
EX LUNA, SCIENTIA

Ex Luna, Scientia

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Chapter 1

Forward

This book started as a series of notes for a general, survey-level university class I teach on the Apollo lunar missions at the University of Washington in Seattle. While the literature covering the Apollo missions is shelf-saggingly massive, I have never found a text that covers the material I want to teach, at the appropriate level. So I wrote this book, focusing on just one aspect of the Apollo missions –the one aspect I do not think gets enough attention: the story that the *samples* collected on the surface tell us about the Moon.

The main protagonists in this story are the samples returned from the lunar surface. These fantastically complicated characters get little respect outside of the technical literature, which is unfortunate, since I believe their story is every bit as interesting, and far older, than any other story in the Apollo program. There is no way I could do justice to all of the samples collected by Apollo in so short a book, so I am only going to tell the story of *one* sample from each mission. I chose these samples to fit my story, not because they are the most important, or the most representative, or even the most well-known sample from each mission.

The fact that I am only covering one sample from each mission means that I am only going to discuss the part of each mission that directly concerns that one sample. In most cases this means that we will be looking at only a few minutes of work on the lunar surface for each mission.

The dialogue between the astronauts and Mission Control back on Earth plays an important part in this story. The dialogue of the astronauts on the lunar surface will be set off like this:

> `109:24:13` **CDR**: I'm going to step off the LM now.
> `109:24:48` **CDR**: That's one small step for man; one giant leap for mankind.

The time stamp in front of each line is the Mission Elapsed Time (MET), or the time since lift-off from the Earth (`H:M:S`). The speaker is identified by their role on the mission. **CDR** is the mission Commander, leader of the mission and first one on the surface of the Moon. **LMP** is the Lunar Module Pilot, the other astronaut on the surface. **CMP** is the Command Module Pilot, the astronaut keeping station in lunar orbit. **CAPCOM** is the Capsule Communicator, an astronaut on Earth in Mission Control who is usually the only one in direct contact with the astronauts on the mission. In this example, the commander of Apollo 11, Neil Armstrong, speaks his famous lines 109 hours, 24 minutes, and 48 seconds after the lift-off of Apollo 11.

I should say a few words about the names, or rather, *numbers*, of my main characters. All of the Apollo samples were assigned a five-digit number by the Lunar Sample Preliminary Examination Team (LSPET). This number is called the *generic sample number*.

For the first four missions (Apollo 11, 12, 14, and 15), the first two digits identify the mission[1], and the final three digits identify the specific sample. For example, `12033` is sample `033` from Apollo 12.

For Apollo 16 and 17, the initial `1` is dropped and the second digit refers to the specific location (called a station) where the sample was collected[2]. For example `72535` is sample `535` collected by Apollo 17 at collection site `2`.

Sources

This book is entirely based on the work of others. I have tried my best to be complete and up-to-date in referencing all of my sources. Any omissions are unintentional and completely my fault. There are a few sources that I used extensively throughout this book. Really, without these, this book would not exist:

- Don E. Wilhelms, *To a Rocky Moon — A Geologist's History of Lunar Exploration*. [`http://www.lpi.usra.edu/publications/books/rockyMoon/`] This is the story of the scientific exploration of the Moon by one of the scientists deeply involved with the Apollo project. What could be better? My class on the Apollo missions is based largely on this book. Wilhelms' book is now available for free online, so there is no excuse not to read it.

- *Apollo Lunar Surface Journal*. Edited by Eric M. Jones and Ken Glover. [`http://www.hq.nasa.gov/office/pao/History/alsj`] This is an amazing online resource. It offers the complete documentation of the surface activities of the Apollo missions. Not only does it bring together a massive volume of the Apollo literature and images in one place, but the editors have added extensive commentary by themselves and by ten of the twelve moon-walking Apollo astronauts.

[1] The digits 10 are used to identify the samples from Apollo 11

[2] Actually, the last three digits of the sample number from Apollo 16 and 17 contain information about the type and size of the sample. For a complete explanation of the sample numbers, see page 10 of [32]

Images

I am continually astounded by the fact that nearly every image taken by the Apollo program is available in high-resolution online. I could not imagine trying to put this book together in the pre-Internet age. The main online archives I used for this book were:

- *Apollo Lunar Surface Journal* (see above). The most complete source for images taken by the astronauts on the surface of the Moon.

- *Lunar Sample Atlas*. Lunar and Planetary Institute. [`http://www.lpi.usra.edu/lunar/samples/atlas/`] My source for all of the images of the samples in the Lunar Receiving Laboratory.

- *USGS Geologic Atlas of the Moon*. U.S. Geological Survey. [`http://www.lpi.usra.edu/resources/mapcatalog/usgs/`] My source for the geological maps.

- *Lunar Reconnaissance Orbiter Camera*. Arizona State University. [`http://www.lroc.asu.edu/images/index.php/`] A high-resolution mapping camera currently in orbit around the Moon. This is my main source for the large-scale images of the Moon and the high-resolution images of the Apollo landing sites. The exploration of the Moon did not end with Apollo.

Toby Smith, Seattle - January 2014

Chapter 2

Introduction

On Display

On September 17, 1969, the first public display of a rock returned from the Moon took place at the Smithsonian Institution in Washington, D.C. The excitement of seeing this Moon rock must have been tempered by the realization that the rock itself was an aesthetic disappointment. Nothing glowing. No colors, no shiny crystals. An official at the time described it as “Not dark or light grey, just grey grey.”[65] A month later, another lunar sample went on display at the American Museum of Natural History in New York City and 42,195 people filed past it on its first day of display.[66] “It looks like a piece of something you could pick up in Central Park”[26] was a typical reaction to the rock’s appearance.

Adding to the underwhelming appearance of the rock was the fact that these samples were far from the first extraterrestrial rocks that had been seen by the public. Meteorites have been falling to the Earth for the last 4.6 billion years. Both the Smithsonian and the American Museum of Natural History house world-class meteorite collections, each containing hundreds of samples from worlds much farther away than the Moon. Many of these meteorites are also far more visually striking than the lunar samples. However, those particular samples brought back to the Earth by the crew of Apollo 11 have one very important characteristic that *all* the meteorites lacked: **context**. We know *where* these rocks came from; we know their relation to a specific place on the Moon. These rocks tell a *story*. A story about a specific place on the Moon at a specific time. A story that led to a fundamental new understanding of the worlds in our solar system.

2,415 samples were returned from the Moon by six Apollo missions. This book is the story of just six of those 2,415 samples — one from each mission. The story they tell covers 4.6 billion years of history. It covers a time that is all but lost to us on the Earth, due to the ever-changing nature of the Earth’s crust. Most importantly, it is a history that is shared by the worlds around us — Mercury, Venus, Earth, and Mars — and, with some important caveats, shared by all of the worlds in our solar system.

Book Title

Seven Apollo missions were sent to land on the Moon, six landed, and one came back home safely without landing. The story of Apollo 13 is now so famous, via books and movies, that it need not be repeated here. The loss of the Apollo 13 lunar landing meant, among many other far more important things, that the best mission patch of the Apollo program did not land on the Moon (Figure 2.1). I have always considered the Apollo 13 patch the cream of the Apollo emblems for two reasons. The first reason is for what the patch *does not* say. Like the Apollo 11 patch, the Apollo 13 patch lacks the names of the three astronauts, a wonderfully ego-free gesture that illustrates that the Apollo programs were always about more than just the astronauts. Michael Collins, the Command Module Pilot of Apollo 11, put it perfectly in his book *Carrying the Fire*[16], still my favorite book written by an astronaut:

Figure 2.1: The mission patch of Apollo 13 (NASA S69-60662)

> We wanted to keep our three names off it because we wanted the design to be representative of *everyone* who had worked toward a lunar landing, and there were thousands who could take a proprietary interest in it, and yet who would never see their names woven into the fabric of the patch.

The second reason for the awesomeness of the Apollo 13 patch is for what is *does* say. On the left side of the patch is the Latin phrase *Ex Luna, Scientia*, meaning *From the Moon, Knowledge*. There is no better three-word summary of the scientific results of the Apollo missions.

My Goals

The story that the lunar samples tell us, is a story teased out by countless scientists in labs all over the world.[1] It is a story that is still being written over forty years after the first Moon landing. And it is a story that will continue to be revised, and possibly completely rewritten, by a generation of scientists who were not yet born during the Moon landings; new techniques continue to dig new stories out of the samples. This book will only touch on an infinitesimal fraction of the scientific work done on the Moon rocks; my main goal is that the book will give readers some small idea of how the story of the history of the Moon was put together.

[1] For a nice summary of the scientific teams involved in the initial investigation of the Apollo samples, see Chapter 1 of *Lunar Science: A Post-Apollo View* [79].

I do have another goal for this work, and that is to bring a little bit of interest back to the lunar samples, at least for my students who are forced to read this book. Barely four years after the end of the Apollo mission, the luster of the Moon rocks had already dulled:

> They were rock celebrities five years ago. People traveled hundreds of miles to see them. Politicians cozied up to be photographed beside them. Volumes were written about them. They were studied, oohed, analyzed and aahed. But as usual, Americans proved fickle ... everybody knows they're around but nobody cares.[77]

I witness this attitude towards the Moon rocks every time I visit my favorite local museum. The Museum of Flight[2] in Seattle, Washington, has a fantastic collection of Apollo mission artifacts, including a Moon rock (Figure 2.2). The sample `12047` is a piece of volcanic basalt picked up by the Apollo 12 astronauts near the end of their mission. The sample is tucked away in a wall display near the entrance to the hall containing a life-sized model of the ascent stage of the lunar module. As I watch people walk into the room, I notice that the Moon rock display gets barely more than a very occasional, cursory glance. Since I cannot stand by the sample, carnival-barker-style, all of the time, writing this book will have to do.

Figure 2.2: Lunar sample `12047,6` on display at the Museum of Flight, Seattle, Washington [NASA S92-44066].

Location, Location, Location

The samples collected by the six Apollo missions come from a very small subset of the total surface area of the Moon.

How the actual landing sites of the Apollo missions were selected is a very rich and colorful story full of clashing interests and egos.[3]

The Moon is big, but for a variety of reasons the area of the Moon accessible to the Apollo missions was very small. All six missions landed in the center of the near side of the Moon, all within 20 degrees of the lunar equator (Figure 2.3). Yet, as we will see, from this restricted area comes a surprisingly diverse collection of samples. While the samples themselves may be monochromatic, the story they tell is not.

[2] `http://www.museumofflight.org/`

[3] By far the best accounts of the Apollo landing sites selection process can be found in Don Wilhelms' book *To a Rocky Moon* [87].

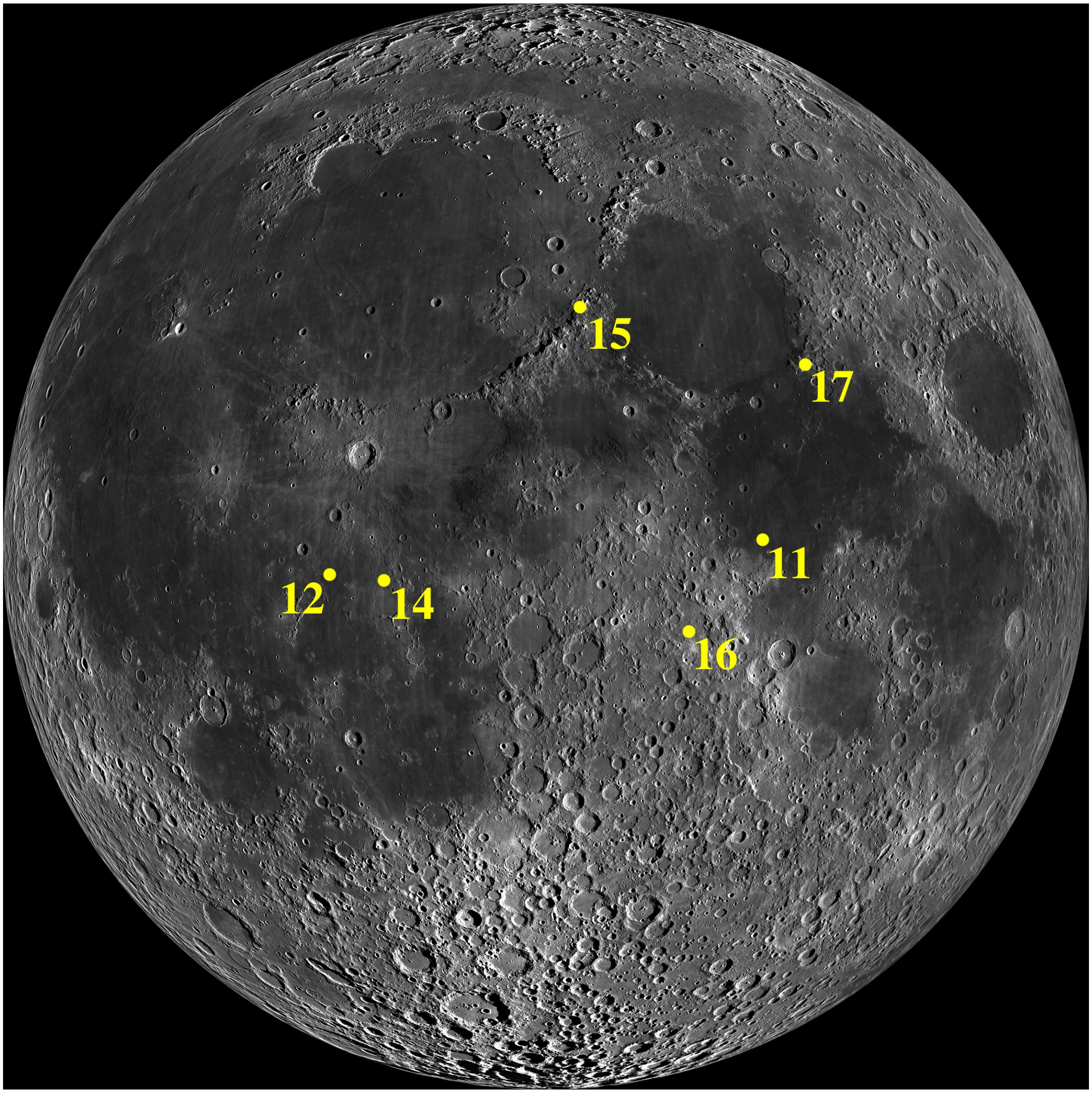

Figure 2.3: The landing sites of the six Apollo lunar missions. The base image is from the Lunar Reconnaissance Orbiter Wide Angle Camera (LROC WAC) mosaic of the lunar near side [NASA/GSFC/Arizona State University].

Chapter 3

Apollo 11

Mare Tranquillitatis

It only takes a casual glance at the full Moon to notice that the Moon does not have a uniform surface. There are regions that appear dark and smooth, and regions that are brighter and rougher looking. The dark, smooth regions are referred to as *maria* (singular: *mare*) after the Latin word for seas. The brighter, rougher surfaces go by many different names in the scientific literature; I will use the term *highlands* for these surfaces.

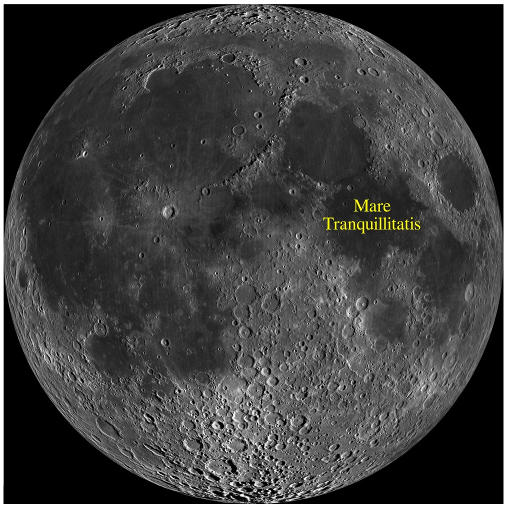

Figure 3.1: Location of Mare Tranquillitatis [NASA/GSFC/Arizona State University].

If you are going to attempt to land on the Moon for the first time, the large, smooth, flat, mare surfaces present a much more inviting target than the rough highlands. It takes less fuel to land near the lunar equator. Plus, landing on the eastern part of the lunar surface allows the use of more westerly sites as backups. (The lunar module travels east to west in orbit around the Moon.) An eastern mare site near the equator fulfilled all of the requirements for the initial landing on the Moon. The particular eastern mare surface near the equator that was chosen for Apollo 11 to land on is called *Mare Tranquillitatis*, the Sea of Tranquility (Figure 3.1). Safety and accessibility are the main criteria for choosing the early Apollo sites.

Apollo 11 landed near the southwest edge of *Mare Tranquillitatis*, about 75 km from where the mare surface laps up against the underlying highlands. As you can see in Figure 3.2, there is little to distinguish the landing site from any other piece of *Mare Tranquillitatis* within 100 km. The uniform nature of the Apollo 11 site means that the geological history of this site will be easier to figure out than that of most

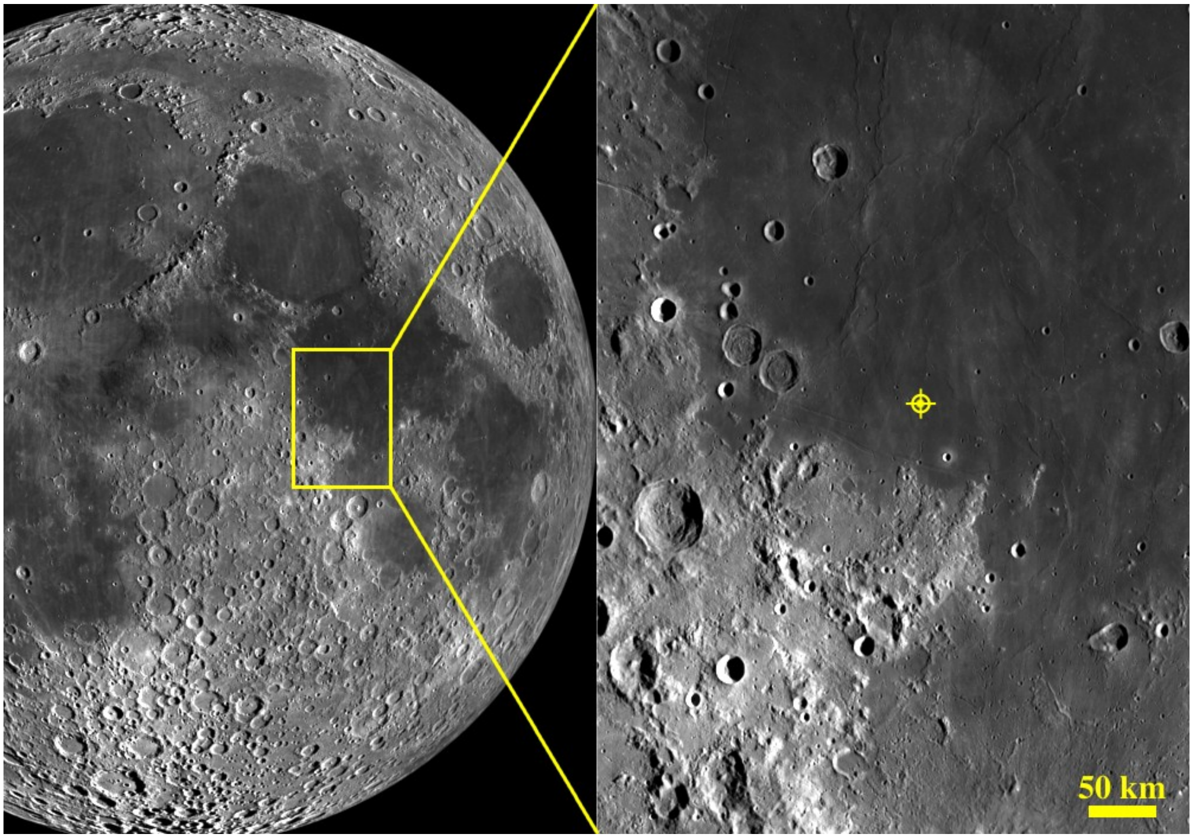

Figure 3.2: The context of the Apollo 11 landing site in the Sea of Tranquility. Both images are from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

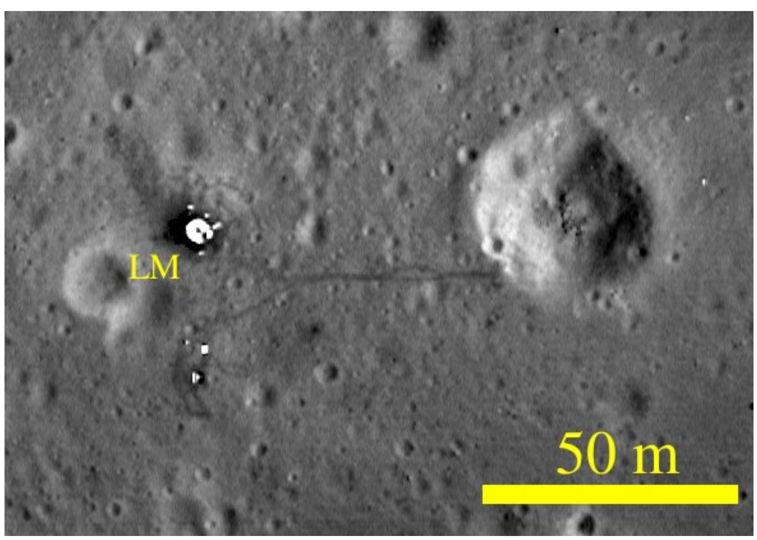

Figure 3.3: A high-resolution, recent (Nov 5, 2011) image of the Apollo 11 landing site. The lunar module is labeled `LM`. The footprints of the astronauts are clearly visible. The patch of disturbed ground to the upper left of the lunar module is where the astronauts spent most of the EVA. LROC M175124932R [NASA/GSFC/Arizona State University].

other Apollo sites.

