4 Apollo 12

The Lunar Geological Time Scale

For the Apollo 11 site, I used the fact that the *Mare Tranquillitatis* was the topmost stratigraphic layer to claim that it was relatively the youngest of the local layers. This idea of *superposition* can be used both locally (for a particular landing site), and globally (expanded to the Moon as a whole). By relating the superposition of land forms across the Moon, we can construct a *geological time scale* for the Moon as a whole. This geological time scale provides a helpful framework for discussing the global history of the lunar surface.

We have partitioned the 4.6-billion-year history of the surface of the Earth into various units of geological time, forming the geological time scale of the Earth. The boundaries between the various eras are defined by major, **global** events in the Earth's history.

Boundaries are important, since they allow scientists to correlate events in time all across the Earth. For example, a fossil uncovered in Utah just below the boundary that marks the end of the reign of dinosaurs, can be assumed to be of similar age to a fossil found just below the same boundary in the mountains of Italy.

As in the example above, many of the Earth's geological time scale boundaries are defined by major extinction events. Obviously, this cannot be the case for the Moon. On the Moon, the boundaries between the various units of the geological time scale are set by **impact events**.

Regolith Formation

The surface of the present-day Earth is constantly being modified by myriad different processes: volcanism, tectonics, rain, wind, people, etc. By contrast, the surface of the present-day Moon is being modified, at a *much* slower rate, by only one process: impact cratering.

Every year, about 20,000 metric tons (20 million kg) of extraterrestrial material enters the top of the Earth's atmosphere.[22]

[22] Love and Brownlee (1995)

The vast majority of this material is very small (< 1 mm), with the most typical size of a particle being about 0.2 mm in diameter (about twice the thickness of a human hair). These particles hit the top of the Earth's atmosphere at a velocity of about 12 km/sec (~ 27,000 mph). At this high velocity, nearly all of this material burns up high in the Earth's atmosphere.

This same flux of material is also raining down onto the Moon, and has been for the past 4.6 billion years. Since the Moon has no atmosphere, even the smallest of these particles can freely impact the surface of the Moon. This constant influx of small impactors slowly changes the surface of the Moon. It is continually grinding the surface into a fine powder; softening the jagged peaks of mountains; destroying, transporting, and burying the rocks on the surface; and removing them from their original context. This bombardment is also erasing the boundaries between different geological features.

