.

Erosion on the Moon

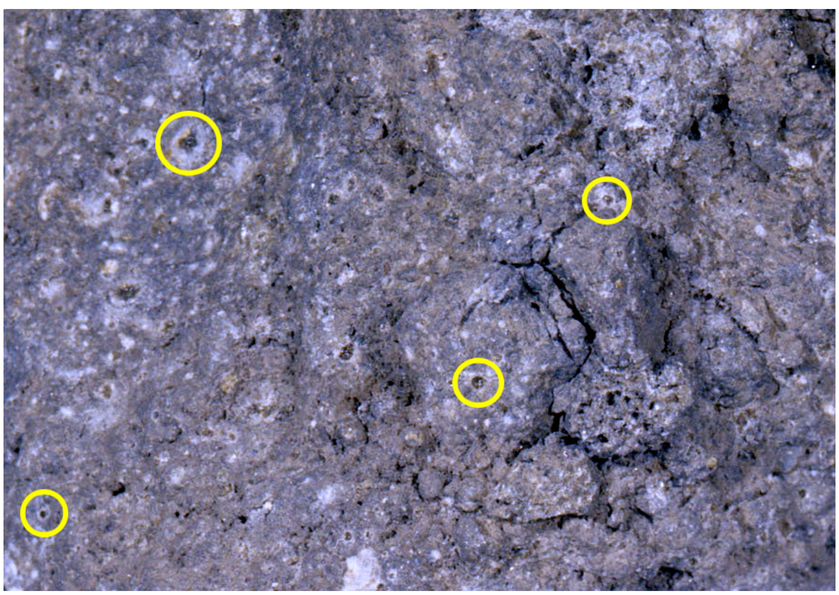

Figure 8.11: Close-up of the sample 72535 at the Lunar Receiving Laboratory. A few of the micro-meteorite craters are circled [NASA S73-19581].

For the last 96 million years, the surface of the Moon has appeared almost completely unchanged, as seen from the surface of the Earth. However, this does not mean that the lunar surface is unchanging; it just means that the present-day rate of change of the lunar surface is very, very slow. Just how slow can be determined by examining the outer surface of the lunar samples.

One of the most distinguishing external characteristics of the sample 72535 is that its surface is covered in micrometeorite craters (Figure 8.11). These small (< 1 mm) pits were formed by the impact of the microscopic-sized particles that continuously rain down onto the surface of the Moon. The population of craters on the surface of 72535 follows the exact same trend for the Moon as a whole: there are far more small craters than large craters. Occasionally, one of these impacts will be large enough to completely fracture a rock and expose new surfaces to impacts. A study of the crater population on lunar samples has found that typical crystalline rocks, like 72535, are completely fractured by impacts about every few million years.[99] Over time, these impacts will reduce the rocks to a powder, creating the lunar regolith (see Chapter 4).

[99] Hörz et al. (1971)

The rate of change at a site on the Moon is exceedingly slow. Every few million years, a rock will break in half; the destruction of material within about 1 meter of a specific site will create about 8 mm of regolith every million years.[100] Not all of the regolith at a site is derived from the destruction of local rocks; we have now seen many examples of materials transported over long distances by impact events. However, these distant events make only a small contribution; material from 10 km away accumulates at a rate of only about 0.08 mm every million years. A very recent re-analysis of the power output of solar cells of the Apollo surface experiments has set an upper limit of 1 mm of regolith accumulation over 1,000 years.[101]

[100] Arvidson et al. (1975)

[101] Hollick and O'Brien (2013)

Figure 8.12: Footprint on the surface of the Moon. The LMP of Apollo 11 documenting a bootprint on the lunar surface as part of a lunar surface properties experiment [NASA AS11-40-5880 (left) and AS11-40-5877 (right)].

Footprints on the surface of the Earth are an exceedingly temporary phenomena, rarely lasting more than a few days. Only under the most unusual circumstances will a footprint last longer than a typical human lifetime. *All* of the footprints (Figure 8.12) left by the Apollo astronauts will far outlive us. The average depth of an Apollo footprint is a few centimeters, [102] so that means that they will last a few million years before they are obliterated by impact processes. A few million years is not only way longer than a human lifetime; it is longer than *Homo Sapiens* have been on the Earth.

[102] Houston et al. (1972)

The History of 72535

3.89 billion years ago, a giant impact into the northeast portion of the Moon formed the Serenitatis Basin. The energy from this impact melted a vast amount of material, scattered ejecta all across the Moon, and lifted deep-seated material to form a 920-kilometer-diameter rim. Some of the melted material covered a portion of the basin's southeastern rim that forms the South Massif.

From about 100 to 200 million years after the formation of the Serenitatis Basin, lava up-welled from the lunar interior and flooded the region around the South Massif, forming the Taurus-Littrow valley.

For over 3 billion years, the constant flux of impactors ground up the impact melt material of the South Massif.

96 million years ago, an impact some 2,000 km away, formed the Tycho Crater. Material from this impact traveled across the Moon and landed on the top of the South Massif, setting off a landslide that sent boulders made of earlier impact melt tumbling onto the floor of the Taurus-Littrow valley. One of these boulders lost fragments as it rolled down and came to rest right at the base of the South Massif.

Over the next 96 million years, micrometeorite impacts slowly covered the boulder and its exposed fragments with small craters, occasionally fracturing the fragments into smaller pieces.

On December 12, 1972, the Apollo 17 astronauts arrived at this boulder, swept a rake through the nearby regolith, and collected fragments from the boulder. About a dozen pieces of the boulder were returned to the Earth, including the largest fragment, 72535.