No mission to the Moon is more famous than Apollo 11, and no mission spent so little time on the surface of the Moon. All told, the Apollo 11 astronauts spent a little over two and a half hours exploring the lunar surface. In those few hours, they explored an area that is roughly equivalent to the infield of an American baseball diamond (Figure 3.3). This small area of exploration meant that nearly all of the samples collected shared a very similar geological history.

Geological Setting

Before each of the Apollo missions, scientists created maps of the landing sites. These maps, called *geological* maps, not only identified features, but also expressed how the scientists believed the surfaces had formed, indicated what types of rocks the scientists thought the astronauts would find, and gave some indication of how the scientists thought these surfaces fit into the history of the Moon. In a sense, the geological map is a pictorial representation of all the hypotheses scientists had about the site. Visiting the sites was the experiment done to determine the validity of those hypotheses.

The geological map that includes the Apollo 11 landing site (Figure 3.4) is dominated by one color: pink. This was the scientists' way of expressing that they believed that the site was dominated by one geological unit — a unit with a common origin, history, and composition. This geological unit is referred to in the geological map as *flat mare material*. They characterized it as *Albedo low compared to most other units...Surface level and relatively smooth at telescopic resolution.* In other words, it was a smooth, dark surface.

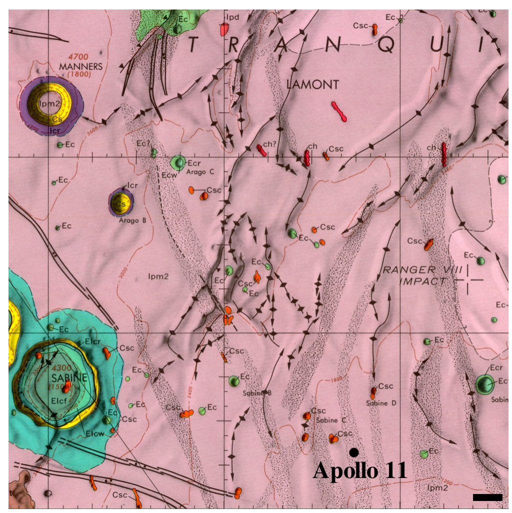

Figure 3.4: A detail of the geological map of the Apollo 11 site [59]. The black bar is 10 km.

In most of the geological maps we will see, shades of red are usually used for volcanic features, so the pink color that dominates the map indicates that the scientists believed that this flat mare material had a volcanic origin. The origin of this unit was postulated to be *volcanic materials: flows or ash beds, or both ... Albedo differences probably reflect differences of age or composition of the uppermost layer only.* This interpretation implies that the scientists believed that the first samples returned from the Moon would be volcanic material — material from a surface that had once been geologically active.

Scientists have long believed that mare surfaces, like Tranquility, were formed when lava flowed across a portion of the Moon, covering over a previously formed surface. The fact that they covered over an older surface implies that these mare surfaces are relatively young compared to the surface they covered. The determination of the relative ages of surfaces based on their vertical relationships is called the *Principle of Superposition*. Nicholas Steno, a seventeenth-century physician, is first credited with stating this simple but powerful geological principle. He wrote that ... *at the time when the lowest stratum was being formed, none of the upper strata existed.* Or in its modern restatement: Young formations overlap old formations.

The superposition of the mare surfaces implies that they are young. Just what *young* means in this context is the main point of this chapter.

The Contingency Sample

About ten minutes after first stepping onto the lunar surface, Neil Armstrong reached out with a scoop and, in about three minutes, collected a small (492 g, just over one pound) sample of rocks and soil which he immediately placed in a pocket on the thigh of his spacesuit (Figure 3.5). This sample was called the contingency sample, the idea being that if the astronauts had to leave immediately, they would not go home empty handed.

> `109:33:25` **LMP**: Okay. Going to get the contingency sample there, Neil?
> `109:33:27` **CDR**: Right.
> ...
> `109:34:09` **LMP**: Looks like it's a little difficult to dig through the initial crust ...
> `109:34:12` **CDR**: This is very interesting. It's a very soft surface, but here and there where I plug with the contingency sample collector, I run into a very hard surface. But it appears to be a very cohesive material of the same sort. I'll try to get a rock in here. Just a couple.
> ...
> `109:37:00` **CDR**: Contingency sample is in the pocket.

Sample Documentation

The exact location and orientation of the contingency sample is known. This sort of information is very important to scientists. Knowing what part of the rock was exposed to space, and what part of the rock was in contact with the surface, opens up a whole new set of questions scientists are able to explore. The location and orientation of a sample is called the **documentation** of the sample.

Samples for which the location and orientation are well known are called *well documented*. The documentation of the contingency sample was unusual; most of the Apollo 11 samples were not documented. [74]:

> ...time was not available for the astronauts to document, by planned procedures, the localities from which the specimens were collected. A critical effort

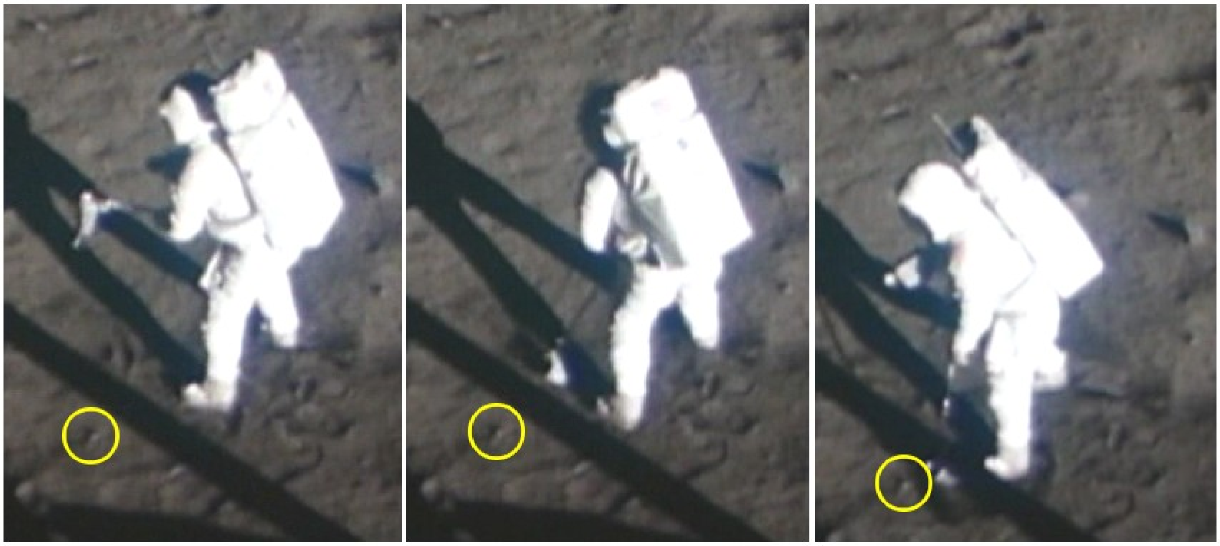

Figure 3.5: The collection of sample 10022. The sample is indicated by the circle in each frame. The images are frames from the 16mm data acquisition camera mounted in the lunar module [NASA].

> of the experiment team, therefore, has been an attempt to discover the specimen localities by using photographs taken for other purposes.

We shall see that the level of sample documentation increased over the course of the Apollo program, as the time spent on the Moon and the time spent training the astronauts to be field geologists increased.

The main character of this chapter was collected in that first scoop of the contingency sample. Its location and orientation were determined by comparing images taken before and after the astronauts worked on the lunar surface (Figure 3.6).

In amongst this contingency sample was an irregular dark rock about 4 cm across, that the scientists in the Lunar Receiving Laboratory in Houston designated 10022. 10022 is a 95.6-gram piece of volcanic basalt that looks exactly like your garden variety piece of Earthly volcanic rock (terrestrial basalt). However, the story this sample tells is far different from the story told by its Earthly counterparts.

Sample Appearance

The naked-eye appearance of the 10022 tells us a couple of interesting things (Figure 3.7). First of all, the sample is vesicular. The term *vesicular* refers to the large number of millimeter-sized spherical pits on the surface of the sample. These pits or *vesicles* are small cavities that were formed when gas (mostly CO_2) came out of the molten magma and expanded while the rock cooled and solidified. The presence of vesicles tells us that

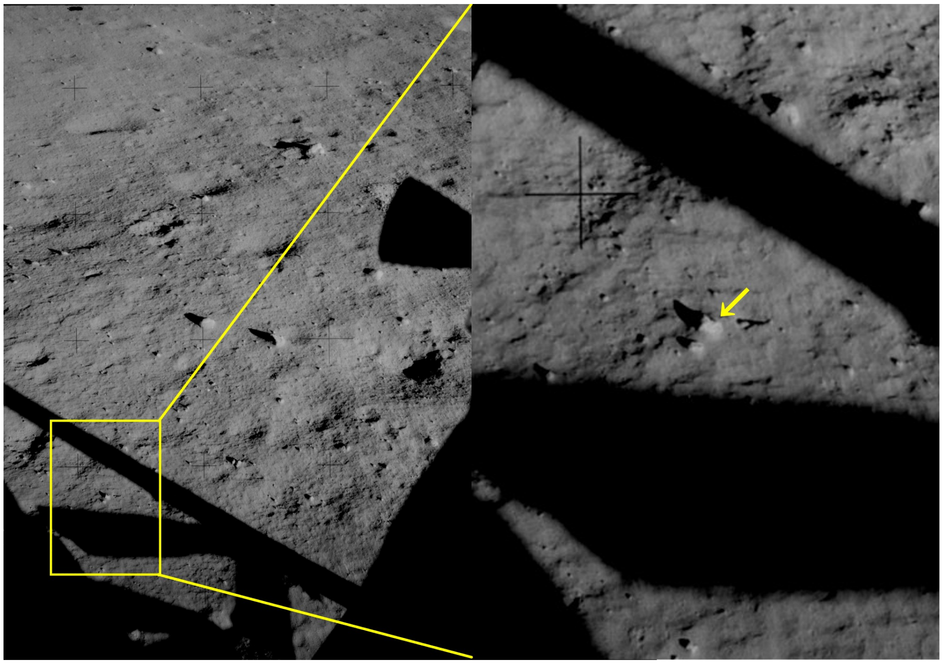

Figure 3.6: The location of sample 10022. The arrow indicates the sample 10022 in its context on the surface of the Moon before collection. The shadows are caused by the legs of the lunar module. [NASA AS11-39-5777]

this sample cooled under relatively low pressure, meaning at (or very near) the surface of the Moon.

Another property of 10022 that is easily observable is that it is a fine-grained rock. *Fine-grained* refers to the fact that the crystals of the minerals that make up the sample are very small, much less than a millimeter across. These small crystal sizes are an indication that the sample cooled quickly, further evidence that 10022 formed very near or at the surface of the Moon.

Both the vesicles and the small crystal sizes suggest that 10022 represents a sample from the top of the lava flow that covered *Mare Tranquillitatis*. It is a perfect sample to study if you want to know *when* this flow occurred.

Radiogenic Age

The most striking difference between 10022 and a fine-grained vesicular basalt from a lava flow on the Earth is its **age**. Remember, the lava flow that Apollo 11 landed on was interpreted to be relatively young. But what does *young* mean in this context?

One quick aside about what is meant by *age*. The age of a rock is really just a measure of how mush time has elapsed since the rock cooled to become a rock, not how long the material has been around. The vast majority of material on the Moon has been around the same amount of time, about 4.6 billion years. If you take any rock, melt it, and let it cool back to a rock, it will be a new rock, with its age clock reset to zero years old.

The first scientific results from the study of the Apollo 11 samples were published in a special issue of the journal *Science* on January 30, 1970[1], only six months after the samples were returned from the Moon. This is about as close as you could get to instantaneous publication in science back then. On page 466 of that issue is a paper entitled *Argon-40/Argon-39 Dating of Lunar Rock Samples.*[81] This paper was the first study to determine the age of 10022.

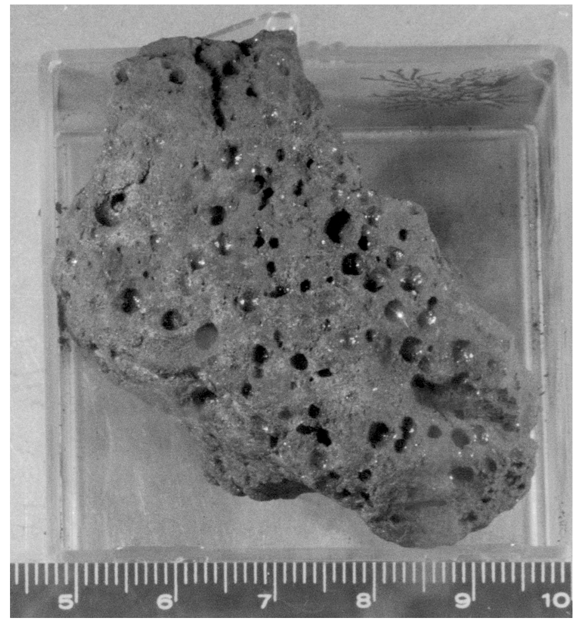

Figure 3.7: Photo of 10022 in the Lunar Receiving Laboratory. The scale at the bottom is in cm. [NASA S69-45209]

To determine the age of rock, geologists use a technique called *radioactive dating*. This technique relies on the fact that some elements in the rocks spontaneously change into other elements at a well-defined rate. (Some elements in a sample are more stable than others, and if nature gives the unstable elements a path to become more stable, they will take it.) This spontaneous change is called *radioactive decay*. The age that is determined using this technique is referred to as the **radiogenic age** of the sample.

To determine the radiogenic age of 10022, scientists placed a small piece of 10022 (about 100 mg) into a nuclear reactor for two days. This process transformed all of the solid Potassium-39 in the sample into the gas Argon-39. The sample was then heated to release all of its Argon gas. By measuring the amount of Argon-39 (formerly Potassium-39) and Argon-40 released, and by knowing the rate that Potassium-39 decays into Argon-40, this technique was able to determine how long it has been since 10022 was last molten — when 10022 became the rock that Neil Armstrong picked up.

The radiogenic age of 10022 is 3.59 billion $\pm$ 0.06 billion years old.

This means that the lava flow that formed Apollo 11's landing site solidified 3.59 billion years ago. This is really old! The *young* surfaces on the Moon are really old compared to almost any surface on the Earth.

The histogram in Figure 3.8 shows the relative abundances of rocks of different ages on the Earth's surface. You can see that there are two peaks. The younger peak, at about 0.2 billion years ago, represents the oceanic crust; the older peak, at about 1.6 billion years ago, represents the older continental crust. Notice that there are very few rocks on the Earth that are older than about 2.5 billion years old, and almost none older than 3 billion years old. Our young lunar sample 10022 is older than nearly every rock on the surface of the Earth. The very ancient age of the young lunar basalts may be the most fundamentally important result of the study of the samples from the Apollo 11 mission:

> Perhaps the most exciting and profound observation made in the preliminary examination is the great age of the igneous rocks from this lunar re-

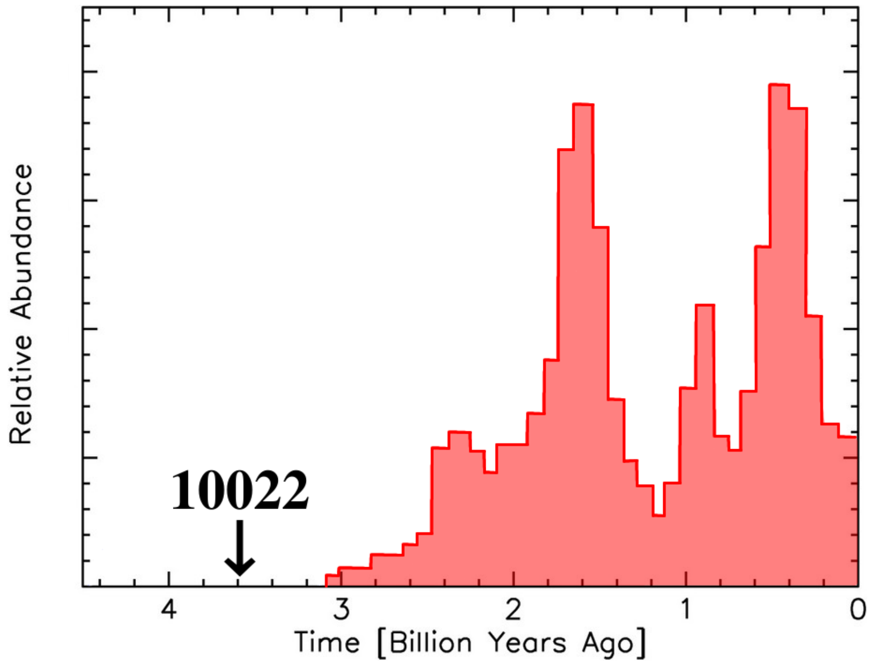

Figure 3.8: Histogram of the ages of the Earth's crustal rocks (red).

> gion...there is a very good chance that the time of crystallization of some of the rocks returned by Apollo 11 may be earlier than that of the oldest rocks found on Earth. It seems quite likely that if the rocks from Apollo 11 do not take us back to the time of formation of our sister planet, then rocks from other regions on the moon will[50].

The sample 10022 shows that the Moon was once geologically active, and that that activity happened a long time ago. The fact that this lava flow has not been covered by another geological layer means that after this activity 3.59 billion years ago, not much has really happened. The Moon is ancient and still preserves this very early history — a piece of history that has long since been erased from the surface of the Earth. This is a theme that I am going to keep coming back to in this book: If you want to know about the very early history of planetary surfaces, look to the Moon.

Chemistry

Another characteristic, besides age, that distinguishes a lunar basalt from a terrestrial basalt is its chemistry, the relative abundance of elements and compounds that comprise the rocks. The differences in chemical properties can lead to important differences in the physical properties of the rocks; those differences in chemistry can give us some important clues to the rocks' origin and history as well.[1]

[1]This is really just the barest overview of the chemistries on lunar basalts. Chapter 8 of the *Lunar Sourcebook* [32] treats this topic in all the gory detail it deserves.

Table 3.1 shows the chemical abundance of a few important compounds in 10022 and provides the ranges of abundances found in lunar and terrestrial basalts.

	10022	Lunar Basalt	Terrestrial Basalt
H_2O	0.0	0.0	0.9 – 1.3
SiO_2	40.1	38 – 48	45 – 55
TiO_2	12.2	0.4 – 13	0.5 – 2
FeO	18.9	16 – 22	5 – 14

Table 3.1: The chemistry of 10022 compared to the ranges in values for lunar and terrestrial basalts [wt.%]. Values for 10022 from [69], lunar basalt ranges from [32], and terrestrial basalt ranges from [22].

As you can see, their chemistries are quite different. First off, all lunar basalts are bone-dry. They utterly lack water (H_2O) and show no evidence of having been altered in any way by water in the past. By contrast, terrestrial basalts can commonly have up to or over 1% of the total mass of the rock (1 wt. % H_2O) be water-rich or water-altered minerals. There are very few basalt samples on the Earth that have not interacted with water at some point in their history. No lunar basalts (10022 included) have interacted with water in their history; they all have 0.0 wt. % H_2O.

Another couple of important chemical differences are that lunar basalts generally have less silicon-rich minerals (SiO_2) and more titanium-rich and iron-rich minerals (TiO_2, FeO) than terrestrial basalts. 10022 in particular is very rich in TiO_2, a characteristic it shares with most of the basalt samples from Apollo 11.

Albedo

It is very easy to pick out the lava flows on the near side of the Moon. The lava flows (mare surfaces) appear dark compared to the rest of the lunar surface. The percent of light that is reflected from a surface is called its **albedo**. Mare surfaces on the Moon reflect between 7% and 11% of the light that hits them (Albedo 0.07 - 0.11).[23] By contrast, the brighter lunar surfaces have albedos between 0.12 and 0.18.

The mare surface that 10022 comes from, *Mare Tranquillitatis*, is really dark. It has an albedo of 0.07, low for mare surfaces on the Moon. This low albedo is a consequence of the very high TiO_2 abundance of the *Mare Tranquillitatis* basalts like 10022. The reason that a high abundance of TiO_2 in these basalts results in very low albedo is that TiO_2 primarily occurs in the mineral ilmenite ($FeTiO_3$). Ilmenite is a dark, opaque mineral; even in small amounts ilmenite can lower the albedo. Since 10022 has one of the highest abundances of TiO_2 of any lunar basalt sampled, it makes sense that *Mare Tranquillitatis* has a very low albedo.