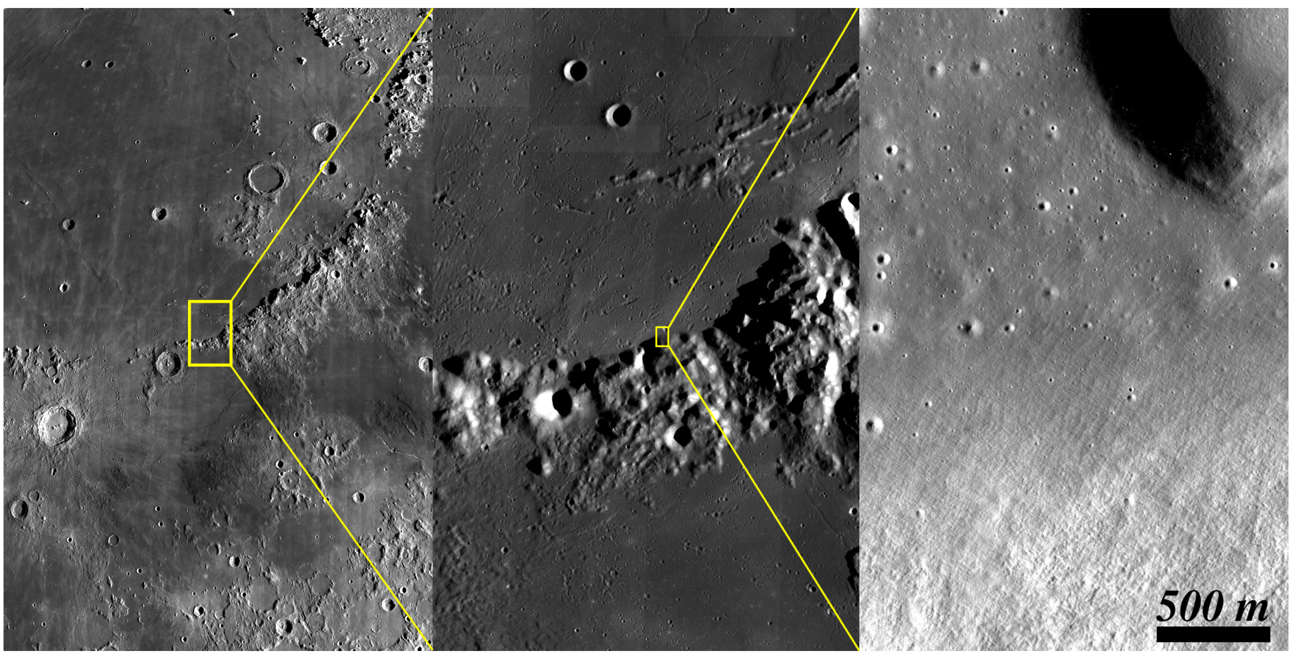

Figure 4.1: Three views of the southern rim of the Imbrium impact basin at increasing resolution. The first two images are from the LROC WAC mosaic of the lunar near side, and the last image is a detail from LROC NAC frame M1096543764LE [NASA/GSFC/Arizona State University].

The boundaries between different geological features are called **contacts**. In images of the lunar surface taken from the Earth or lunar orbit, the contacts between geological units can seem very obvious. However, to the astronaut on the surface of the Moon, these contacts may be completely indiscernible. For example, take a look at Figure 4.1. The left two panels show what appears to be a very sharp contact between a mare lava flow and series of hills that the lava flow laps up against. The right panel shows a close-up of the contact between these two units, and as you can see, there is really no contact visible. Astronauts walking across this landscape would not even know where the lava flow ended and the hills began. Often times, the only clue the astronauts had that they had moved across a geological contact was the feeling of the surface underfoot: [23]

23 Wilhelms (1993), page 223

> "They understood the principles of geological units and stratigraphy, and reported that these differences in footing were about the only clues to different units; few sharp contacts were discernible."

The fine, impact-generated powder that covers the Moon is called the **lunar regolith**. The thickness of the regolith varies greatly across the Moon. It is typically believed that the regolith may average about 10–15 meters on the old highland regions of the Moon, while it may be only 4–5 meters thick on the younger mare surfaces.[24]

24 Heiken et al. (1991)

The very first geological observation from the surface of the Moon was a description of the lunar regolith. The next words Neil Armstrong said after his famous "That's one small step ..." line was:

> 109:24:48 CDR: Yes, the surface is fine and powdery. I can kick it up loosely with my toe. It does adhere in fine layers, like powdered charcoal, to the sole and sides of my boots. I only go in a small fraction of an inch, maybe an eighth of an inch, but I can see the footprints of my boots and the treads in the fine, sandy particles.

Since the regolith is ubiquitous across the surface of the Moon, all Apollo missions sampled this material. This chapter is the story of one of these samples.

Fresh Impacts

Fresh impacts on the Moon eject material that appears to us as streaks that radiate from the center of the impact (Figure 4.2). This radially ejected material is commonly referred to as **rays**. Over time, the constant bombardment of the lunar surface softens these rays until they blend into the background. The presence of rays around an impact crater is a indication of a *fresh* impact.

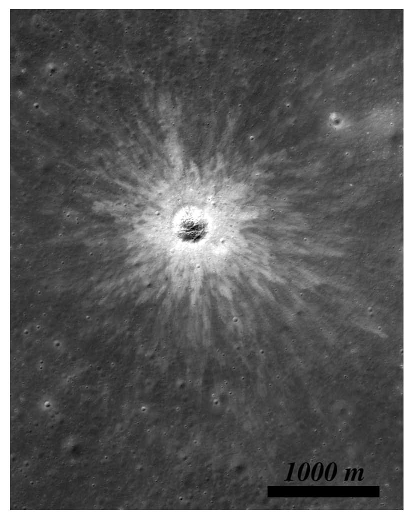

Figure 4.2: A fresh impact crater in the lunar highlands. The rays of ejecta are easily visible against the background. LROC NAC M1104423389 [NASA/GSFC/Arizona State University].

It is these fresh impacts that identify the most recent geological age of the lunar surface. This slice of lunar history is named the *Copernican* age, after one of the most prominent of the fresh-rayed craters.

The rays of Copernican-aged craters fade into the older surrounding terrain, from the lunar geological era called the Eratosthenian (named after the crater Eratosthenes). Both the

Eratosthenian and the Copernican era are defined by post-mare cratering, craters formed after the last of the lunar mare solidified. Craters of these two eras are ubiquitous at all Apollo landing sites. If you take a look at the geological map of any of the Apollo sites, you will see that they are dotted with Eratosthenian-aged craters and Copernican-aged craters. Not only will these craters appear on all of the other geological maps of the Moon, they will also play a major role in the chapters that follow.