This connection between albedo and composition is an important one, as it tells us about surfaces that were not visited by the Apollo missions. Of course we have to be careful, as composition is not the only variable that determines the albedo of a lunar surface.

Viscosity

A typical mare on the Moon is larger than a typical mare on the Earth. (Of course, there have been extremely large lava flows on the Earth. The Earth has been far more geologically active than the Moon. For example, the Deccan Traps in India are estimated to cover an area of at least 1,500,000 km^2.) The area that is cover by the *Mare Tranquillitatis* lava flow is approximately the size of the state of California[86] (*Mare Tranquillitatis* is about 436,000 km^2, California is about 423,971 km^2.) This is much larger than the area covered by even large volcanoes on Earth, such as Mauna Kea in Hawaii. *Mare Tranquillitatis* is big, but it is far from the largest mare region on the Moon. The large extent of the lava flows on the Moon is in part due to the fact that lava on the Moon flows very easily compared to terrestrial lava. The property that characterizes how easily a liquid flows is called *viscosity*.

To determine the viscosity of lunar lava, you would need to completely melt a sample of lunar basalt. Since completely destroying an Apollo lunar sample is not a good option, the viscosity of lunar lava was determined by making an analogous laboratory lava based on the chemical composition of 10022.[85] The viscosity of 10022 lava is a factor of 10 lower than the viscosity of typical terrestrial basalt. This means that even a modest amount of lunar volcanism can cover a lot of ground. The low viscosity of the 10022 lava is believed to be a consequence of the low SiO_2 abundance, a chemical property that is common to all lunar basalts.

Rare Earth Elements

We saw that the radiogenic age of 10022 was determined by sticking a small piece of 10022 in a nuclear reactor. The age of a sample is not the only information you can learn by placing a sample in a nuclear reactor. One can also accurately determine the quantities of elements that occur in only minute amounts.

One of the most important pieces of data that comes from using this technique on lunar samples, is the abundance of rare earth elements. The rare earth elements are a set of seventeen chemical elements that hang out in one of the bottom two detached rows on the periodic table (Figure 3.9). Rare earth elements are actually relatively common in the Earth's crust, but are usually found dispersed throughout a sample, rather than concentrated in minerals. It was their rarity in minerals that led to the term *rare earth*.

While knowing the amount of rare earth elements in a sample is interesting, it is much more informative to know the ratio of the abundances in a sample to the abundances of a well-known standard. The well-known standard that is almost always used is a type of meteorite called a *C1 chondrite*.[6] These meteorites are composed of materials that

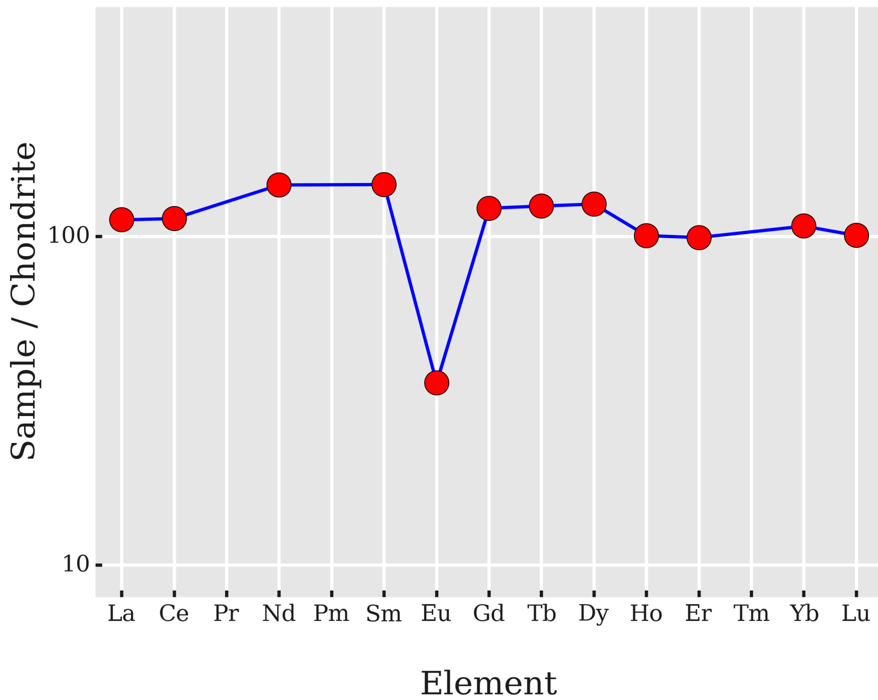

Figure 3.10: The abundance of rare earth elements in the sample 10022. The abundances are plotted relative to the abundances in chondrite meteorites.

have not been significantly altered over the age of the solar system. This type of unaltered material is called *primitive*. The chemical composition of primitive C1 chondrites is a very close match to the atmosphere of the Sun, and can be thought of as representing the average composition of the solar system. By comparing the abundances in a sample to the abundances in C1 chondrites, you are essentially comparing the sample's abundance to average solar system material.

Figure 3.10 shows the abundance of rare earth elements in 10022 relative to the abundance in C1 chondrites.[2] A couple of things are quickly apparent in the plot. One, rare earth elements are about 100 times more abundant in 10022 than in chondrites. Two, all of the rare earth elements in 10022 have about the same relative abundance except for the element europium (Eu). In 10022, europium is about 10 times less abundant than the other rare earth elements. This chemical signature will tell us something important about the origin of the material that formed 10022, but that story will have to wait for the collection of another sample in Chapter 6.

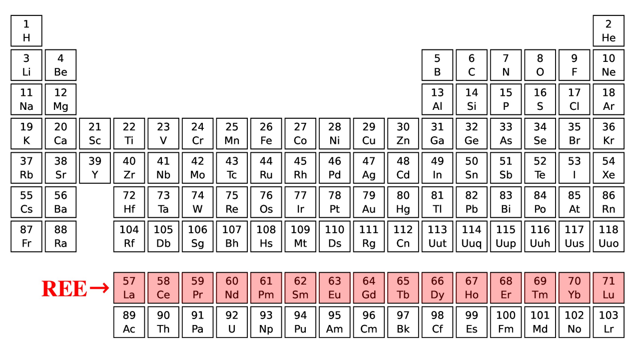

Figure 3.9: Periodic table of the elements. The rare earth elements are in red at the bottom of the table.

[2] The abundances were taken from [31].

The History of 10022

3.59 billion years ago, the *Mare Tranquillitatis* region of the Moon was geologically active. Low viscosity magma — rich in iron and titanium — flowed across the lunar surface. The outer surfaces of this lava flow cooled relatively quickly, creating a low-albedo, basalt-rich surface.

Since that time, not much has happened to this surface, other than the transformation of the uppermost surface to a fine powder by the continual rain of very small impactors.

About 380 million years ago (3.2 billion years after it was formed) a piece of this lava flow was broken off and exposed on the surface, probably by a small impact.

This piece sat undisturbed for hundreds of millions of years until it was collected on July 20, 1969.

This sample collected in **context** tells a specific story about a specific place on the Moon. Prior to the Apollo missions, we could not have told this story for any other world than the Earth However, this is just the beginning of the story that the Apollo samples will tell. The Moon is a complex place. One sample from one geologically simple landing site cannot tell the whole story of the Moon:[85]

> Igneous rocks returned from the maria surface hold many clues to the conditions of the moon's near-surface regions during their formation early in the moon's history. With the first Apollo 11 sampling it was appropriate to exercise caution in extrapolating these clues to moon-wide interpretations. Any terrestrial geologist is conscious of the futility of too much extrapolation from the study of one sampling somewhere on the earth's equatorial belt.

Chapter 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

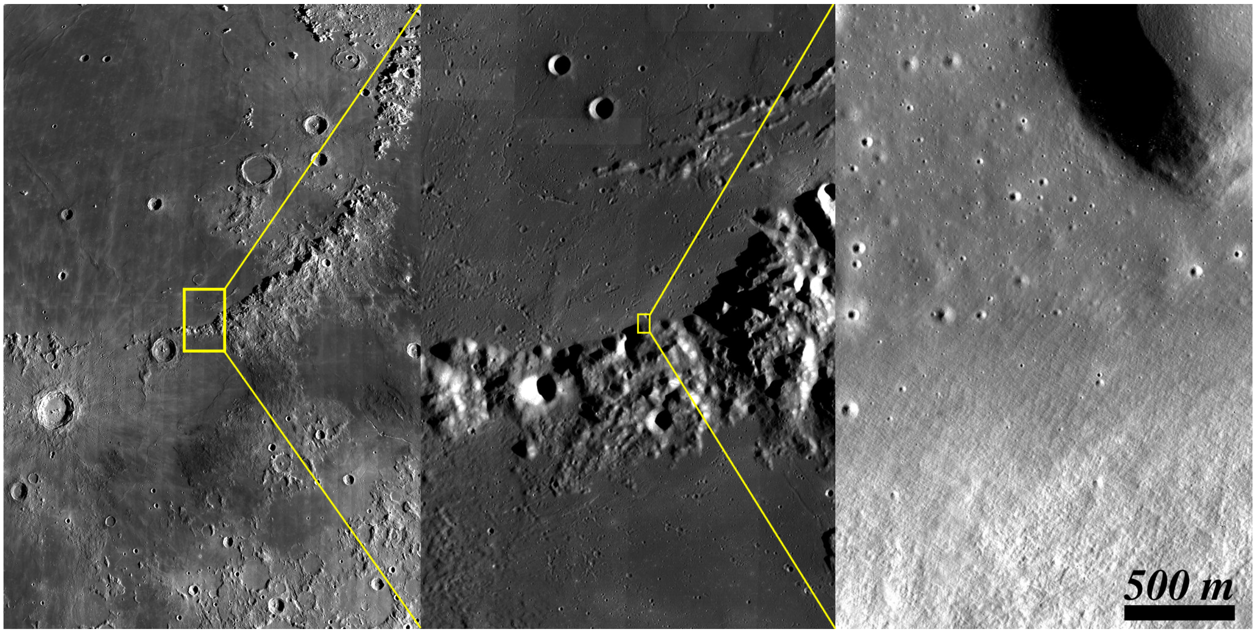

Figure 4.1: Three views of the southern rim of the Imbrium impact basin at increasing resolution. The first two images are from the LROC WAC mosaic of the lunar near side, and the last image is a detail from LROC NAC frame M1096543764LE [NASA/GSFC/Arizona State University].

the top of the Earth's atmosphere.[47] 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 ($\sim$ 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.

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: [87]

> 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.[32]

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.

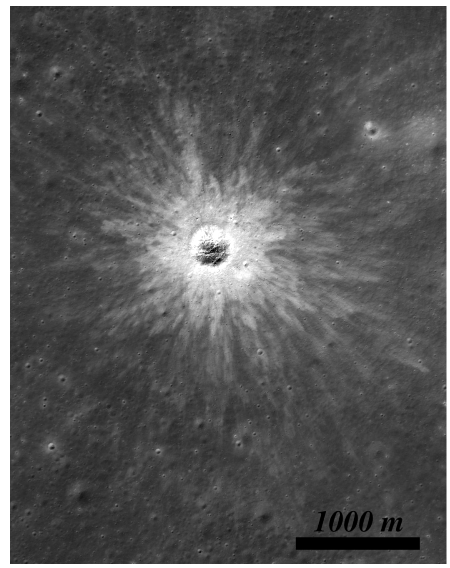

Figure 4.2: A fresh impact crater in the lunar highlands. The rays of ejecta are easily visible against the background. LROC NAC M1104423389 [NASA/GSFC/Arizona State University].

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.

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

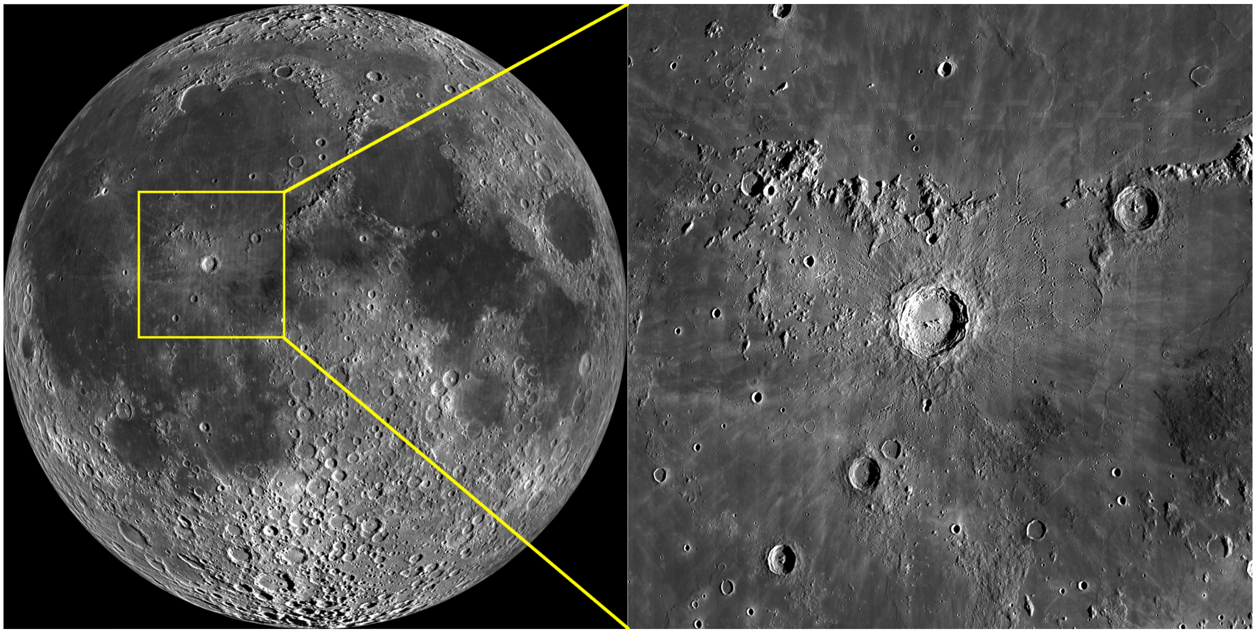

Figure 4.3: An image of the near side of the Moon, showing the context of the crater Copernicus. The inset is centered on the Copernicus crater. Both images are from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

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

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.[73]

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*

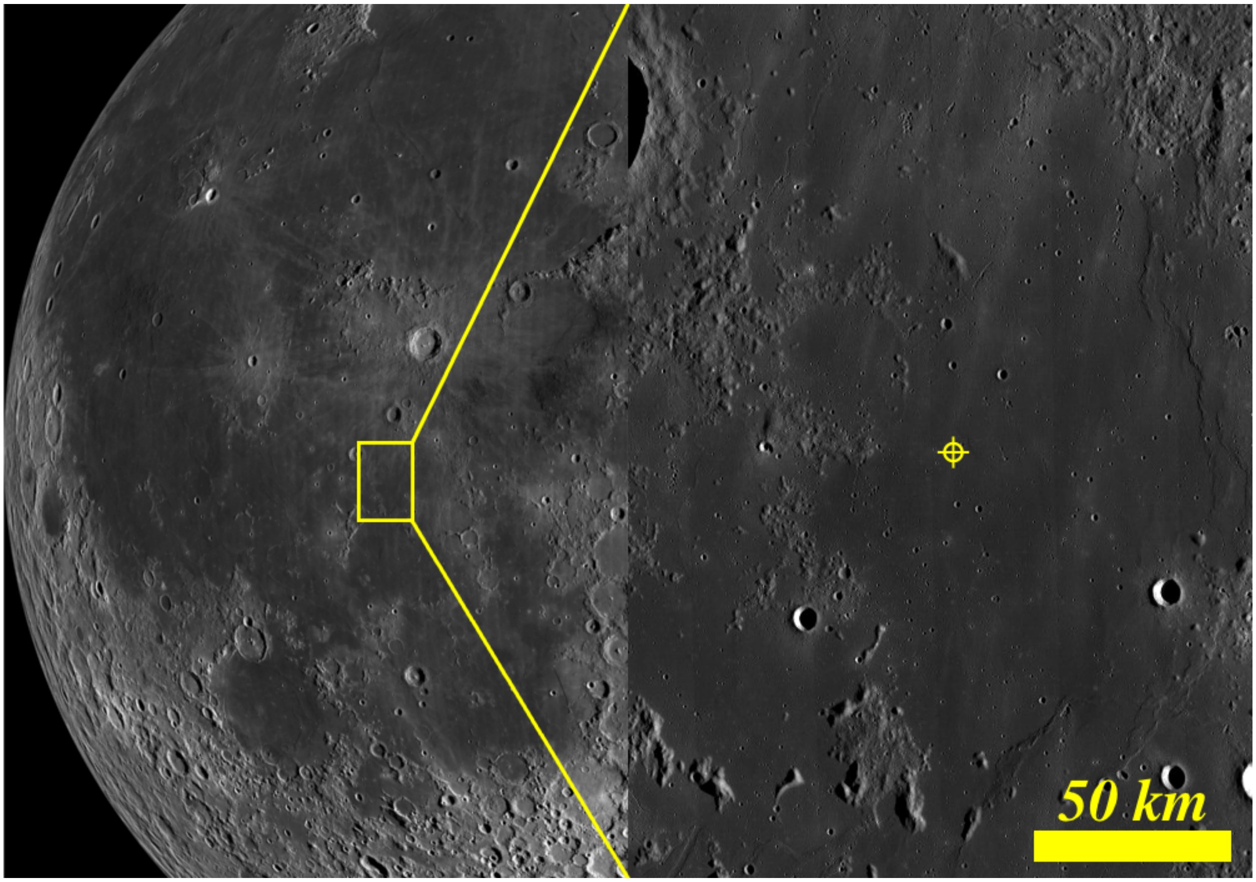

Figure 4.4: The context of the Apollo 12 landing site in the Ocean of Storms just south of the Copernicus crater. The rays from Copernicus can be seen as the higher albedo streaks running north–south in the image on the right. Both images are from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

mission crashed. [87] 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.

Geological Setting

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 4.4). 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 4.5) 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.[1]

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.

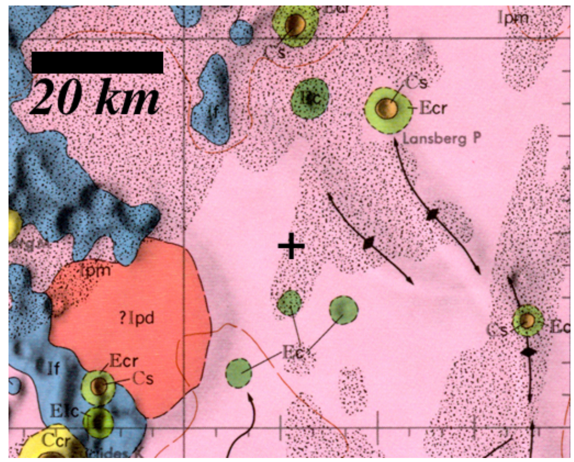

Figure 4.5: A detail of the geological map of the Apollo 12 landing site. The landing site of Apollo 12 is marked by the +. The black-stippled pattern represents material that we interpret as either a very thin blanket of Copernicus ejecta, or an area where the mare surface material has been disturbed by the downrange movement of material [21].

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* (Fig-

[1] 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 [29]. The science uncovered by this technique starts with [25] and continues to the present (*e.g.,* [93]

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

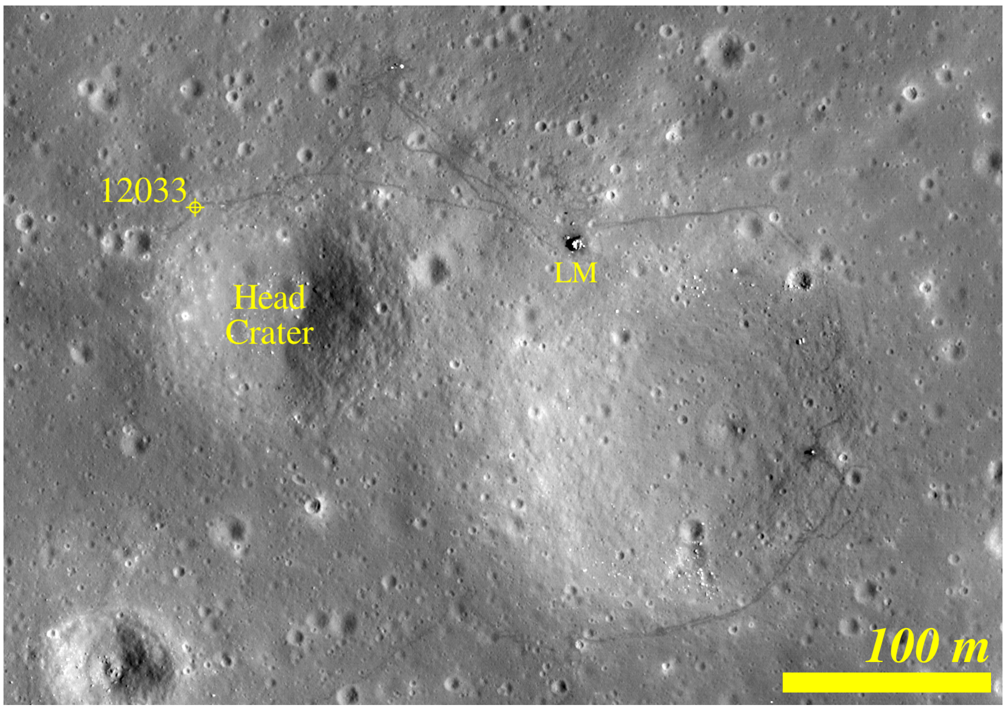

Figure 4.6: High-resolution image of the Apollo 12 landing site. The collection location of sample `12033` is marked on the northern rim of Head crater. The footprints of the astronauts are clearly visible. LRO NAC M175428601R [NASA/GSFC/Arizona State University

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.

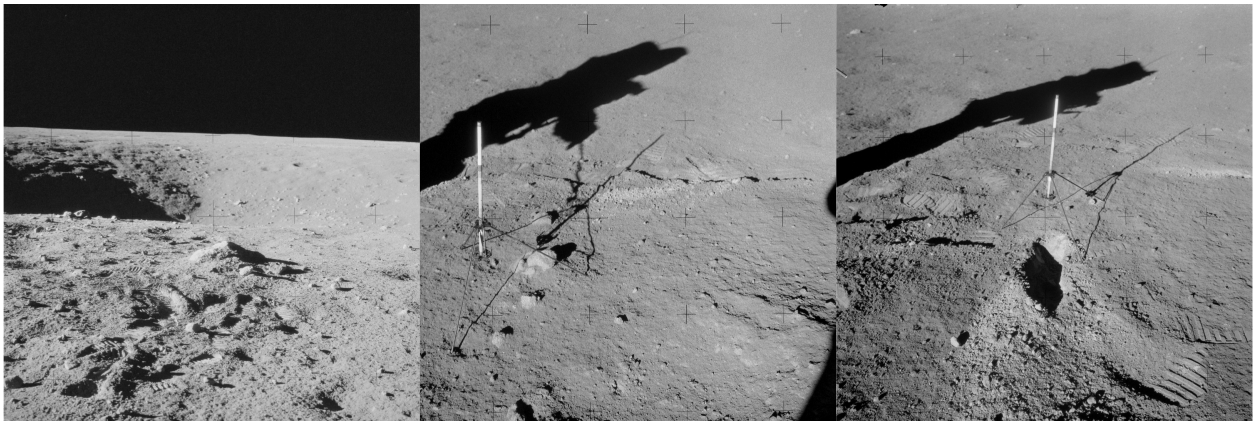

Figure 4.7: (Left) Image of the site at the top of Head crater, looking south across the crater. The sample 12033 will be collected near the mound in the foreground [NASA AS12-49-7183]. (Center) Getting ready to dig a trench and collect sample 12033. Note the footprints beyond the gnomon. These are the 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].

> . . .
> 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.
> . . .
> 132:25:0 **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:[83]

> 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

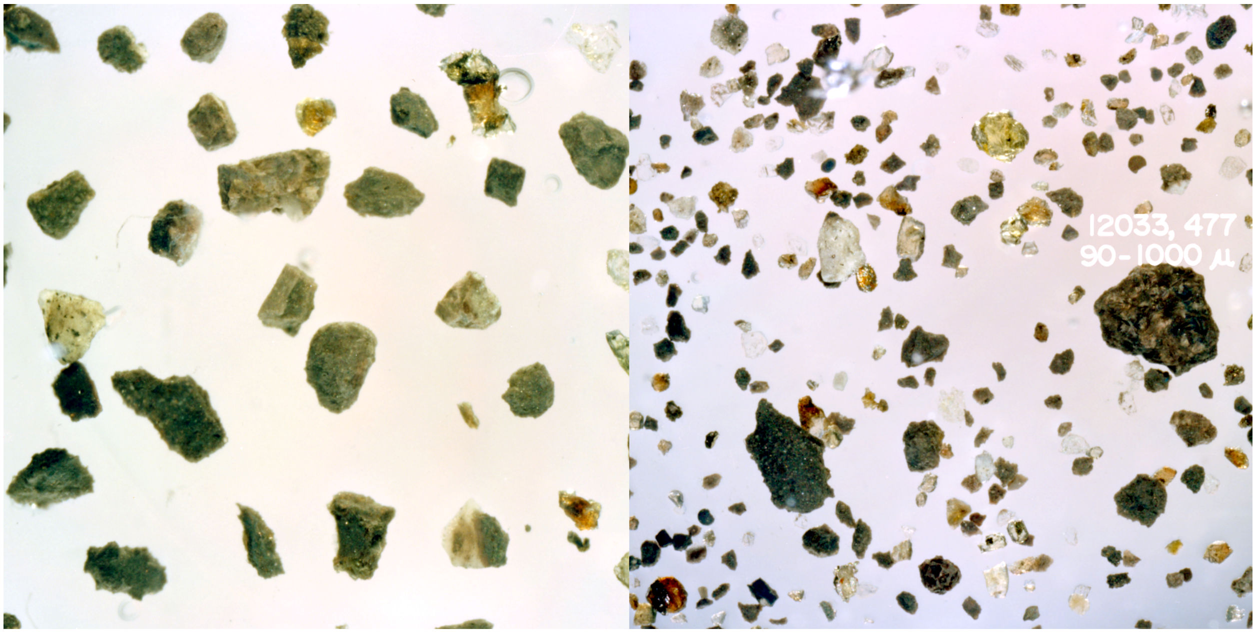

Figure 4.8: Close up images of the particles in the sample 12033. Both images are at approximately the same scale. (Left) Particles with sizes between 0.25 - 0.50 mm [NASA S79-34501]. (Right) Particles with sizes between 0.09 - 1.00 mm [NASA S79-34499].

> less than 0.05 mm in diameter. ... Several of the larger fragments pulled out are twisted pumiceous glass fragments. Dark brown glass.

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:[61]

> 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.[15] The management of the lunar regolith is one of the primary concerns for the long-term exploration and occupation of the Moon.

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[52] found that 6% of the particles are fragments of crystalline basalt and 29% are clumps 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 6 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.

Glass

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

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*.[51] 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.

Most of the glasses in 12033 are called *ropy glass*. They look like they *have been pulled or twisted while hot*[52] 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.

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.[56] 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.[42] 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 6.

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,[2] 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.

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.[20] This study found that *all* of the particles had gone through a major heating

[2] See section 6.1.9 of [32]

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.*[3] 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 that they all had undergone a major heating event 800 million $\pm$ 15 million years ago.[13] 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. [11]

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.[40] 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.

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[33] utilizing very high-resolution imaging from the Lunar Reconnaissance Orbiter[3] has used the time-honored method of crater counting (see Chapter 9) 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.

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

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

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).[88] 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.

Controversy

The link between sample 12033 and the Copernicus Crater is not universally accepted.[4] 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.[92] 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.

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.[5] 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.

[4] See the references on page 269 of [88]

[5] 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[91] 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.

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.

Chapter 5

Apollo 14

The Full Moon

When you look at a full Moon with the unaided eye, one of the most obvious features are the large, circular, dark features (Figure 5.1). These features are giant impact basins filled with mare, and they represent the largest-scale geology on the surface of the Moon. The fact that they are mare-filled means that they formed before the lava flows that created the mare. In Chapter 3, we learned that these mare surface are old — the Apollo 11 mare was formed 3.6 billion years ago. This means that the giant impact basins have to be very old. Just how old is going to be the main theme of this chapter.

The largest of these giant impact basins on the near side of the Moon is the Imbrium Basin. The Imbrium Basin is over 1,100 km (700 miles — about the distance between Seattle and San Francisco) across and formed when an object between 50 and 100 km in diameter impacted the lunar surface. The Imbrium Basin dominates the northwest portion of the full Moon, and is the main character of this chapter.

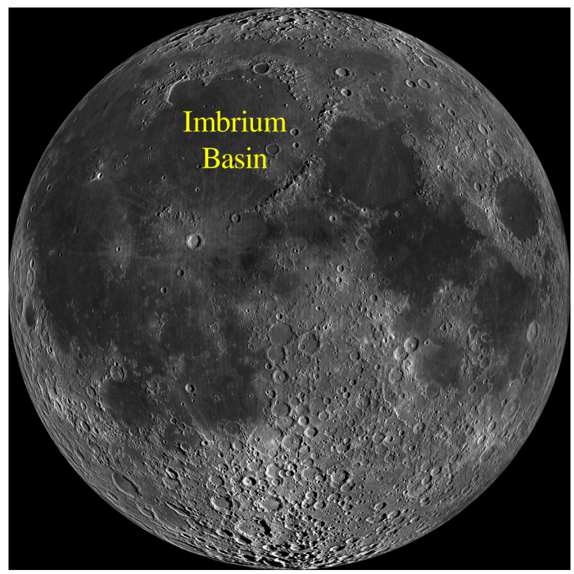

Figure 5.1: Image of the full Moon with the Imbrium Basin labeled. LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

Imbrium

The formation of the Imbrium Basin ejected material across a large portion of the Moon; in fact, it is the most extensive geological unit on the near side of the Moon.[87] Since this ejected material was all formed at the same time and is found all over the Moon, it is one of the most important time references on the Moon. Any feature anywhere on the Moon that is covered by this ejecta was formed before the Imbrium impact; any feature anywhere that formed on top of this ejecta was formed afterwards. This allows us to relate features all across the Moon. It is this ability to relate distant surfaces in time that makes determining the time of the Imbrium formation event so important.

In the previous chapter, we saw how the most recent era of lunar history was defined by the Copernicus impact crater. In this chapter, the Imbrium Basin will play a very similar role and will, likewise, lend its name to an era: the Imbrium Era.

The Imbrium Era begins when the giant impact basins were created and ends when the last of the mare surfaces were formed. Unlike the Copernican Era, the features formed in the Imbrium Era are numerous and cover a large portion of the lunar surface. For example, the majority of the mare surfaces on the near side of the Moon were formed during the Imbrium Era. (The Imbrium Era is subdivided into two time slices — the early and late Imbrium Era — but for this chapter I am going to treat the Imbrium Era as one unit of continuous time.) The beginning of the Imbrium Era is defined by the formation of the Imbrium basin.

Geological Setting

The primary criterion for the selection of the landing sites of Apollo 11 and 12 was safety. Big, smooth mare surface ensured a safe landing and the highest chance of a successful resolution of the space race (beating the Russians to the Moon). The scientific importance of the site was a secondary consideration at best. By the time the Apollo 13 mission was being planned, the scientific relevance of a landing site started to play a more important role in mission planning.[1]

Dating the Imbrium event was the main consideration in choosing the landing site for the next mission, Apollo 13. Landing in the middle of the Imbrium Crater would not have been useful; it is far from the lunar equator, and a mare surface covers the material that was formed during the impact. The best bet for dating the Imbrium impact was to land on the material ejected by the impact. This ejected material is all over the near side of the Moon, and it can be found in the equatorial region accessible by the early Apollo missions (Figure 5.2). Very early on, a patch of Imbrium ejecta on the lunar equator was selected as the landing site of Apollo 13. (In fact, the Apollo 13 landing site was selected 6 weeks before the landing of Apollo 11.)

This particular patch of Imbrium ejecta is called the *Fra Mauro* formation (Figure 5.3). In the billions of years since the Imbrium impact, the Fra Mauro formation has had material tossed onto it from younger impacts, and the continuous bombardment from space has

[1] A slightly more cynical, but more realistic, reason for the increasing role of science was suggested by Don Wilhelms [Wilhelms [87], page 230]. He suggested that science did not so much come to the forefront; rather, the engineers lost interest because there was nothing new to build, there were no *new developments of the type that could keep the engineers and the manufacturers interested and rich.*

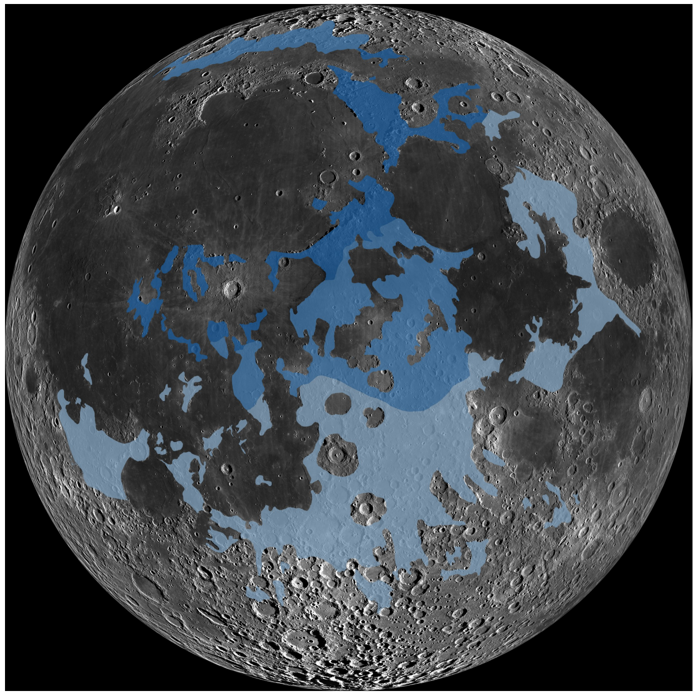

Figure 5.2: The extent of material ejected from the Imbrium Basin (blue). Image of the Moon from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University], overlay of Imbrium ejecta adapted from Wilhelms, McCauley, and Trask [88], plate 8A.

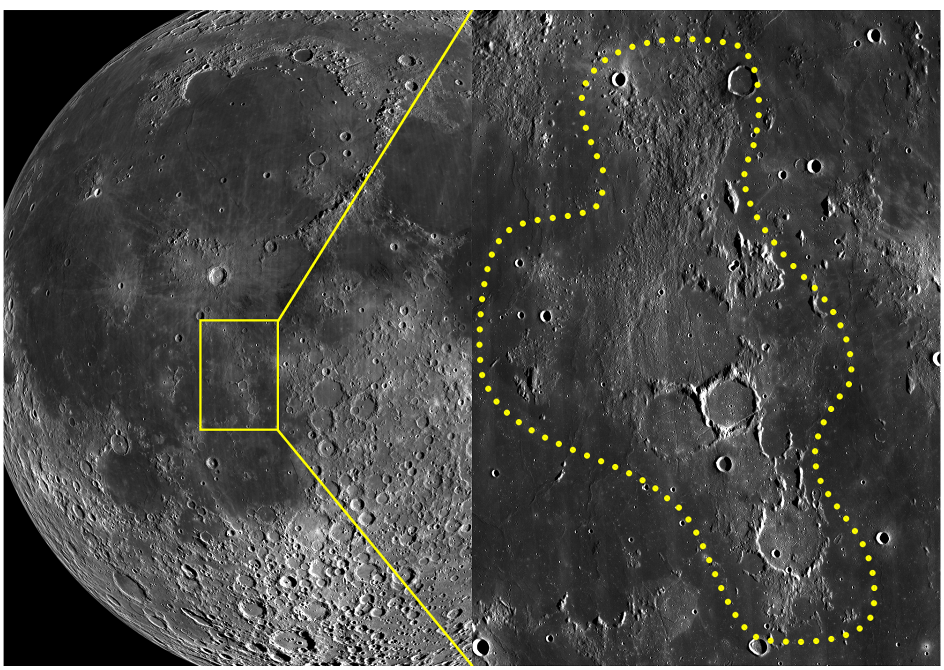

Figure 5.3: The Fra Mauro formation. (Left) Location of the Fra Mauro formation. (Right) Detail of the Fra Mauro formation (the boundary is only approximate). Both images are from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

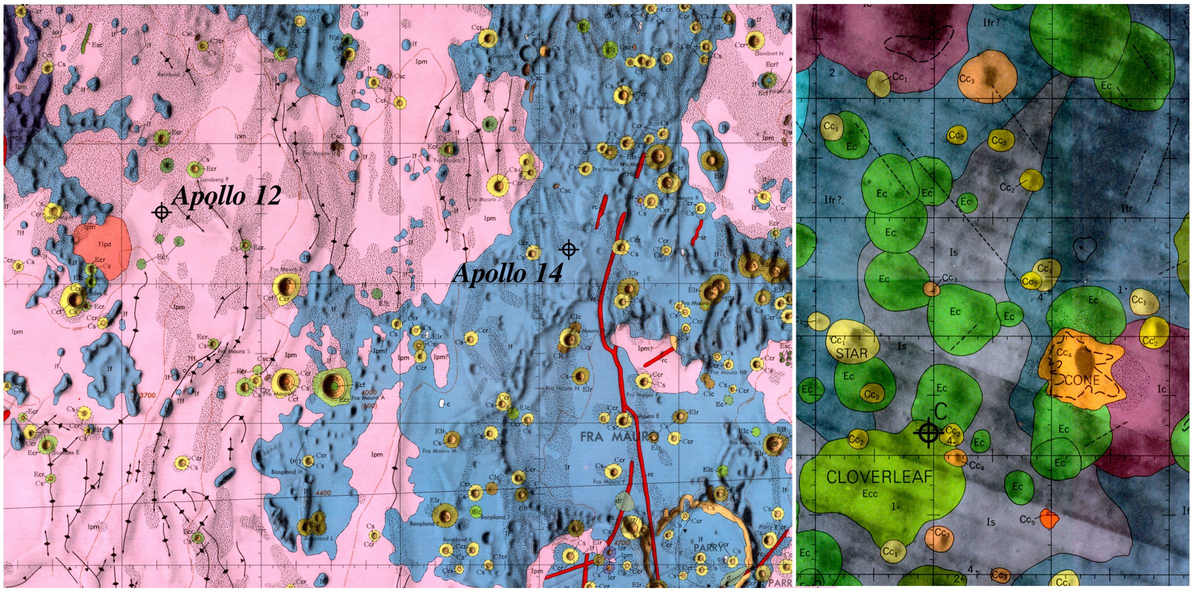

Figure 5.4: (Left) Detail of the geological map of the Fra Mauro region [21]. The landing site of Apollo 12 and 14 are indicated. (Right) A detail of the immediate vicinity of the Apollo 14 landing site [67].

created a layer of regolith over the formation, 5–12 meters thick. The goal of Apollo 13 was to sample the Imbrium ejecta below this layer of regolith. A fresh (Copernican-aged) impact crater named the Cone Crater provided a way to do that. The Cone Crater was going to be used as a drill to reach the underlying Imbrium ejecta.

Landing at the Fra Mauro site and determining the age of the Imbrium impact was a major scientific goal of the Apollo program. So when Apollo 13 was not able to land on the Moon, the Fra Mauro site became the target for Apollo 14.

The selected landing site of Apollo 14 was only 180 km to the east of the Apollo 12 site. While this is physically very close, a casual look at the pre-mission geological map of the area (Figure 5.4, left) shows that the two landing sites sample very different geological units. On the map, the blue of the Fra Mauro formation is very distinct from the pink of the younger mare material that surrounds it and overlaps it in places. The detailed pre-mission geological map of the specific landing site (Figure 5.4, right) shows the dominant blue of the Fra Mauro formation covered with mostly Eratosthenian-aged craters. The youngest mapped feature, the Copernican-aged Cone crater, is readily seen.

The Impact Process and Radial Sampling

The decision to land near Cone Crater was a very deliberate one. Experiments of crater formation using buried explosives and theoretical modeling had shown that the deepest material evacuated during the formation of an impact crater comes from a depth of about

1/10 the crater diameter.[2] In the case of the 370-meters-in-diameter Cone Crater, this means the deepest material comes from a depth of about 37 meters.

Meteor Crater, located outside of Flagstaff, Arizona, is one the best-preserved impact craters on the Earth. The geologist Eugene Shoemaker[3] made an extensive study of this crater in the early 1960s.[72] By examining the ejected material around the crater and comparing it to the local, pre-impact stratigraphy, he found that the material evacuated from the deepest layers ended up mostly as large blocks on the crater rim. Material from shallower layers was smaller in size and distributed farther from the crater rim.

Given the severe time constraints and the limited mobility offered by the suits worn on the Moon, digging for deep-seated samples is not practical during an Apollo mission. However, by using the relationship Shoemaker noticed between the depth and distribution of ejecta, digging can be replaced by walking and collecting rocks. The idea is simple: walk to the rim of an impact crater, collecting samples (and documenting where you collected them) as you go. Samples collected far from the rim came from shallow layers; the samples collected from the rim came from the deepest layers.

This technique is called a *radial traverse* of an impact crater, and it is a classical example of planetary exploration, whether carried out by humans or robots. This basic idea was used on all of the subsequent Apollo missions as well as on the robot rover missions on the surface of Mars.

Apollo 14 at Fra Mauro

On February 5, 1971, the Apollo 14 lunar module *Antares* set down on the Fra Mauro formation, exactly on target, a little over a kilometer southwest of Cone Crater. The mission time line of Apollo 14 was similar to Apollo 12: two surface EVAs of a little under five hours each, with the first devoted to setting up the surface experiments and the second devoted to the geological exploration of the site.