Copernicus

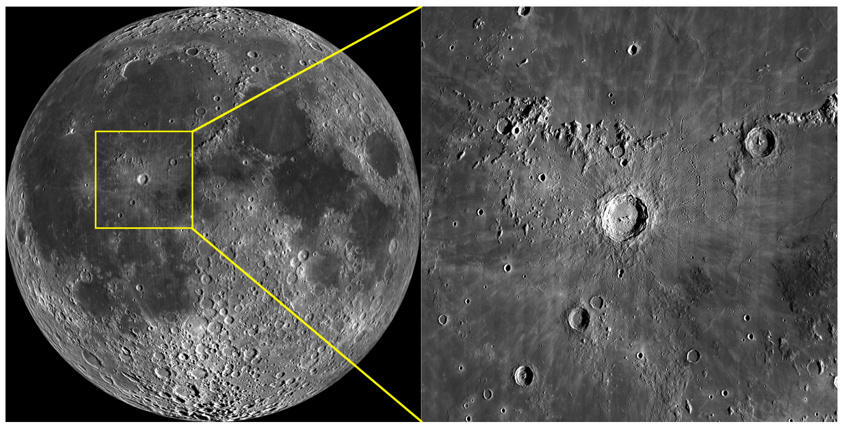

Figure 4.3: An image of the near side of the Moon, showing the context of the crater Copernicus. The inset is centered on the Copernicus crater. Both images are from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

The Copernicus crater is a fresh-rayed crater, 93 km in diameter, easily visible on the near side of the Moon (Figure 4.3). This crater has played a key role in helping us understand the history of the lunar surface. The original study that set the lunar geological time scale was based on a detailed telescopic observation of the region around the Copernicus crater.[25]

[25] Shoemaker and Hackman (1962)

For lunar scientists, determining the age of the Copernicus crater is of primary importance, as that crater is the key marker for the Copernican era. It should be noted that the start of the Copernican period does not correspond to the formation of the impact crater Copernicus. Rather, the Copernicus crater is just the most prominent crater of the era (more on this later).

The Copernicus crater and its immediate surrounds were deemed far too rough for an Apollo mission landing site. The lunar scientist Don Wilhelms noted that at one of the Apollo Site Selection Board meetings, someone commented that “...there was no hope in Hell of ever landing inside Copernicus because Congress would kill the Apollo program when the mission crashed."[26] The inaccessibility of the Copernicus crater itself meant that sampling of the crater would have to be accomplished by picking up material launched by the impact event onto a site that was accessible by Apollo.

[26] (Wilhelms, 1993)

Geological Setting

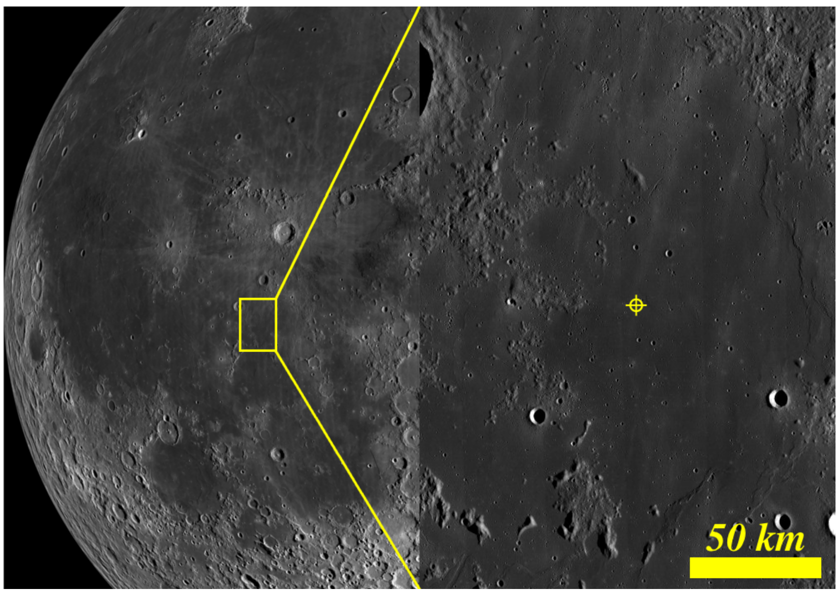

Figure 4.5: The context of the Apollo 12 landing site in the Ocean of Storms just south of the Copernicus crater. The rays from Copernicus can be seen as the higher albedo streaks running north–south in the image on the right. Both images are from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