The geological traverse of the second EVA of Apollo 14 was a radial traverse of Cone Crater (Figure 5.5). One of the main goals was to collect a sample from the rim of the crater. A sample from the rim of Cone Crater would have come from a depth of about 40 meters. Since the overlying regolith was estimated to be about 5–12 meters thick, a sample from 40 meters deep would be from the underlying Fra Mauro formation, material ejected by the Imbrium impact and the main goal of the mission.

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[2] H. J. Melosh's monograph *Impact Cratering: A Geological Process* Melosh [54] is pretty much the go-to references for all aspects of impact cratering

[3] Eugene Shoemaker played a very large role in the scientific planning of the Apollo missions and the geological training of the astronauts. His role is discussed in detail in Wilhelms [87].

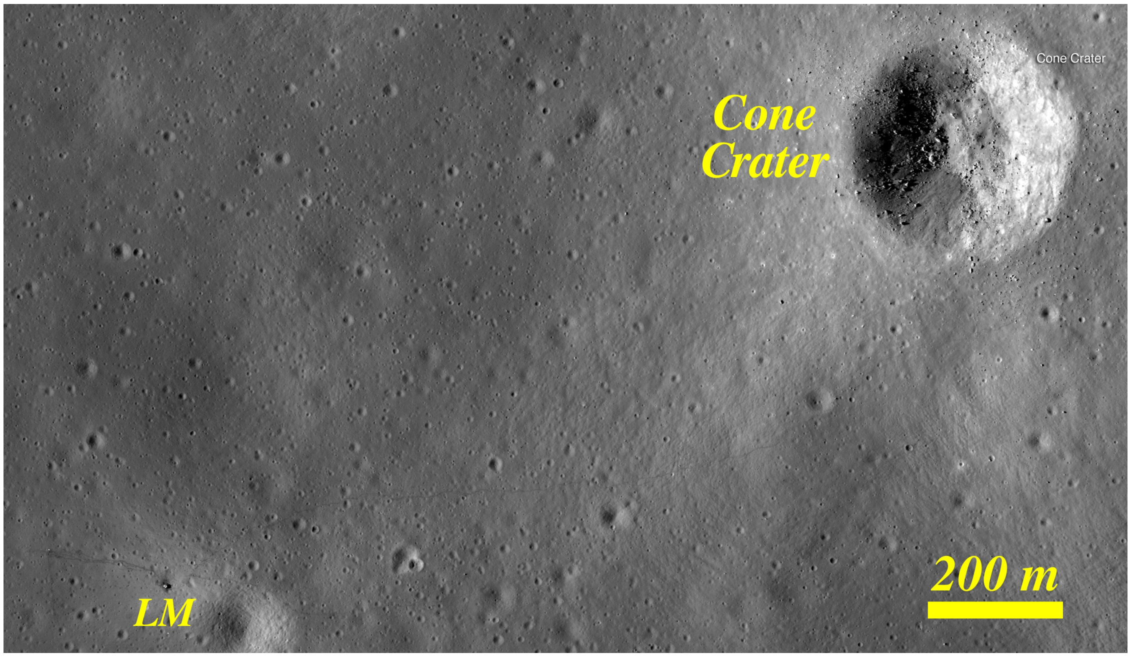

Figure 5.5: Landing site of Apollo 14. The footprints of the astronauts leading from the lunar module to the rim of Cone Crater are visible. LROC NAC image M150633128LR [NASA/GSFC/Arizona State University].

Sampling at the Rim of Cone Crater

The second EVA of Apollo 14 took place on February 6, 1971. After a rather difficult and lengthy trek covering about 1.5 kilometers in over a little more than two hours[4] the two Apollo 14 astronauts arrived very near the rim of Cone Crater, amongst a field of boulders:

> `133:24:26` **CDR**: Okay, Houston. We are in the middle of a fairly large boulder field. It covers perhaps as much as a square mile. And, as the pan will show, I don't believe we have quite reached the rim yet. However, we can't be too far away and I think certainly we'll find that these samples (come from) pretty far down in Cone Crater.

The astronauts notice a white boulder a short distance from their current location and decide to sample the boulder:

> `133:37:3` **CDR**: I mentioned there's a boulder definitely whitish in color, Fred. We'll be over there in a minute. Not in our immediate vicinity. But it definitely looks worthwhile sampling.
>
> ...

[4]The climb up Cone crater by the Apollo 14 astronauts is an informative study on the difficulty of navigating the surface of the Moon on foot. See Wilhelms [87] and Jones and Glover [44] for details and astronaut commentary.

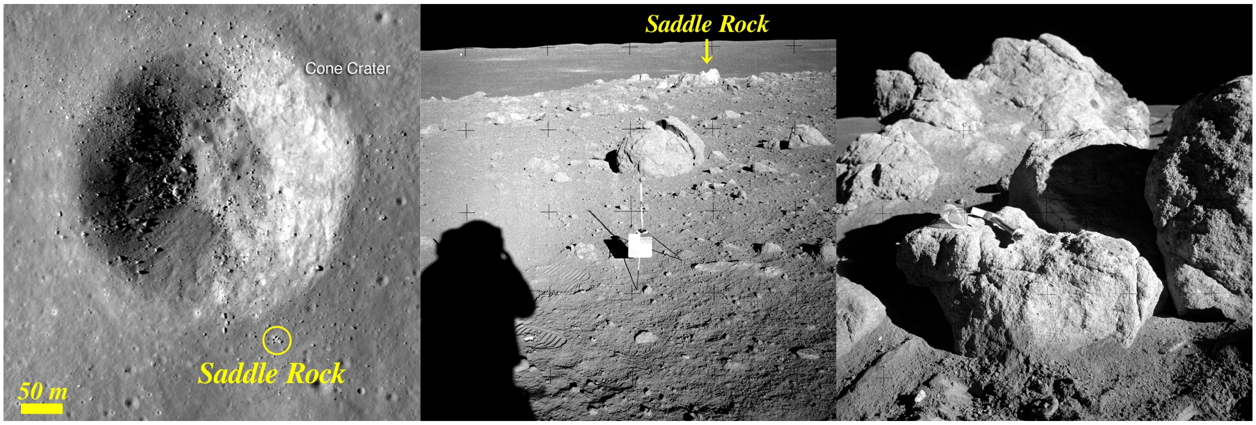

Figure 5.6: The sampling location on the rim of Cone Crater. (Left) Close-up image of Cone crater, showing the location of the boulder field (circled) on the southern rim. The northernmost boulder in that field is Saddle Rock (LROC NAC image M150633128LR [NASA/GSFC/Arizona State University]). (Center) At the southern edge of the boulder field. Saddle Rock is labeled near the horizon [NASA AS14-68-9445]. (Right) A close-up of the boulder field. Saddle Rock is the large rock in the background [NASA AS14-68-9452].

> `133:37:5` **CAPCOM**: . . . They concur here and would like a sample from the white boulder. Go ahead, Ed.

This white bolder is *Saddle Rock* (labeled in Figure 5.6). The astronauts then describe the rocks nearby and collect a large football-sized sample:

> `133:40:2` **LMP**: Okay, Fredo. I'm right in the midst of a whole pile of very large boulders here. Let's see what I can do to grab a meaningful sample.
> . . .
> `133:44:2` **LMP**: . . . help with that one?
> `133:44:3` **CDR**: That's all right, I think I got it. There's a football-size rock, Houston, coming out of this area, which will not be bagged. It appears to be the prevalent rock of the boulders of the area. Got it?
> `133:44:41` **LMP**: Got it.

This large sample collected at the rim of Cone Crater is `14321`, nicknamed *Big Bertha* (Figure 5.7). At a mass of nearly 9 kg ($\sim$ 20 pounds), `14321` is the largest sample collected by Apollo 14 (and the third largest of all the Apollo samples). This sample alone accounts for over 20% of the total mass of all the rocks returned by Apollo 14.

Big Bertha

Figure 5.8 shows an image of `14321` in the Lunar Receiving Laboratory. Two things are immediately apparent in this image: (1) `14321` is a VERY large sample, and (2) `14321` is a

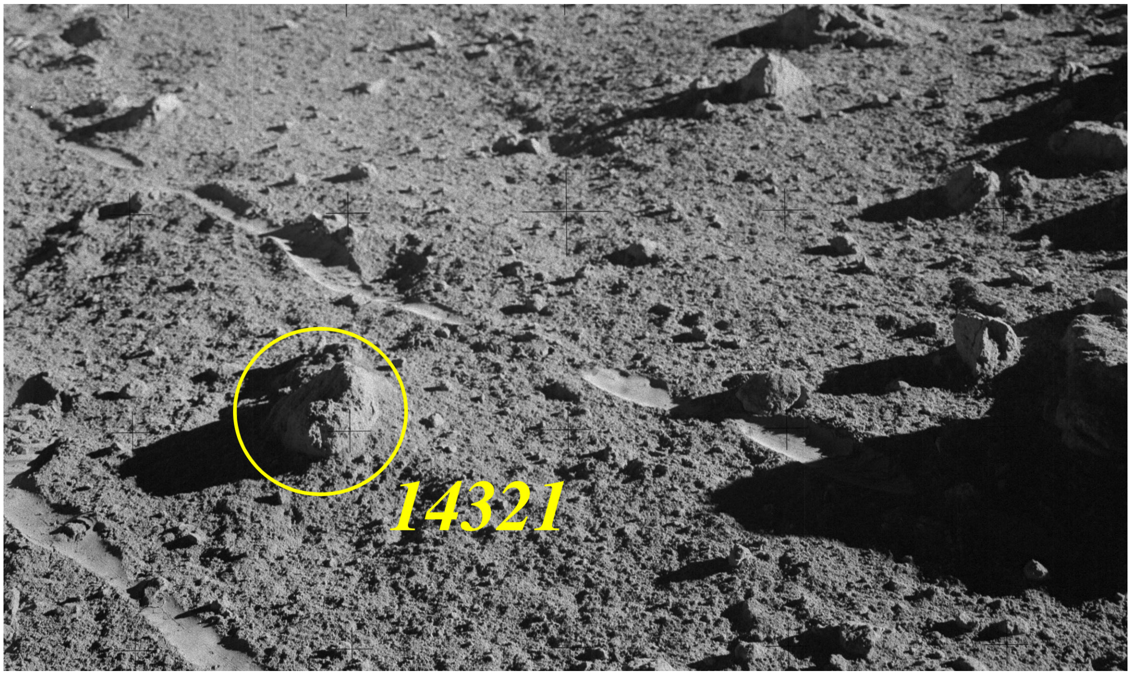

Figure 5.7: The football-sized sample 14321 near *Saddle Rock* just before collection [NASA AS14-64-9128].

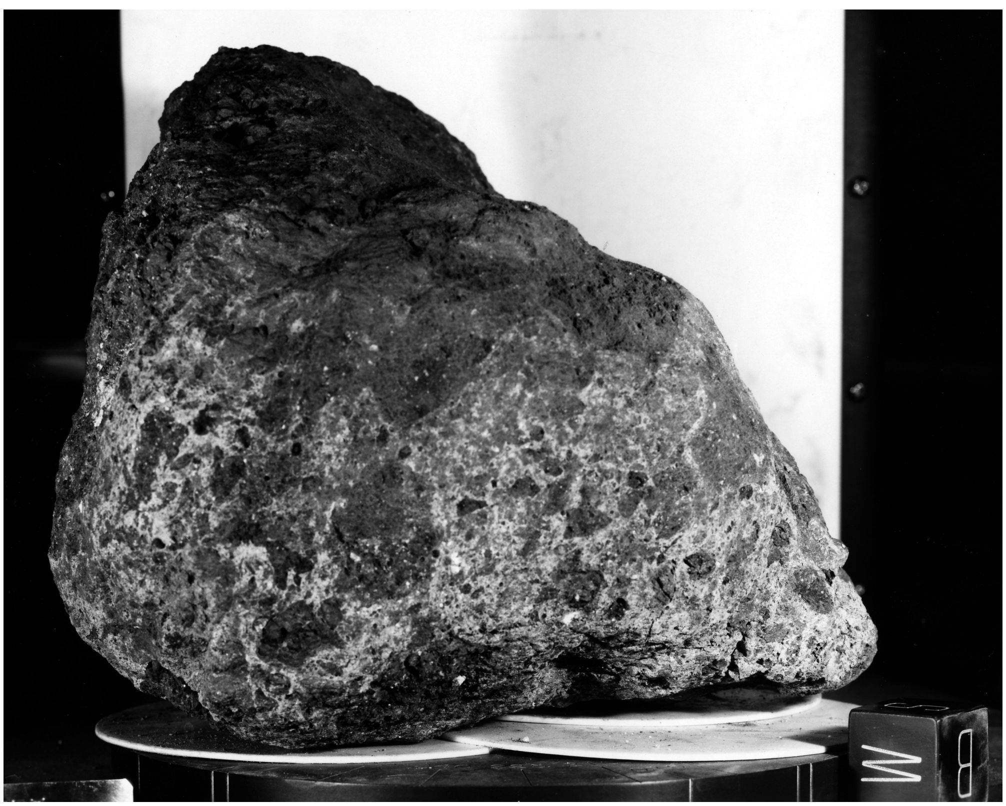

Figure 5.8: Image of 14321 at the Lunar Receiving Laboratory. The cube at the lower right is 1 inch across [NASA S71-28417].

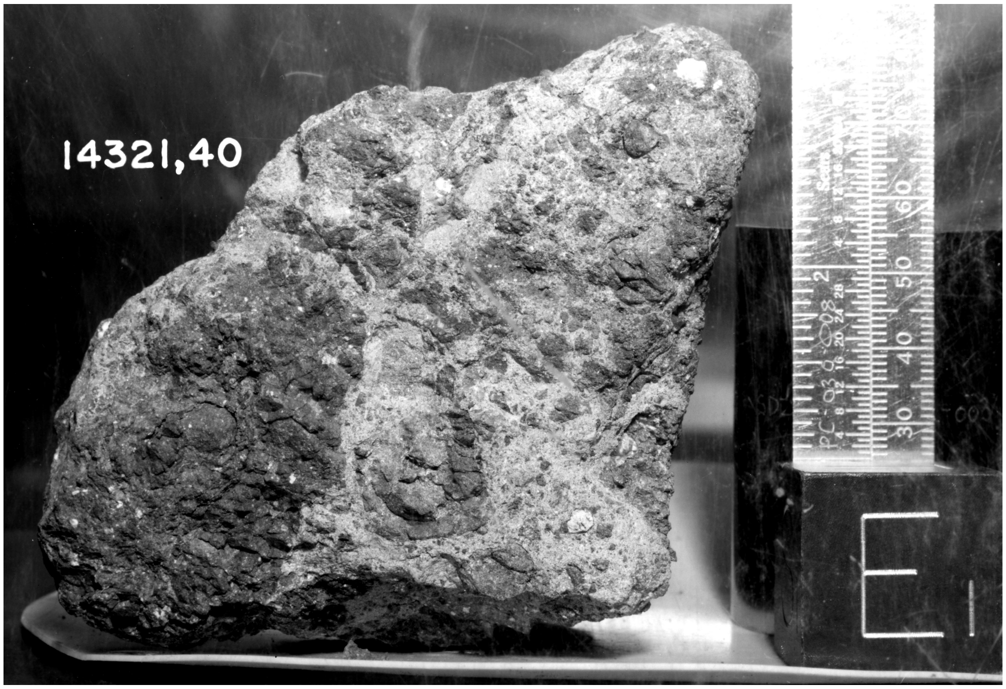

Figure 5.9: A piece of sample 14321 showing the nature of impact breccia [NASA S76-24007]. The cube is 1 inch across.

very complex sample. 14321 is a classic example of an **impact breccia**.

Breccia is a general geology term that refers to a rock that is composed of broken fragments of minerals, rocks, or even other pieces of breccias. These various fragments are often referred to as *clasts*. The clasts of a breccia are all embedded in a fine-grained surrounding material called a *matrix*. Looking at the image of 14321 (Figure 5.9) you can see that the sample is composed mostly of dark-ish, angular clasts embedded in a white-ish matrix.

Impact breccia is a specific type of breccia that is formed by a meteoroid impact. The energy of an impact can fracture, partially melt, or completely melt a target rock. When this fractured, partially melted, and completely melted material fuses together and eventually cools, the result is impact breccia.

If we assume that 14321 was formed by the Imbrium impact event, it would seem straightforward that determining the age of 14321 would tell us the age of the Imbrium impact event. However, determining the history and age of 14321 is anything but straightforward.

Complexity

The story of a single impact breccia is complicated, and 14321 is no exception.Impact breccias are composed of the materials from the site of an impact event. This material may be made of many different pieces that have many different origins. Some of these pieces will even be other impact breccias, from earlier impact events, with their own histories. What this means is that a single piece of impact breccia will contain fragments with a wide diversity of types, compositions, ages, and histories.

The first comprehensive studies of 14321 were published in March 1975, 4 years after the sample arrived on Earth. [5] These studies were the first of many to characterize the composition and histories of the pieces of 14321. One of these studies characterized 14321 as being composed of three major components: clasts of older breccias, clasts of igneous basaltic fragments, and the lighter-colored matrix they were embedded in. [27]

The oldest pieces of 14321 are the fragments of embedded breccias. These breccias have their own complicated histories. The basaltic fragments also have a wide diversity of composition and ages. Some of these basalt clasts are older than any mare basalt found by other Apollo missions, and may represent the only samples we have of pre-mare volcanism.

The size and complexity of 14321 is matched by the number and complexity of the scientific papers it has generated. A recent (2009) compendium[6] of the scientific results of studies done on 14321 boasts a reference list of over 100 scientific publications. But this list is not complete. The compendium includes the side note: *14321 has so many studies that they simply can't all be included in this compilation. Sorry!*

Age of the Imbrium Event

The major goal of landing on the Fra Mauro formation was to determine the age of the Imbrium impact event. The sample 14321 has many different ages from many different events. Which age dates the Imbrium event?

The simplest idea is that the Imbrium event must be younger than the youngest clast found in 14321. The youngest pieces of 14321 are basalts, with ages of about 3.87 billion years old, suggesting that the Imbrium impact event must have occurred just after this time.

But of course the story is not that simple. A recent survey of papers on the geological time scale of the Moon based on samples from all missions to the Moon has found that there are two major proposals for the age of the Imbrium impact. One is 3.85 ± 0.02 billion years old. This is based on the age of the Fra Mauro formation, determined from samples collected on Cone Crater (including 14321). The other age for Imbrium is slightly younger, 3.77 ± 0.02 billion years old. This age is based on rocks that are believed to have been directly melted by the Imbrium event and collected at both the Apollo 14 and 16 site (more on these Apollo 16 samples in Chapter 7). [78]

In this book, I will adopt an age of 3.8 billion years as the age of the Imbrium Basin formation event.

[5] The studies were published as four papers in a single volume of the Journal *Geochimica et Cosmochimica Acta* Duncan, Grieve, and Weill [18], Grieve et al. [27], Duncan et al. [19], and Morgan, Ganapathy, and Kraehenbuehl [58]

[6] The compendium can be found at: `http://curator.jsc.nasa.gov/lunar/lsc/14321.pdf`

The History of 14321

The Imbrium impact event was just one event in the history of the sample 14321. One of the papers from the series published in March 1975 was titled *The Life and Times of Big Bertha - Lunar Breccia 14321*.[18] This paper laid out a possible history of 14321. It goes something like this:

The story of 14321 begins with a prologue, when an older impact deposited material onto the Imbrium area. This material makes up the oldest breccia embedded in 14321.

This was followed by a series of volcanic flows of KREEPy basalt.

Further, smaller impacts in the Imbrium region combined the older breccias and these basalts, forming other breccias.

Then, the main event: About 3.8 billion years ago, an object of between 50 and 100 km impacted the Moon, creating the Imbrium Basin. This event fractured, heated, and fused the target rock (composed of older breccias and basalts) and sent this material all over the near side of the Moon. Some of this ejected material landed over 500 km to the south of the Imbrium impact site, creating the Fra Mauro formation.

Later, local volcanic events created other basalts that mixed with the Fra Mauro material.

Subsequent impact events (including the one that created the Fra Mauro Crater at the southern end of the Fra Mauro formation) further heated and mixed the Fra Mauro formation.

Then, about 24 million years ago (0.024 billion years), an object about 30 meters in diameter hit the Fra Mauro formation, creating the Cone Crater. This event evacuated a football-sized piece from deep down inside the Fra Mauro formation and deposited it on the southern rim of Cone Crater.[7]

Finally, on February 6, 1971, after a long climb up the Cone Crater, the two Apollo 14 astronauts collected this football-sized sample and returned it to the Earth.

[7] The exposure age of 14321 was found to be 24 ± 2 million years old Arvidson et al. [8]. This is the accepted age of the formation of Cone crater.

Chapter 6

Apollo 15

The Scientific Apollo

The final three missions to the Moon belong, in many ways, to a completely different program than the first three. Upgrades to the rockets allowed the landing sites to move away from the lunar equator; these upgrades also vastly increased the mass of material that could be both delivered to the Moon as equipment and returned from the Moon as samples. Included in this equipment was the Lunar Rover, a vehicle that allowed the astronauts to traverse over 30 km across the Moon. Increased supplies allowed longer EVAs on the surface; three EVAs of eight hours each, compared to the two five-hour EVAs of Apollo 12 and 14. The most important change, however, may have been the astronauts' training.