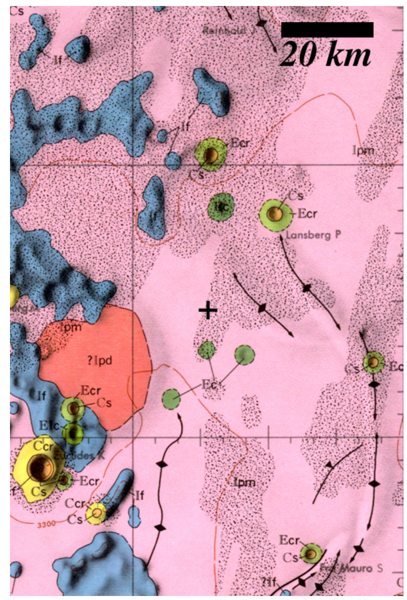

Figure 4.4: A detail of the geological map of the Apollo 12 landing site. The landing site of Apollo 12 is marked by the **+**. The black-stippled pattern represents material that we interpret as either a very thin blanket of Copernicus ejecta, or an area where the mare surface material has been disturbed by the down-range movement of material (Eggleton, 1965).

Apollo 12 landed about as far away from the Apollo 11 site as constraints would allow, on a mare called *Oceanus Procellarum*, the Ocean of Storms (Figure 4.5). It is the largest mare surface on the Moon, covering most of the western hemisphere of the near side of the Moon.

The Apollo 12 landing site actually shares many of the same qualities of the Apollo 11 site: it is a vast, relatively smooth mare surface. Both sites are geologically rather simple. The geological map of the Apollo 12 site (Figure 4.4) is dominated by one color (pink), signifying a single geological unit, the underlying mare surface. Also notice the Eratosthenian-aged craters (green), and Copernican-aged craters (yellow and red) all over the site.

However, the star of this chapter is not the dominant mare surface of *Oceanus Procellarum*, nor the overlying craters, but, rather, the thin wisp of material ejected from the Copernicus crater 370 km north of the landing site. This Copernican ray can be seen in the image of the Apollo 12 site and is indicated on the geological map as the black stippled pattern.

The Landing Site

Apollo 12 was the first Apollo mission where a precision landing at a very specific point on the Moon was a major mission priority.[27]

[27] The story of the technique Apollo 12 used to achieve a precision landing and what this technique tells about the deep structure of the Moon is a fascinating tale that, unfortunately, is not central to the theme of this chapter. For a nice summary of the technique, see p 18 of Harland (2011). The science uncovered by this technique starts with Gottlieb et al. (1970) and continues to the present (*e.g.,* Zuber et al. (2013)

Apollo 12 achieved this precision landing when the mission commander Pete Conrad set the lunar lander *Intrepid* down at the north end of the Eratosthenian-aged Surveyor crater, just 200 meters from target of the landing. The target was the Surveyor III spacecraft, which had arrived 31 months earlier as part of a series of seven Surveyor spacecrafts sent to the Moon from 1966 through 1968 to demonstrate the feasibility of soft landings on the lunar surface. (The Surveyor III spacecraft is marked by the S3 in Figure 4.6).

The Apollo 12 mission set the template for the later Apollo missions, by using the first EVA primarily to set up the lunar surface experiments, and then using the subsequent EVA(s) for the geological exploration of the landing site. In the case of Apollo 12, the geological traverse consisted of a single, 3.8–hour, 1.6–km, counter-clockwise circuit of the local impact craters. This circuit included a visit to the Surveyor III spacecraft near the end of the EVA.

Sample Collection

The second EVA of Apollo 12 started with the astronauts heading due west from the lunar module, across the top of another Eratosthenian-aged crater named the *Head Crater* (Figure 4.6). About 30 minutes after the start of the EVA, the astronauts were just past the top of Head Crater when the lunar module pilot, Alan Bean, noticed that his commander, Pete Conrad, was kicking up something unusual:

> 132:20:24 LMP: Okay. Hey, that's interesting; look where you kicked. Got some lighter material there.
>
> 132:20:32 CDR: Boy, sure did, didn't I!
>
> 132:20:34 LMP: Yeah, that's interesting; that's the first time we've seen that.
>
> ...
>
> 132:20:46 LMP: Houston, kind of interesting here. Pete walked across one edge of the rim here. We're about, oh, 50 feet inside the upper rim and he