All of the astronauts for the final three missions had been part of the back-up crews for earlier missions. This meant that they were extensively trained on the operation of the spacecraft, even before they trained for their own missions. As Dave Scott, the commander of Apollo 15, put it[10]:

> We felt that the Apollo system was mature and reliable and that we no longer had to devote the time to engineering that we had on past flights... So once you get this confidence in the system, you ask: Where should I spend my time? It was obvious to me that the time should be spent in learning the science. We had additional opportunity, too, because we were the backup crew on Apollo 12 and spent that time learning how to fly the machine. When our turn came on Apollo 15, we already knew how to work together. This gave us a great opportunity to devote our time to the science part. That's the whole purpose behind Apollo. The original concept was to have test flights to make sure it worked, a few more to make sure we could land on the moon and return, and then, by golly, to get into the real meat of the subject. That was the whole purpose. We were lucky enough to be in the position to participate in the meat part.

With extra training time available, the astronauts became excellent field geologists,[1] good enough that the lunar scientist Bill Muehlberger estimated that each astronaut earned the equivalent of a master's degree in geology, and probably saw more geology than the average master's recipient. [87]

One of the main results of the extended capabilities of the machines, longer EVAs, and (especially) scientifically trained astronauts was that the landing sites chosen were *much* more complicated.

A Multi-Objective Landing Site

The landing sites of the first three Apollo missions can be characterized rather succinctly. Apollo 11: a mare surface. Apollo 12: a different mare surface with a ray of Copernicus on top of it. And Apollo 14: the ejecta material from the Imbrium impact. These types of sites are perfect for missions with short EVAs and limited (walking-only) range. These types of sites are completely inappropriate for extended, rover-range EVAs with a scientifically trained crew. Ten kilometers in any direction from the early Apollo sites has pretty much exactly the same terrain as the landing site. Not so with the later missions.

The Apollo 15 site was the first multi-objective site. These sites offered many different geological settings within rover-driving distance, which means that many different scientific objectives could be addressed from a single landing site.

The landing site of Apollo 15 was one of the most complex of all of the Apollo missions; it was also one of the most aesthetically beautiful sites of the whole program (Figure 6.1). Apollo 15 landed on the southwest rim of the Imbrium Basin, right where the infilling mare (*Palus Putredinus* - Marsh of Decay) laps up against Imbrium's huge, uplifted rim (the Apennines Mountain front). The stand-out feature of the site is a lava channel that meanders across the mare surface. This lava channel, named the Hadley Rille, lends its name to the landing site.

The large-scale geological map of the landing site shows the diversity of the region (Figure 6.2, left). The detailed geological map shows that this diversity is still very apparent at even small scales (Figure 6.2, right). Within a few kilometers of the landing point are Copernican and Eratosthenian-aged craters, a mare surface, the Apennine Mountain front, and the Hadley Rille.

The Falcon on the Plain at Hadley

The Apollo 15 lunar module, *Falcon*, landed right on target next to Hadley Rille on July 30, 1971. The extended capabilities of Apollo 15 meant there were now three longer surface EVAs. Like earlier missions, the first EVA was mostly devoted to the surface experiments.

[1] The geological field training of the Apollo 15, 16, and 17 astronauts is covered in great detail in [87] as the author of that book played a large role in the training.

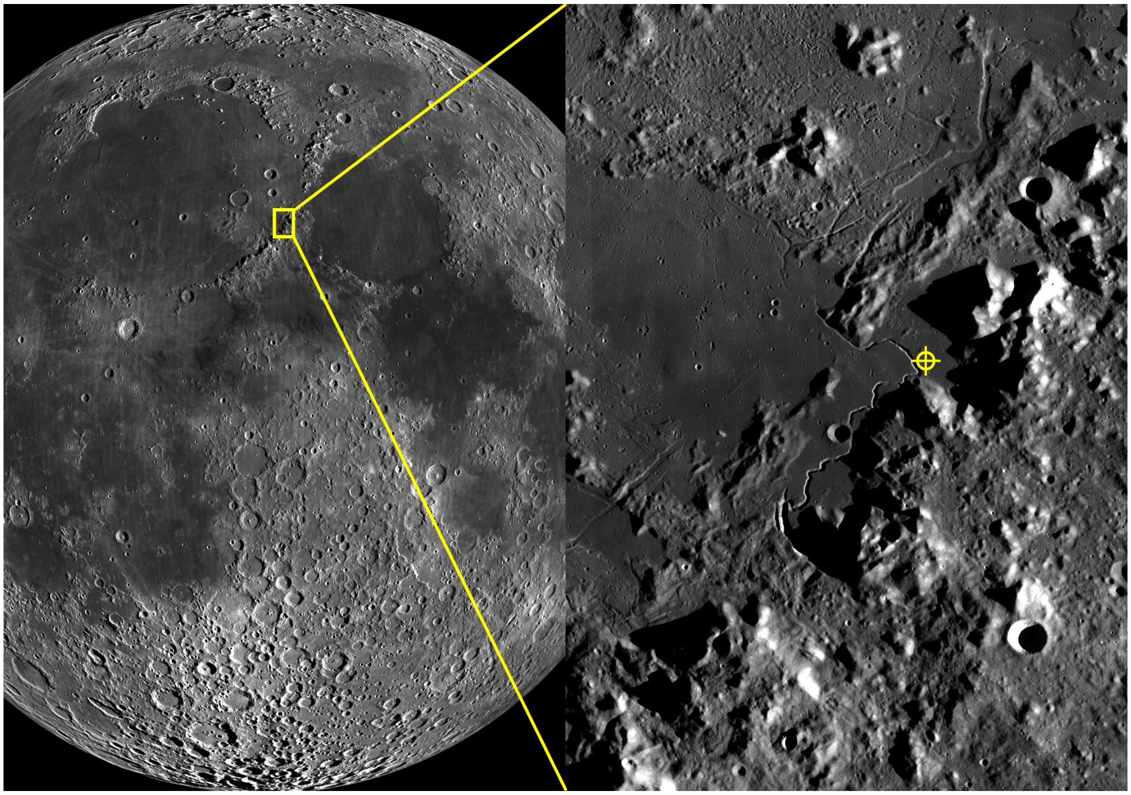

Figure 6.1: The landing site of Apollo 15 on the rim of the Imbrium Basin. Images from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

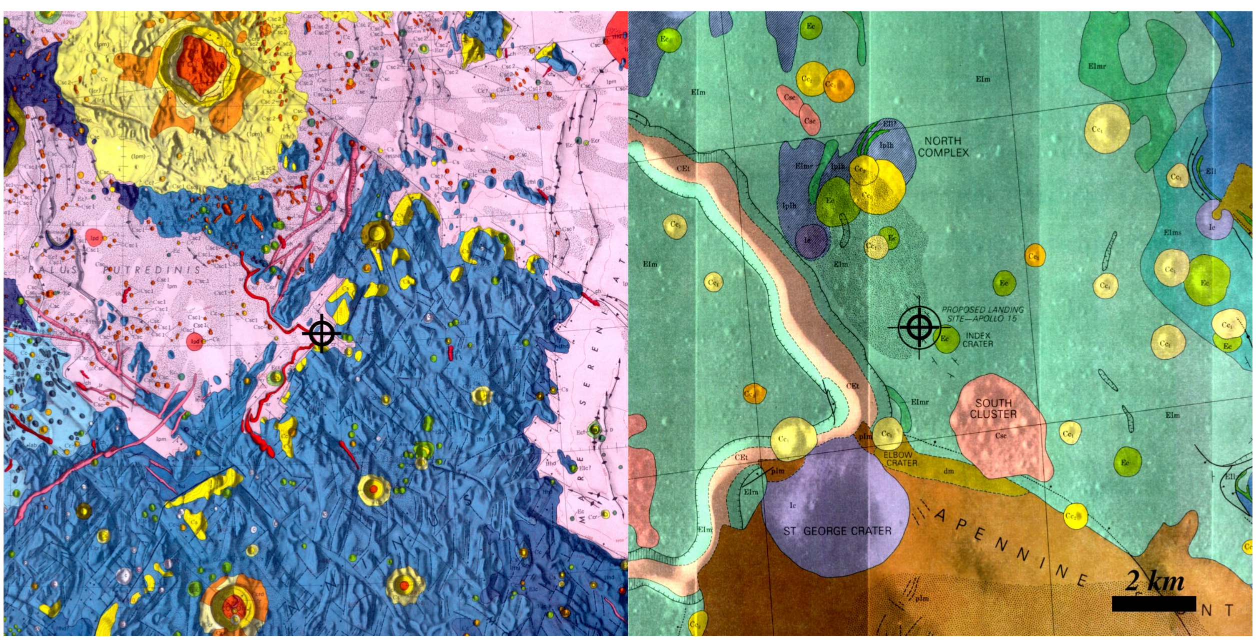

Figure 6.2: Geological maps of the regions of the Apollo 15 landing site. (Left) A detail of the large-scale geological map of the Apennine Mountains [28]. (Right) A detail of the geological map of the immediate vicinity of the Apollo 15 landing site [39]

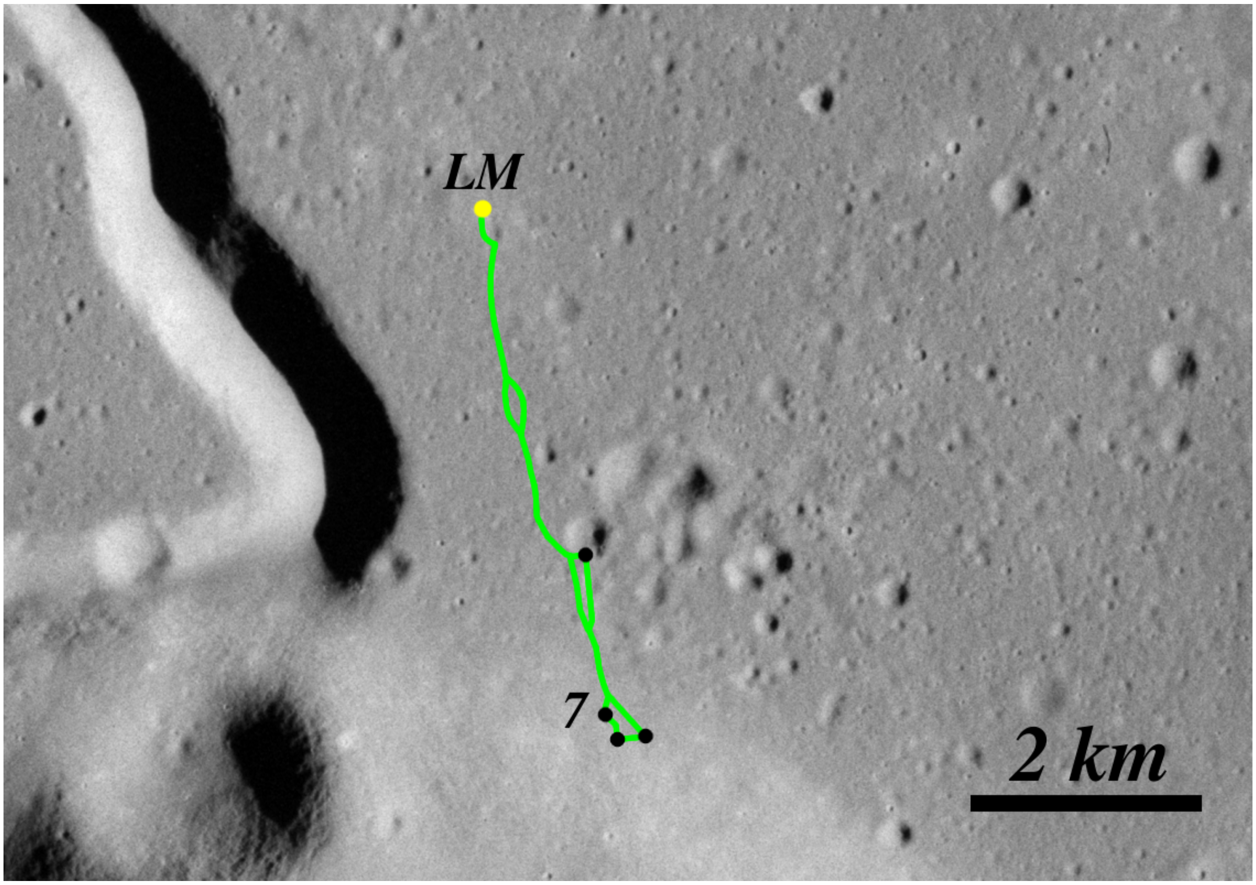

Figure 6.3: The path of the second EVA of Apollo 15. The point labeled with a *7* is Station 7, the location of Spur Crater [background image: NASA AS15-M-0585]

The bulk of the geological traverses were done during the second and third EVAs. The second EVA turned out to be the most rewarding, finding a treasure trove of interesting samples.

The second EVA of Apollo 15 began on August 1, 1971. The path of the traverse was a four-kilometer rover trip due south of the landing site (Figure 6.3). The goal was the flank of the Apennine Mountain front (the rim of the Imbrium Basin). It was assumed that the material found at the rim of the huge Imbrium impact basin would include material from deep within the crust of the Moon — very ancient material.

About three hours into the second EVA, the Apollo 15 astronauts arrived at a small crater on the uphill flank of the Apennine Mountain front (Figure 6.4). This small crater, named Spur Crater, is about 100 meters in diameter. The astronauts noticed a large boulder on the northern rim (Figure 6.5):

> `145:24:02` **CDR**: We're almost to Spur now.
> `145:24:03` **CAPCOM**: . . . we've got some parking instructions.
> `145:24:09` **CDR**: Parking instructions? Okay. Let's see, do we want to hit the upper rim or the lower rim of Spur?
> `145:24:18` **LMP**: You see that large block on the . . .

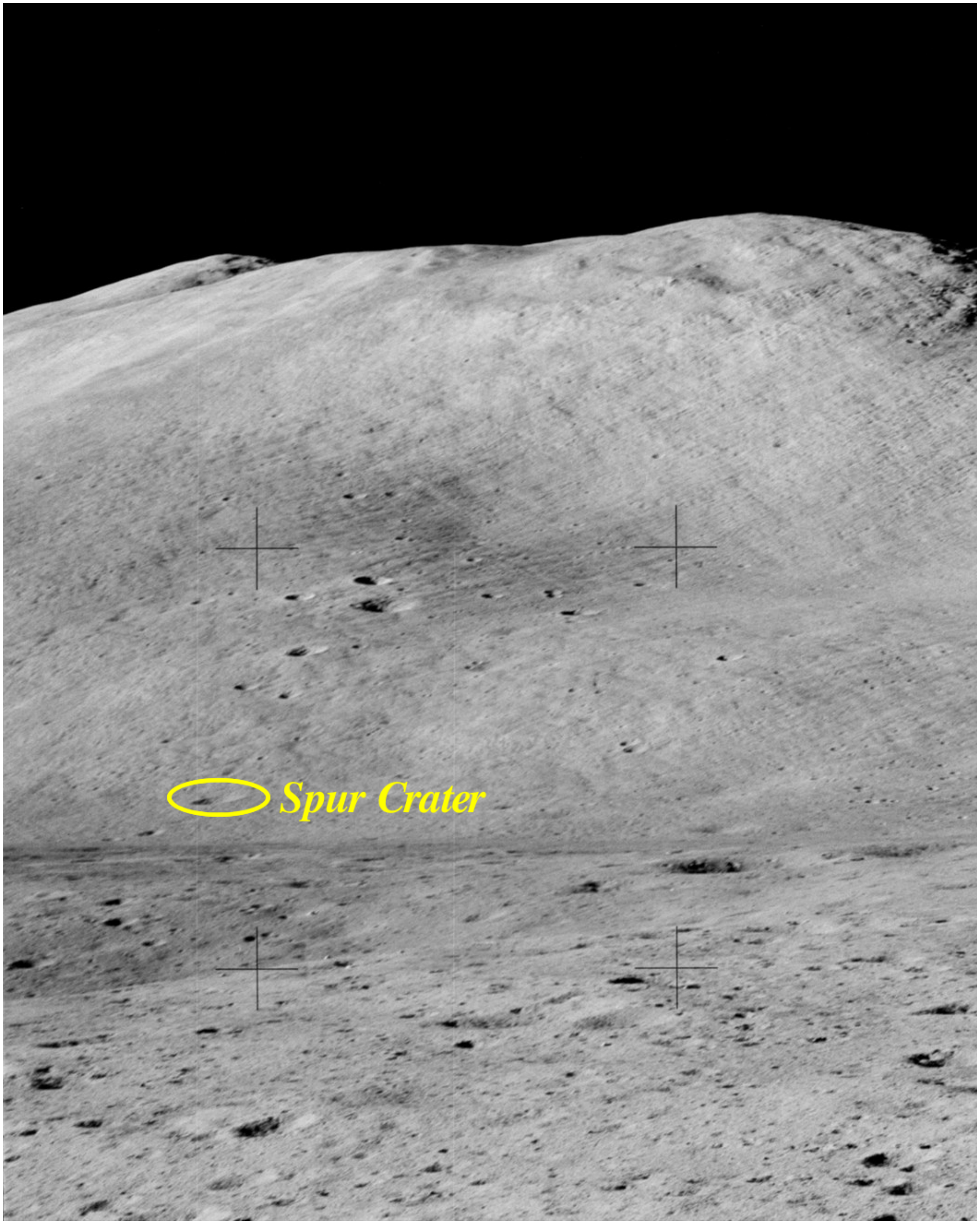

Figure 6.4: A view of the Apennine Mountain front as seen from the lunar module [NASA AS15-85-11377]. The route of the second EVA is essentially straight from this spot to the Spur crater.

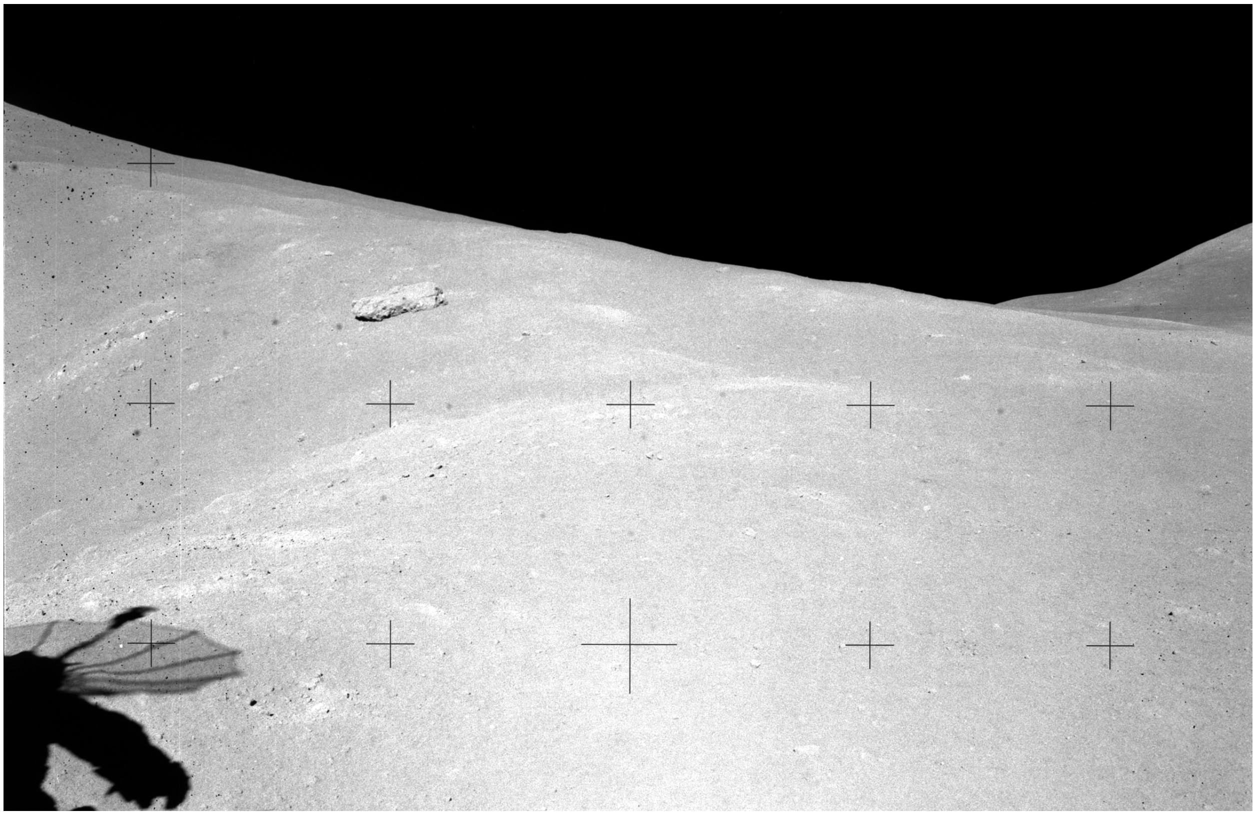

Figure 6.5: The northern rim of Spur Crater. The large boulder is easily visible just inside the rim of the crater [NASA AS15-90-12201].