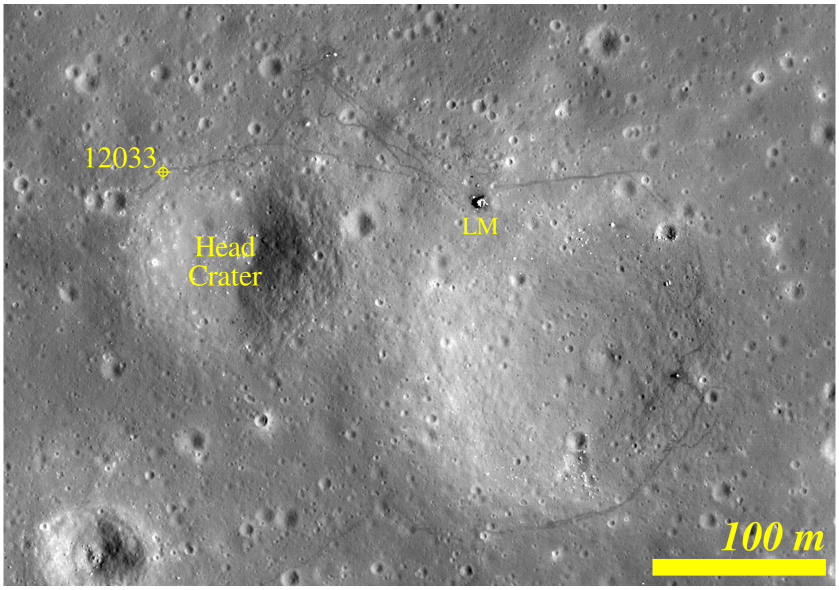

Figure 4.6: High-resolution image of the Apollo 12 landing site. The collection location of sample 12033 is marked on the northern rim of Head crater. The footprints of the astronauts are clearly visible. LRO NAC M175428601R [NASA/GSFC/Arizona State University]

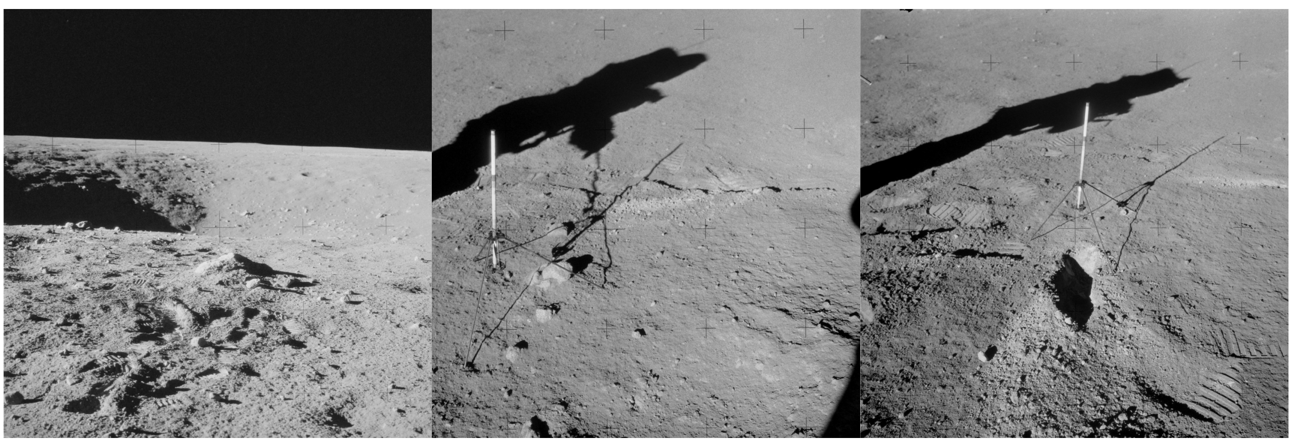

Figure 4.7: (Left) Image of the site at the top of Head crater, looking south across the crater. The sample 12033 will be collected near the mound in the foreground [NASA AS12-49-7183]. (Center) Getting ready to dig a trench and collect sample 12033. Note the footprints beyond the gnomon. These are the footprints that revealed the light-colored soil layer [NASA AS12-48-7048]. (Right) The “after” image of the trench. The sample 12033 was collected at the bottom of this trench. The lighter regolith is visible around the trench [NASA AS12-48-7051].

> happened to scrape an area there with his foot. It’s a much lighter colored soil...

The discovery of the light soil was important enough that the astronauts documented the site and began to collect samples (Figure 4.7). The astronauts started by collecting a small rock sample (the 185 g sample 12031) and then Pete Conrad started to dig a small trench about 15 cm deep.

132:21:32 CDR: Okay. Al, let me photograph this thing, and let's trench this whole area.

...

132:23:48 LMP: There's not much in here. Okay. Where Pete digs up...Sure enough, right underneath the surface, you find some much lighter gray...Boy, I don't exactly know why it's this point, and you can look around now and see several places where we've walked that the same thing's occurred. We never have seen this at all...Boy, that's going to make a good picture, Pete. Never seen this at all on the area we were before. Hey, that looks nice.