> `145:24:2` **CDR**: Yeah.
> `145:24:21` **LMP**: . . . the northern rim.
> `145:24:22` **CDR**: Yeah, I think we should work down to the northern rim, right?
> `145:24:25` **LMP**: Yeah, if we're going to sample any blocks there on the rim, that'd be the place to do it.

They parked the rover and started collecting samples on the rim:

> `145:40:4` **CAPCOM**: . . . is it your impression that you are sampling on the ejecta blanket of Spur Crater, now?
> `145:40:48` **CDR**: Yes, sir; probably from the deepest part, because we're right on the rim.

The large boulder on the rim of Spur Crater (Figure 6.5) was very distinctive, as were the samples scattered around the boulder:

> `145:41:48` **CDR**: Okay, there's a big boulder over there down-Sun of us, that I'm sure you can see, Joe, which is gray. And it has some very outstanding gray clasts and white clasts, and oh, boy, it's a beaut! We're going to get ahold of that one in a minute.

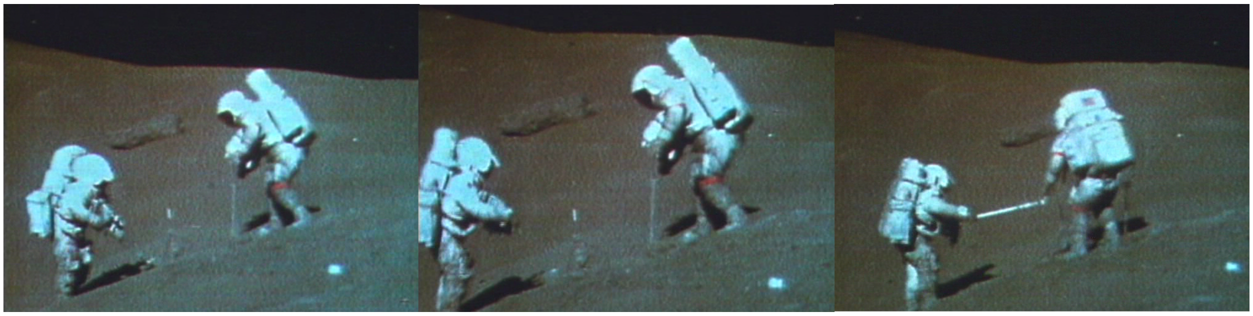

Figure 6.6: A series of frames from the television video of the astronauts at work on the rim of Spur Crater, showing the collection of the sample 15415 [NASA].

. . .
145:42:41 **LMP**: Oh, man!
145:42:4 **CDR**: Oh, boy!
145:42:42 **LMP**: I got . . .
145:42:42 **CDR**: Look at that.
145:42:44 **LMP**: Look at the glint!
145:42:45 **CDR**: Aaah.
145:42:46 **LMP**: Almost see twinning in there!
145:42:47 **CDR**: Guess what we just found. Guess what we just found! I think we found what we came for.
145:42:53 **LMP**: Crystalline rock, huh?
145:42:55 **CDR**: Yes, sir. You better believe it.
145:42:57 **CAPCOM**: Yes, sir.
145:42:58 **CDR**: Look at the plage in there.
145:42:59 **LMP**: Yeah.
145:43:00 **CDR**: Almost all plage.
145:43:02 **CDR**: As a matter of fact . . . Oh, boy! I think we might have ourselves something close to anorthosite, 'cause it's crystalline, and there's just a bunch . . . It's just almost all plage. What a beaut.
145:43:18 **LMP**: That is really a beauty. And, there's another one down there!
145:43:22 **CDR**: Yeah. We'll get some of these.
145:43:24 **CAPCOM**: Bag it up!
145:43:27 **CDR**: Ah! Ah!
145:43:29 **LMP**: Beautiful.

One of the things the astronauts learned in their geological training was how important it was to document the sample. While a sample alone is interesting, its real value is the story it tells. This story depends on the context of the sample: its orientation, how deeply it is buried, where it is compared to other features. By documenting the samples before and after collection, the context of the sample can be recreated after the sample as been returned to the Earth. One of the most basic parts of documenting a sample is photography (Figure 6.7). Much of the talk during the collection of this sample is about making sure the photographs get taken:

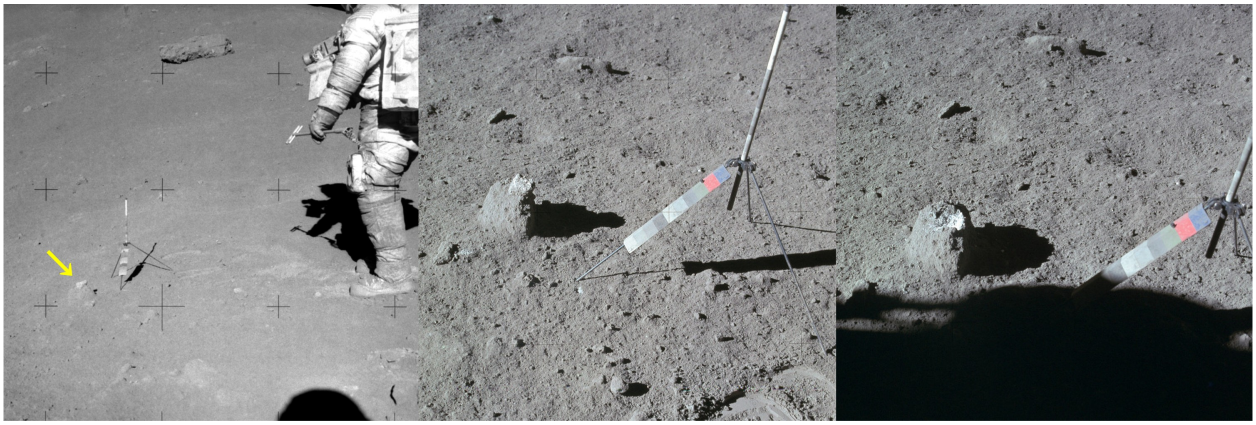

Figure 6.7: Documentation of the collection of sample 15415. (Left) The sample *in situ* on the rim of Spur crater (yellow arrow) [NASA AS15-90-12228]. (Center) Close up of the sample just before collection [NASA AS15-86-11671]. (Right) Close up of the site just after sample collection [NASA AS15-86-11672].

> `145:43:52` **CDR**: Okay, let's get some of the other ... Maybe ... Let me take a picture first in here. I got it. No sweat.
>
> `145:43:59` **CDR**: Now, we got to think of how to get that other piece there. Maybe if you could put your scoop in it, and break off a chip, do you think?
>
> ...
>
> `145:44:27` **LMP**: Want to take this piece here?
>
> `145:44:28` **CDR**: Yeah. Let me get you a bag. Wait. Let me take a picture first, so you know which one we got.
>
> `145:44:35` **CDR**: Okay. Go ahead. Number 170.
>
> `145:44:41` **CAPCOM**: Roger. 170.
>
> ...
>
> `145:45:22` **CDR**: There's a contact, sort of, on there. We ought to try and get the contact if we can. Okay, babe. Open the bag.
>
> `145:45:44` **LMP**: Okay, I got.
>
> `145:45:46` **CDR**: Got it? That a boy. Good show. Post-pick-up picture.

The sample that the astronauts collected and placed in bag 170 is the main character of this chapter, and it is one of the most well-known Apollo samples: `15415`.

The notoriety[2] of `15415` is due, in large part, to the fact that the excited exchange between the astronauts during the sample's collection was captured on live video and transmitted around the world. The first three Apollo missions carried video cameras, but they were planted in one place and never moved. (The video camera for Apollo 12 failed very early in the mission.) There is nearly no video of the astronauts collecting samples from the first three missions.

[2]Such is the notoriety of `15415` that it even got its picture on the front page of the *New York Times* [70]

For the last three missions, a video camera was mounted on the Lunar Rover; it followed the astronauts on their exploration of the lunar surface.[3] (Figure 6.6) This allowed the scientists and engineers working with the astronauts, as well as the general public, to follow the progress of the mission and to experience, in a remote way, the exploration of the Moon. The rover-mounted camera of the last three missions meant that there is video of nearly all of the sample collecting from these missions.

The rim of Spur Crater turned out to be one of the richest sample collection sites of the Apollo program. The sample 15415 was just one of the many important samples collected:

> 145:45:54 **CDR**: Okay; roll that beauty up. Let's go get some more of that.
>
> 145:45:58 **LMP**: I think we ought to get over to that big rock.
>
> 145:45:59 **CDR**: Yeah. We're getting there.
>
> 145:46:23 **CDR**: And if you could put that in my bag and then check my film. Joe, this crater is a gold mine!
>
> 145:46:33 **CAPCOM**: And there might be diamonds in the next one.

Photography and video were just two documentation methods for the Apollo samples. The astronauts themselves added an important component by describing the samples before and after collection. One of the samples collected on the rim of Spur Crater was a baseball-sized rock with big, distinctive, white inclusions. Note how clearly and accurately the scientifically trained astronauts describe the sample, giving the size, shape, colors, and their interpretations (which are correct) of the minerals that make up the rock. This sort of description of the samples and surroundings (the context) is a hallmark of all three final Apollo missions:

> 145:48:01 **CDR**: I've got... Man, oh man! I got about a 4-incher, Joe. It's subrounded, and on one half of it, we have a very dark, black, fine-grained basalt with some — it looks like some very thin laths in it of plage. Nothing else. And, in one region, there is some millimeter-type vesicles along a linear pattern very close to the contact. And, the other side of the contact, we have a pure, solid-white, fine-grained frag, which looks not unlike the white clasts in the 14 rock. But it's a beautiful contact in here. And, we'll call this one bag number ...
>
> 145:48:52 **LMP**: 198.
>
> 145:48:53 **CDR**: 198.

All of the astronauts who walked on the Moon (save one) were military test pilots. Apollo 15 demonstrated that these pilots could also be very fine field geologists.

---

[3] Complete video of the collection of 15415 can be found at http://www.hq.nasa.gov/alsj/a15/a15.spur.html

Genesis Rock

Even before sample 15415 arrived on the Earth, it had already earned a nickname. On August 6, 1971 (the day before splashdown), during the coast back to the Earth, the Apollo 15 astronauts held a televised press conference, answering questions submitted by the reporters covering the mission.[4] The second question put to the astronauts was about 15415:

> 270:25:45 **CAPCOM**: Question number 2. Near Spur Crater, you found what may be *genesis* rock, the oldest yet collected on the Moon. Tell us more about it.
> 270:25:59 **CDR**: Well, I think the one you're referring to was what we felt was almost entirely plagioclase or perhaps anorthosite. And it was a small fragment sitting on top of a - a dark brown larger fragment, almost like on a pedestal. And Jim and I were both quite impressed with the fact that it was there, apparently waiting for us. And we had hoped to find more of it, and, I'm sure, had we more time at that site, we would have been able to find more. But I think that this one rock, if it is, in fact, the beginning of the Moon, will tell us an awful lot. And we'll leave it up to the experts to analyze it when we get back, to determine its origin.

The reporter-coined nickname *Genesis Rock* has stuck, despite the fact that, as we will see, 15415 was not the oldest sample collected by Apollo 15.

Appearance

Even before 15415 was collected, its appearance attracted the attention of the astronauts. Unlike nearly all of the rocks on the Moon, 15415 is not a darkish gray, nondescript rock; rather, it is nearly completely white in color. The laboratory mugshot of the sample shows it to be a white, baseball-sized, coarse-grained crystalline rock (Figure 6.8). Its most interesting property is that it is composed almost entirely of a single mineral. The astronauts recognized this property on the lunar surface even before they picked it up:

> 145:43:02 **CDR**: As a matter of fact ... Oh, boy! I think we might have ourselves something close to anorthosite, 'cause it's crystalline, and there's just a bunch ... It's just almost all plage. What a beaut.

The *plage* they refer to is shorthand for a series of minerals called *plagioclases*. Plagioclases are very common rock-building minerals throughout the solar system, and are a major component of the Earth's crust. The specific plagioclase mineral that makes up 15415 is a calcium-rich plagioclase mineral called *anorthosite*.

[4]The complete press conference can be found at: http://www.hq.nasa.gov/office/pao/History/ap15fj/24day12_presser.htm

Figure 6.8: Image of 15415 at the Lunar Receiving Laboratory. The cube is 1 inch across [NASA S-71-42951].

Anorthosite is an unusual rock type: it is not part of the original inventory of solid material that the Moon formed out of; rather, it is a product of a complex geological process. In fact, the discovery of anorthosite in the lunar samples was very unexpected. One of studies from the initial Apollo 11 samples noted *anorthosite is one of the few rock types that have not been previously proposed by one writer or another as the substance of the lunar surface.* [90]

The final part of anorthosite's formation process is cooling from the liquid state. This means anorthosites like 15415 are igneous rocks. The first sample we looked at (10022) is also an igneous rock, but it could not be more different from 15415. In fact, the differences between these two samples are going to tell a very important story.

15415 **vs.** 10022

In Chapter 3 we learned that the sample 10022 is a dark, vesicular, fine-grained, 3.6-billion-year-old rock that cooled on the surface of the Moon. The sample 15415 shares none of these characteristics with 10022.

The most obvious difference is the color of the sample. Color is an important clue to composition. We learned that 10022 was dark because it was abundant in the titanium-rich mineral ilmenite. In a similar way, the light color of 15415 is due to its composition,

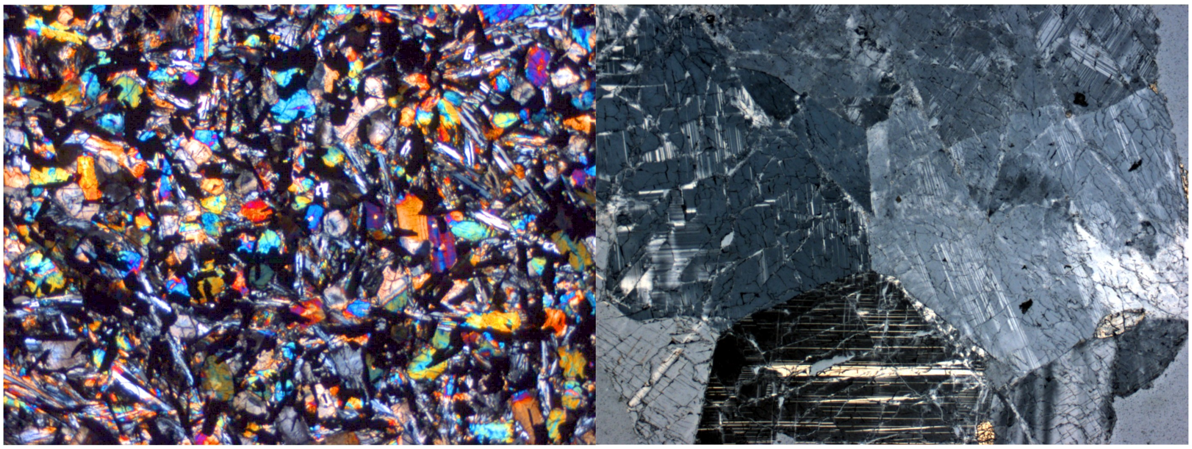

Figure 6.9: Thin sections of 10022 (left) and 15415 (right). Polarized light microscope images. The field of view for each image is approximately 2.85 mm wide. [NASA JSC01082 and JSC03885].

specifically the calcium-rich mineral anorthosite.

The vesicular nature of 10022 is an indication that the sample cooled at, or very near, the surface of the Moon. The sample 15415 has no vesicles, telling us it cooled under much higher pressure, deep below the surface of the Moon. The other indicator that 15415 cooled below the crust of the Moon is the large size of its mineral crystals. For igneous rocks, the size of the mineral crystals is an indication of how fast the rock cooled. Fast cooling leads to small crystals, and slow cooling leads to larger crystals.

Thin Sections

One of the most common laboratory techniques used to study rock samples is to slice and polish a piece of the sample so that it is only 0.03 mm thick. This is thin enough so that light can pass through all but the most opaque minerals. This thin slab is then mounted on a glass slide so it can be viewed through a microscope. A sample prepared in this manner is called a *thin section*. Thin sections were prepared for nearly all of the rock samples returned by the Apollo missions.[5]

The examination of a thin section reveals the size of its crystals, how they fit together, and the relationship between crystals of different minerals. This is often referred to as the *texture* of the rock. When thin sections are viewed through polarizing filters, the different minerals in that thin section will appear as different colors. The ability to determine the texture and composition of a sample means that this is a very powerful technique. Geologists call this technique *Petrography* and it is a fundamental part of geology.

Figure 6.9 shows thin sections of the samples 10022 and 15415 at approximately the same scale. A number of differences are easily apparent. The thin section of 10022 is

[5] The large sample 14321 (see Chapter 5) had over 100 thin sections (and counting) prepared.

characterized by hundreds of small, thin, and irregularly shaped crystals of many different colors, with many of the crystals being completely opaque. This tells us 10022 cooled quickly and is composed of many different minerals. The most common minerals are iron-rich pyroxenes, calcium-rich plagioclases, and the titanium-rich ilmenite.

By contrast, the thin section of 15415 shows only a few crystals, mostly very large of nearly the same color. The individual crystals have been fractured but it is easy to see they were once one solid crystal. This tells us 15415 cooled slowly and is composed mostly of one mineral, just the calcium-rich anorthosite.

The difference in composition between these two samples means that the densities of the two samples are also different.[45] Titanium-rich basalts like 10022 have densities of about 3.3 g/cm^3, while the anorthosites like 15415 have slightly lower densities of about 2.9 g/cm^3.

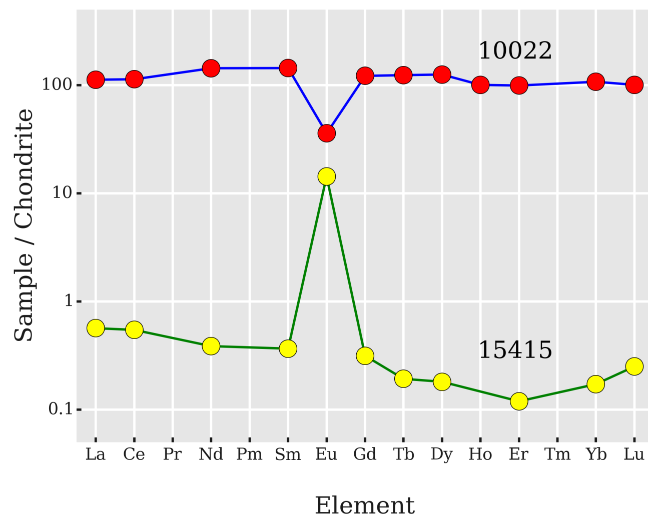

Figure 6.10: The abundance of rare earth elements in the samples 10022 (top) and 15415 (bottom). The abundances are measured relative to the abundances in chondrite meteorites. 10022 abundances are from [31]. 15415 abundances are from [30], [41].

Positive Europium Anomaly

One of the most important differences between 10022 and 15415 is the abundance of rare earth elements. In Chapter 3 we saw that the abundance of rare earth elements in sample 10022 was much higher than the abundance of rare earth elements in chondrite meteorites. In addition, there was an anomaly: the abundance of the rare earth element europium (and only europium) was relatively less than the abundance of other rare earth elements. This same analysis was done on a sample of 15415 and the results were very different: the amount of rare earth elements was less, and there was relatively *more* europium, not less.[68]

Figure 6.10 shows a plot of the abundance of rare earth elements in 10022 and 15415. As you can see, they are essentially mirror images of each other. This finding is a crucial piece of evidence that led to a very important idea about the early Moon.[6]

[6] A BIG caveat is needed here. This model of a lunar magma ocean was developed before the sample 15415 was even collected (and even before the europium anomaly was discovered). The model was originally based on data from small anorthosite fragments in the regolith from Apollo 11 [90]. However, the argument is exactly the same, and it fits in much more naturally with the discussion of 15415.

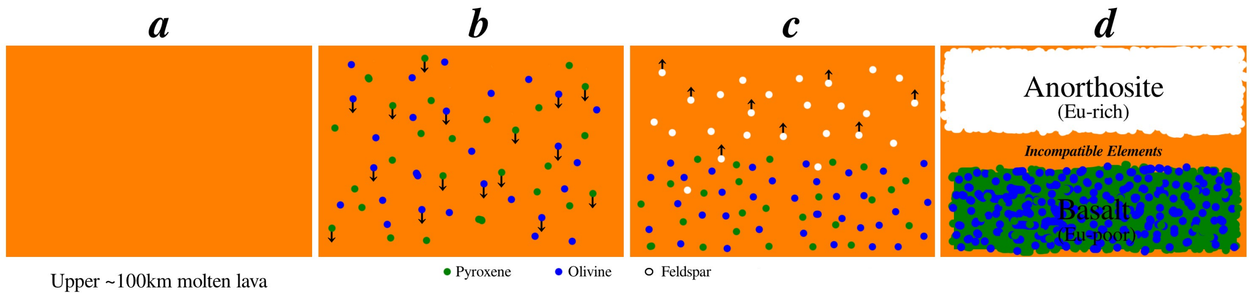

Figure 6.11: A schematic diagram of the global magma ocean model for the formation of the original lunar crust.