...

132:25:03 LMP: Yeah, dig as deep as you can, then give me a sample right out of the bottom, because this will be something new. I'll put it in sample bag number 5D.

Sample bag 5D contained 450 g of lunar regolith collected at the bottom of the small trench. The Lunar Receiving Laboratory designated this bag of regolith: sample 12033.

A Sample of the Regolith

When the bag containing 12033 was opened at the Lunar Receiving Laboratory, the initial description noted:[28]

[28] Warner (1971)

> "Fine grained material ... Much lighter than fine grained soil from elsewhere at the Surveyor site ... There are a number of 1 mm to 10 mm long angular and sub-angular rock fragments in the soil sample ... Most fragments appear to be less than 0.05 mm in diameter. ... Several of the larger fragments pulled out are twisted pumiceous glass fragments. Dark brown glass."

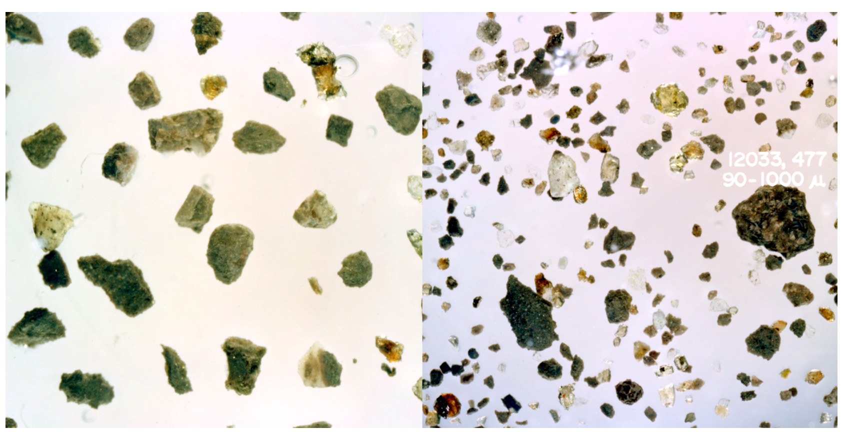

Figure 4.8: Close up images of the particles in the sample 12033. Both images are at approximately the same scale. (Left) Particles with sizes between 0.25 - 0.50 mm [NASA S79-34501]. (Right) Particles with sizes between 0.09 - 1.00 mm [NASA S79-34499].

A close look at the particles that make up the samples shows that 12033 is a collection of very diverse materials (Figure 4.8).

There are a variety of shapes, colors, and textures. Some of the particles are clear; others are completely opaque. Some are fragments of a single mineral; others are complex collections of minerals (rocks). It will come as no surprise that the individual histories of these particles are going to be as diverse as their appearance.

Despite the diversity of the particles in sample `12033`, they all have one thing in common: their sharp, hard edges. While lunar regolith may superficially look like soil or sand from the Earth, the angularity of the particles of regolith make it a much different material. The particles that make up sand on the beaches and deserts of the Earth are generally rounded and smooth due to the erosional processes of wind and water. There are no such processes operating on the lunar surface, so the particles of regolith retain their sharp edges that were formed by the fragmentation of the original material. The sharp, abrasive nature of lunar regolith can wear and clog machinery; it can cause the gaskets that protect the astronauts from the vacuum of space to fail. The Apollo 17 CDR Gene Cernan commented on the effect of the regolith:[29]

[29] NASA (1973)

> "Dust - I think probably the most aggravating, restricting facets of lunar surface explorations is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and it's restrictive friction-like action to everything it gets on ... By the middle or end of the third EVA, simple things like bag locks and the lock which held the pallet on the Rover began not only to malfunction but to not function at all ... The effect of dust on mirrors, cameras, and checklists is phenomenal. You have to live with it but you're continually fighting the dust problem both outside and inside the spacecraft ... You can be as careful in cleaning up as you want to, but it just sort of inhabits every nook and cranny in the spacecraft and every pore in your skin."

The lunar regolith has even recently been found to be a danger to an astronaut's lungs, nervous system, and cardiovascular systems.[30] The management of the lunar regolith is one of the primary concerns for the long-term exploration and occupation of the Moon.

[30] Cain (2010)

Since Apollo 12 landed on a mare surface formed by volcanism, it make sense that a large portion of the particles in `12033` are igneous materials. The initial study of the relative proportions of material in `12033`[31] found that 6% of the particles are fragments of crystalline basalt and 29% are clumps

[31] Marvin et al. (1971)

of basaltic material welded together by the energy of impacts (breccias). This suggests that about 1/3 of the material is derived from the local mare surface. Another 11% of the particles are fragments of another type of igneous rocks called *norites* and *anorthosites*. We will see in Chapter ?? that this 11% originated on the highlands of the Moon, and it is a sample of the ancient original crust of the Moon. This material has either been evacuated from deep under the mare surface at the Apollo 12 site, or has been transported to the site by impacts in the lunar highlands. Finally, the majority (51%) of particles in the 12033 sample are glasses.

The fragments of basalt, norite, anorthosite, and breccias found in the lunar regolith represent pieces of material that can be found as larger, easier-studied, hand-sized rocks. Hand-sized samples of lunar glass, however, are very rare. The small pieces of glass we have in the regolith at all of the landing sites are the major source of samples of this important material.

Figure 4.9: A typical ropy glass particle in the sample 12033. The particle is approximately 1 mm long [NASA S79-34502].

Glass

The glasses in the Apollo 12 regolith were formed from material that was melted by the energy of meteoroid impacts. This material cools very fast, fast enough that the material solidifies before it can crystallize. The structure of glasses are intermediate between the close-packed, highly ordered array of a crystal and the highly disordered array of a gas.

The discovery of glass on the ancient lunar surface was very unexpected. On the surface of the Earth, glasses form in volcanic processes (obsidian is a very common volcanic glass), but this volcanic glass does not last very long. Over thousands to millions of years, the volcanic glass will crystallize into mineral grains in a process called *devitrivication*.[32] On the Earth, the devitrivication of glasses almost always occurs in the presence of water. The fact that lunar regolith is full of glasses that have been around for billions of years, tells us that water has played no role in altering the surface of the Moon.

32 Marshall (1961)

Most of the glasses in 12033 are called *ropy glass*. They look like they "have been pulled or twisted while hot"[33] and are covered by a layer of fine-grained, gray dust (Figure 4.9). It is these ropy glass particles that are the main protagonists of 12033.

33 Marvin et al. (1971)

Ropy Glass - Chemistry

One of the earliest studies carried out on 12033 found that the chemistry of the ropy glass particles was very different from the chemistry of the basaltic rock that covers the Apollo 12 site.[34] This means that the ropy glass particles were not derived from the melting of the local rocks, but that they originated far from the site and were transported to the collection point at the top of Head Crater. The main chemical difference between the ropy glass and the local basalt is that the ropy glass has far more potassium (K), rare earth elements (REE), and phosphorus (P) than the local basalts. Particles that are rich in these elements are referred to as KREEP particles, or are said to be KREEPy. The ropy glass from 12033 was the first lunar material that was found to be KREEPy.[35] For our story about 12033, the presence of KREEPy material in the ropy glass is important because it tells us that they are chemically distinct from the local basalts. The origin, history, and importance of KREEPy material will be a big part of Chapter ??.

[34] Meyer et al. (1971)

[35] Hubbard et al. (1971b)

Ropy Glass - Age

Not only are the ropy glass particles in 12033 chemically different from the local basalt, but their ages are very different as well. The typical ages for the basalts collected at the Apollo 12 site are about 3.2 billion years,[36] making them about 400 million years younger than the basalts collected at the Apollo 11 site. This is important, since it tells us that not all of the lunar mare surfaces were formed at the same time, and that volcanic activity was modifying the surface of the Moon over at least 400 million years, which is a long period of time.

[36] See section 6.1.9 of Heiken et al. (1991)

In the previous chapter, I described how the age of the Apollo 11 sample 10022 was determined. Using the Argon-40 / Argon-39 dating technique, it was found that 10022 cooled from a completely molten lava 3.59 billion years ago. One of the advantages of the Argon-40 / Argon-39 dating technique is that it also has the ability to determine when a sample has been heated but not completely melted.

In 1973, the first Argon-40 / Argon-39 study was carried out for over 100 glassy particles in 12033.[37] This study found that *all* of the particles had gone through a major heating event 800 million $\pm$ 40 million years ago, a date that is far later than the formation time of the Apollo 12 basalt samples. This study was only the first of many studies to tease out the history of the glasses in 12033. For example, in 1976, a study also found that the sample "had been subjected to an important thermal episode 850 million $\pm$ 100 million years ago."[38] As dating techniques improved over time, the dates became more precise. In 1992, a study included a larger (4–10 mm) fragment of granite from 12033 along with the ropy glass fragments and found

[37] Eberhardt et al. (1973)

[38] Alexander et al. (1976)

that they all had undergone a major heating event 800 million $\pm$ 15 million years ago.[39] More recently, in 2006, a study of a wide variety of different particle types in 12033 found that all of these particles has been heated 782 million $\pm$ 21 million years ago. [40]

[39] Bogard et al. (1992)

[40] Barra et al. (2006)

Ropy Glass - Origin

The studies above present strong evidence that all of the particles that were collected at the bottom of the trench dug near the northern end of Head Crater experienced a major heating event about 800 million years ago. Since volcanic activity was long over by this time, the heating had to have come from an impact event near enough to heat the material at the Apollo 12 site, or from an impact event that ejected the heated material to the Apollo 12 site.

There are many post-mare-aged craters near the Apollo 12 site that could be the source of the heating 800 million years ago. The crater Copernicus quickly jumps to the top of this list, due to the fact that a ray of the Copernicus crater crosses the Apollo 12 site. In fact, very early in the studies of the Apollo 12 samples, it was suggested that the KREEPy material in the Apollo 12 regolith came from material ejected from the Copernicus crater.[41] Over time, this idea has become mostly accepted by the scientific community, since it best explains how this material, whose composition and age differ so markedly from the local Apollo 12 basalts, ended up at the site.

[41] Hubbard and Gast (1971)

The Age of Copernicus

The evidence from the studies of 12033 points to a formation age of the Copernicus crater of about 800 million years ago. While this is currently the most direct measure of the age of Copernicus, it is not the only one. Recent work[42] utilizing very high-resolution imaging from the Lunar Reconnaissance Orbiter[43] has used the time-honored method of crater counting (see Chapter ??) to determine a formation age of about 779 million years for Copernicus. This is consistent with the age determined from 12033, and lends evidence to the idea that 12033 is indeed ejecta from Copernicus.

[42] Hiesinger et al. (2012)

[43] http://lunar.gsfc.nasa.gov/

The Copernicus Crater lends it name to the Copernican era of the lunar time line, but, as was stated at the beginning of this chapter, the time of the formation of the Copernicus Crater does not define the beginning of this lunar era. Establishing the beginning of the Copernican era is difficult, since there are so few well-dated surfaces formed in this era. The current best estimate of the beginning of the Copernican era is about 1,100 million years ago (1.1 billion years).[44] This means that Copernican-age craters were forming for about 300 million years before the formation of the Copernicus crater. Establishing the younger end of the Copernican era is easy: it is today. That means that all features that are currently forming on the lunar surface are Copernican-aged.

[44] Wilhelms et al. (1987)

Controversy

The link between sample 12033 and the Copernicus Crater is not universally accepted.[45] A lot rests on the assumption that the ray from Copernicus that lies over the Apollo 12 site and the light-colored material of 12033 are the same thing. There are lines of evidence that suggest that this may not be the case. However, one of the intriguing new ideas is that Copernicus may not have been the only impact event 800 million years ago. A new study has found evidence that many different glasses from many different Apollo landing sites have a signature from a heating event 800 million years ago.[46] This may mean that Copernicus was not the only impact event at that time, but was part of an increased flux of impactors 800 million years ago.

[45] See the references on page 269 of Wilhelms et al. (1987)

[46] Zellner et al. (2009)

It is interesting to note that not only was the Copernicus crater one of the main sites considered for the unjustly cancelled Apollo 18 mission, but the crater is always a main contender for landing site for missions planned for the future.[47] The question of the age of the Copernicus Crater may not be settled until a sample is picked up and returned directly from the crater itself.

[47] For example, the Constellation Program designated the Copernicus Crater as a region of interest. (See http://ser.sese.asu.edu/LSM/files/Cx-LROC-Tier1-FINAL.pdf)

The History of 12033

800 million years ago, a 7-km rocky asteroid[48] stuck the Oceanus Procellarum region of the Moon, creating the 93-km Copernicus Crater. The energy from this impact evacuated and strongly heated material from a depth of about 6–9 km deep. This material was ejected across a large portion of the near side of the lunar surface. Some of this material was ejected 370 km to the south onto a 3.2-billion-year-old mare surface.

[48] Yue et al. (2013)

Over the next 800 million years, this material was slowly mixed into the local regolith by the continuous bombardment of particles onto the lunar surface.

Occasionally, a local impact would further bury this Copernican ejecta.

On November 20, 1969, an astronaut walking across this site uncovered some of this material and noticed its contrasting color. A 15-cm trench was dug, and from the bottom of this trench, 450 g of this material was collected and put into a sample bag. This bag was returned to the Earth, delivered to the Lunar Receiving Laboratory, documented, and then distributed to scientists all over the world.