Magma Ocean

Imagine you have a large, deep lake of liquid magma on the surface of a world (Figure 6.11a).

As this lake of magma cools, mineral crystals start to form. The most common minerals to crystallize are olivine, pyroxene, and plagioclases such as anorthosite. The first minerals to crystallize are olivine and pyroxene. These minerals have a relatively high density, so they will sink to the bottom of the magma lake as they crystallize and become the source of basalts. (Figure 6.11b).

After about 3/4 of the magma lake has solidified, the calcium-rich anorthosite will start to crystallize. This is the important part: Europium atoms can sometimes substitute for calcium atoms during crystallization, because the size and charge of europium atoms is very close to the size and charge of calcium atoms. So, as the anorthosite crystallizes, it incorporates some of the europium from the magma. Anorthosite has a relatively low density, so it will float to the top of the magma lake as it crystallizes, forming a solid crust (Figure 6.11c).

Squeezed between the crystallizing basalts and anorthosite is magma that is rich in rare earth elements. The size and charge of rare earth elements make them an unsuitable *fit* for the crystal structure of minerals (they are called *incompatible elements*). This means that as magma is cooling and crystals are forming, the rare earth elements do not become part of the minerals, but will become increasingly concentrated in the remaining liquid magma.

This whole process is called *fractional crystallization*. The fractional crystallization of this magma lake will continue until you end up with a crust of anorthosite-rich rocks sitting on top of a mantle of pyroxene-rich and olivine-rich rock. Squeezed in between these layers will be a region of liquid that is rich in incompatible elements: rare earth elements, potassium and phosphorus. This remaining liquid will cool to form material that is rich in potassium (K), rare earth elements (REE) and phosphorus (P), the KREEPy lunar material (Figure 6.11d). This KREEPy material will not have much europium as that europium is now in the crust.

This model, formulated very early in the study of the Apollo lunar samples, proposed that the original anorthositic crust of the Moon was 25 km thick.[68] To make a crust this thick, the initial magma reservoir must have been massive, the entire upper 100 km of the Moon must have been molten at one time. This model is now know as the *global magma ocean* model.

The global magma ocean model implies that the initial crust of the Moon was composed of anorthositic rocks — rocks like 15415 — slow-cooling, large-grained anorthosites with a positive europium anomaly. Below this crust is the source of the KREEPy lunar material. Some of this KREEPy material subsequently erupted and flowed on top of the original crust, forming the mare rocks — rocks like 10022, fast-cooling, fine-grained basalts with a negative europium anomaly.

In Chapter 4, we saw that the ropy glass in the regolith sample 12033 was KREEPy. This fact implies that the Copernicus impact event evacuated material from the deep-seated KREEP-rich layer, melted it, and launched it to the Apollo 12 site.

Age and the Ancient Crust

The sample 15415 is a piece of almost pure anorthosite. The magma ocean model posits that the original crust of the Moon was composed of anorthosites. It would seem straightforward then that 15415 represents a piece of the original lunar crust. In fact, it was exactly this line of reasoning that led the science reporters to give 15415 the nickname *Genesis Rock*. It turns out, however, that the history of 15415 is not that clear.

Scientists calculated 15415's age of formation using the Argon-40/Argon-39 technique and determined it to be 4.08 billion years old. While this age is very old, it is about 450 million years *after* the formation of the original lunar crust.[7]

It should be noted that there were many anorthosite-rich samples collected in the near vicinity of 15415 that do have very ancient ages. For example, in one of the astronaut dialogs from earlier in the chapter, the commander Dave Scott describes another sample collected on the rim of Spur Crater thus:*on one half of it, we have a very dark, black, fine-grained basalt . . . And, the other side of the contact, we have a pure, solid-white, fine-grained frag.* That sample is 15455 and the white fragment of this sample is an anorthosite-rich clast with an age of 4.58 billion years, the age estimated for the formation of the original lunar crust.

The relatively young age of 15415 may be explained by a couple of different theories. A few studies have suggested that the age of 15415 may represent a later heating event and that the actual age of the sample's formation may be much older.[2] Another idea is that the global magma ocean model is an oversimplification, and that the large-scale fractional crystallization of the Moon happened in many large, more local events over a longer period of time. The sample 15415 may then be a piece from one of these later, but still ancient, events.[8] In either case, 15415 represents a very ancient piece of the early surface of the Moon.

[7] A summary of the age determination of 15415 can be found in [55]

[8] See [84] and Chapter 2 of [32]

The Original Context

There is a very important difference between 15415 and the previous three samples. In the three previous samples we have a very strong connection between the sample and the event and place of formation. We know the *context* of the sample. 10022 is a piece of the *Mare Tranquillitatis* formed with the mare. The ropy glass in 12033 is material formed by, and ejected by, the creation of the Copernicus impact crater. 14321 is a piece of the Fra Mauro formation, created by the Imbrium basin formation event. There is no such direct connection for 15415. We know it is a piece of the ancient crust of the Moon, but where it originally formed is completely unknown. The context of 15415 is not known. The farther you go back in time, the harder it is to establish the context of a lunar sample. For the ancient crust of the Moon, there may be no places exposed on the lunar surface where we can collect samples in their original context (*in situ*).

This is unfortunate, as it means that we may never be able to answer some basic questions about the history of the original lunar crust. Did it form at the same time all across the Moon? Was the magma ocean global or local? Was the composition uniform across the Moon?

As Don Wilhelm noted:[87]

> Basin ejecta has proved to be an important constituent (I think almost the only constituent) of the terrae (highlands). As Gene Shoemaker predicted in the early 1960s, the eagerly sought primitive lunar crust was not sampled in outcrop but only as small *pristine* fragments in the breccias, which have been recycled repeatedly from earlier ejecta blankets.

The History of 15415

Very early in the history of the Moon, an anorthosite-rich layer crystallized in an ocean of magma, floated to the top, then cooled to form the original lunar crust. In the Imbrium area of the Moon, the material that comprises 15415 was formed.

Over the next 500 million years, impact events shattered, heated, and mixed this original surface. Local volcanic events erupted KREEPy material onto this surface. The original surface was buried under 500 million years' worth of lunar geological processes.

3.8 billion years ago, the Imbrium impact basin was formed by an impact. Old, deep-seated material was lifted up to the surface by the enormous uplift and formed the rim of the Imbrium Basin.

Over the next 500 million years, lava eruptions filled in the Imbrium Crater, forming Imbrium Mare. This mare lapped up to and breached the uplifted rim of the Imbrium Basin. As the mare surface cooled, lava channels cut across the surface, creating the Hadley Rille.

Over the next 3 billion years, the continual bombardment of the lunar surface created a layer of regolith over the site.

About 100 million years ago, a small impactor slammed into the base of the rim of the Imbrium basin, forming the 100-meter-diameter Spur Crater. This small impact evacuated material from beneath the regolith. Ancient anorthosites, originally exposed by the formation of the Imbrium Basin rim, were brought back to surface and deposited on the rim the small Spur Crater.

On August 1, 1971, the two astronauts from Apollo 15, exploring the rim of Spur Crater, saw a bright white rock sitting on a small pedestal, collected it, and returned it to Earth.

Chapter 7

Apollo 16

Hot vs. Cold

Ever since the early 1600s, when Galileo first pointed his telescope at the Moon and found that it was a real place with real, three-dimensional geological features and not a perfect etched glass sphere, there has been a debate about the nature of those features. On one side of the debate is the *hot Moon* camp, which argues that most of the lunar features are derived from processes that are powered by energy *internal* to the Moon: volcanism and tectonics are primary processes that have changed the surface of the Moon. The most extreme proponents of the hot Moon theory believe that *all* lunar features are volcanically derived: all the craters are volcanic calderas, the hills and mountains are volcanic domes and cinder cones. On the other side of the debate is the *cold Moon* camp, which argues that most of the lunar features are derived by processes that are powered by energy *external* to the Moon. In this model, impact processes are the primary agents for change on the lunar surface. Extremists in the cold Moon camp believe that the Moon has always been a cold, unchanged rock throughout the age of the solar system, and that its interior has never been heated enough to significantly alter the rocks that comprise the Moon.

As we have seen in the previous chapters, the samples returned by the Apollo missions have been created and altered by both volcanic and impact processes; the most extreme ends of the hot vs. cold Moon debate can be quickly dismissed. However, that leaves a lot of room in the middle of the debate, a debate that ranged over 350 years and lasted all the way into the planning of the last two Apollo missions.

A Highlands Site

At the simplest level, the main goal for Apollo 16 was to land in a pure highlands site far from a mare surface.[1] All of the previous Apollo sites had been on or near lunar mare

[1] The story of how NASA chose the Apollo 16 landing site is a fascinating story and cautionary tale. See chapter 16 in [87].

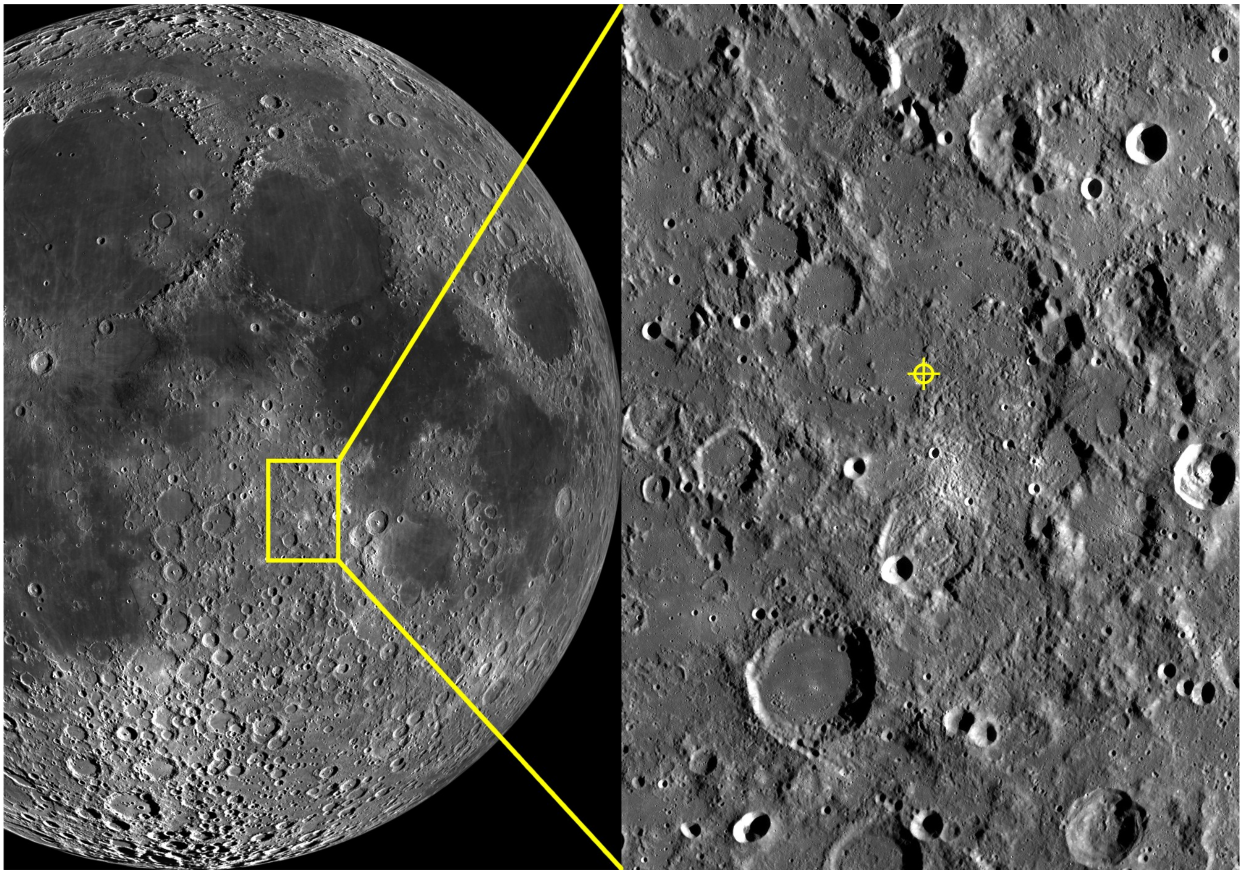

Figure 7.1: The landing site of Apollo 16 in the lunar highlands. The Descartes formation is the hilly patch of material to the immediate right of the Apollo 16 landing site. Images from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

(the Fra Mauro site of Apollo 14 is technically a highlands site, but it is surrounded by and partially overlapped by mare). Another important consideration was to find a site that would allow the astronauts to sample surfaces that had been formed before the Imbrium impact. Since the Imbrium event sent material all across the near side of the Moon (see Chapter 5), special consideration was needed to find a site free from the influence of Imbrium ejecta. A sample from a site like that would allow us to discover the processes that were important in changing the surface of the Moon after the formation of the original crust, but before the formation of the huge impact basins.

The location chosen as the Apollo 16 landing site is called the Descartes formation (Figure 7.1). It is a hilly, furrowed plateau located in the heavily cratered southern highlands on the near side of the Moon, about 380 km due south of the Apollo 11 site. The Descartes formation is surrounded by and partially overlapped by a relatively smooth plain called the Cayley formation. The Descartes formation stands out against the monotonous cratered highlands, and so it has attracted the attention of lunar scientists for a long time.

Figure 7.2: Geological maps of the region of the Apollo 16 landing site. (Left) Detail of the large-scale map [57]. The field of view is nearly the same as the inset of Figure 7.1. (Right) Detail of the immediate vicinity of the Apollo 16 landing site [34].

Pre-Mission Interpretations

In the previous chapters, we have seen that the pre-mission geological maps of the landing sites served as a compendium of what the scientists believed the astronauts would find at the landing sites. In the first four missions, what the geological maps predicted and what the astronauts found were in very close agreement. This was not the case for Apollo 16.

In the large-scale geological map of the region, created in 1968, the Descartes formation stands out as the turquoise feature in the center of the map (Figure 7.2, left). It is the only place on the map where this color is used, implying that the history and composition of the Descartes formation is different from any other place on the map. The interpretation of the Descartes feature on the map reads:[57]

> Volcanic materials that had less tendency to flow to low places than those of the Cayley Formation. Probably a high ratio of lava flows to tephra (volcanic particles such as ash). Possibly similar to plateau basalts of Earth.

In the detailed geological map (Figure 7.2, right) created just before the mission, the Descartes formation is colored red, the traditional color of volcanic units, and interpreted as *Volcanic materials, probably highly viscous at the time of emplacement.* The surrounding Cayley formation (the blue surrounding material) is interpreted as *Probably interfingering volcanic material of initially low viscosity.*[34]

Like the Apollo 15 astronauts, the crew of Apollo 16 embraced geological training, spending an average of two days each month on geological field trips prior to the mission. The geological field trips for the Apollo 16 crew heavily emphasized volcanic sites on the Earth, since the lunar scientists expected the astronauts to find mostly volcanic material at the Apollo 16 landing site. The pre-mission interpretation of the Apollo 16 landing site was heavily influenced by the *hot Moon* model.[2]

First Impressions

On April 21, 1972, the Apollo 16 lunar module *Orion* landed on target on the Cayley plains, right next to the Descartes formation. Immediately after touchdown, even before they acknowledged a successful landing, the astronauts let Houston know that samples would be easy to find:

> `104:29:36` **LMP**: Contact! Stop. Boom.
> `104:29:52` **CDR**: Well, we don't have to walk far to pick up rocks, Houston. We're among them!
> . . .
> `104:31:35` **LMP**: All we got to do is jump out the hatch and we got plenty of rocks.

Just a few minutes after touchdown, the astronauts looked out of the Lunar Module windows, across the landing site, and gave the scientists back on Earth the very first descriptions of the rocks at the landing site:

> `104:39:27` **CDR**: I wish I could tell you what kind of rocks those are Houston. But some of them are very white; and, doggone, if I could see...I'm not close enough to them, but...And I see one white one with some black...Can't tell whether that's dirt or not on it. But it could be a white breccia, if you believe such a thing.

Remember, the astronauts were very well trained in the appearance of volcanic materials, yet their very first description makes no mention of volcanic rocks, just breccia, the rocks of impact processes. The pre-mission volcanic interpretation of the landing site took its first hit.

Over the next couple of hours, the astronauts took care of housekeeping in the Lunar Module, had a meal, and prepared to get a night's sleep before the first EVA. During this time, they took a few moments to look out at the landing site and comment on what that saw:

> `106:18:32` **LMP**: One final comment here so I get back to work. About in my 1 o'clock position, about 30 meters out, just beyond the LM shadow - about twice as far as the LM shadow - there is a secondary crater with

[2] Don Wilhelms notes that before the Apollo 16 landing there was only one published study that doubted the volcanic interpretation of the Apollo 16 site. See page 292 of [87].

a large meter-sized block still in it. It looks like it formed the secondary, and it's got black and white...The top 3 percent or 5 percent of the block is black and white. Apparently, below that is solid white. Over.
106:19:03 **CAPCOM**: Very good.
106:19:07 **LMP**: And those black-and-white blocks, you can see them all over the place.

About an hour later, a question was relayed up from the scientists, asking the astronauts to elaborate on the rocks that they saw:

107:01:59 **CAPCOM**: Okay. Go ahead, Charlie. One thing; you mentioned two rock types: the black and white ones and then the all white ones. Do you see anything else?
107:02:13 **LMP**: Yeah, there was one right out in front of the LM here, just to the right of the footpad that looks like a breccia to me, Tony. Either that or an indurated regolith. We'll tell you when we get out.
107:02:30 **CAPCOM**: Okay.
107:02:45 **LMP**: Tony, we'll give you an analogy of what that black and white rock looks like. It's really a gray and white and looks like a granitic rock with very large crystals to it, though I kind of doubt that.
107:03:05 **CAPCOM**: Outstanding! You're really whetting our appetites.

Still not one mention of volcanic materials. Even before the Apollo 16 astronauts have stepped onto the Moon, the volcanic interpretation of the landing site has taken several hits.

Ground Truth

Following the pattern set by the earlier missions, the first EVA of Apollo 16 was largely devoted to deploying the Lunar Rover and setting up the surface experiments. During this time, the astronauts made an occasional comment on the rocks around them:

119:41:11 **CDR**: Oh, I'm looking at a rock here that's got all kinds of dark clasts in it, and biggies and that's got to be a breccia. Too many different kinds. Yeah. It is.
. . .
120:33:57 **LMP**: Man, look at that breccia, John! Right there. This big, subrounded...
. . .
120:44:01 **LMP**: Tony, I'm looking at this big rock, and it's a two-rock breccia. The matrix is a black rock - blackish to bluish - with some very fine, sub millimeter-size crystals.

During the first EVA, the astronauts collected samples near the site where they set up the surface experiments:

> 122:50:29 **CDR**: That big rock right there is a breccia - look at all those clasts in there.
> 122:50:33 **LMP**: I know it. Most of them in here are breccias.

The first EVA of Apollo 16 ended with a short geological traverse on the Lunar Rover. During the short drive to the first collection site, the scientists wanted to know about the rocks collected so far:

> 123:04:23 **CAPCOM**: Okay, Charlie. Those rocks that you collected, were they...Were they all breccias, or could you tell?
> 123:04:32 **LMP**: I'm not sure, Tony. I think they were breccias, but they were really dust covered, so I couldn't tell you, really.
> 123:04:40 **CAPCOM**: Okay, understand. And have you seen any rocks that you're certain aren't breccias?
> 123:04:54 **LMP**: Negative. I haven't seen any that I'm convinced is not a breccia.

By the end of the first EVA, it was clear that the landing site was not volcanic at all, but had been formed by impact processes. While the two astronauts on the lunar surface slept, the astronaut who kept station in lunar orbit learned of the day's results:

> 126:10:38 **CAPCOM**: And, Ken, the guys are back inside. I don't know whether you heard me a while ago or not, but EVA-1 was a total success. They had a seven hour and 11 minute EVA.
> 126:10:49 **CMP**: Outstanding. Did they have anything particularly significant to say or...
> 126:11:01 **CAPCOM**: I didn't catch all of it, let me ask...
> 126:11:02 **CMP**: Did they have any surprises in the things they saw or that they didn't expect?
> 126:11:30 **CAPCOM**: I guess the big thing, Ken, was they found all breccia. They found only one rock that possibly might be igneous.
> 126:11:40 **CMP**: Is that right?
> 126:11:45 **CAPCOM**: Yeah. I guess the guys are a little bit surprised by that.
> 126:11:46 **CMP**: Well, that ought to that ought to call for a session with the - yeah, yeah. Well, it's back to the drawing boards or wherever geologists go.

North Ray Crater Rim

The specific landing site for Apollo 16 was chosen because it allowed access to both the Cayley and Descartes formations within rover-driving distance. The two EVAs devoted to the geological traverses followed a well-established model: use recent (Copernican-aged) impact craters as drills to sample material from beneath the veneer of relatively recent

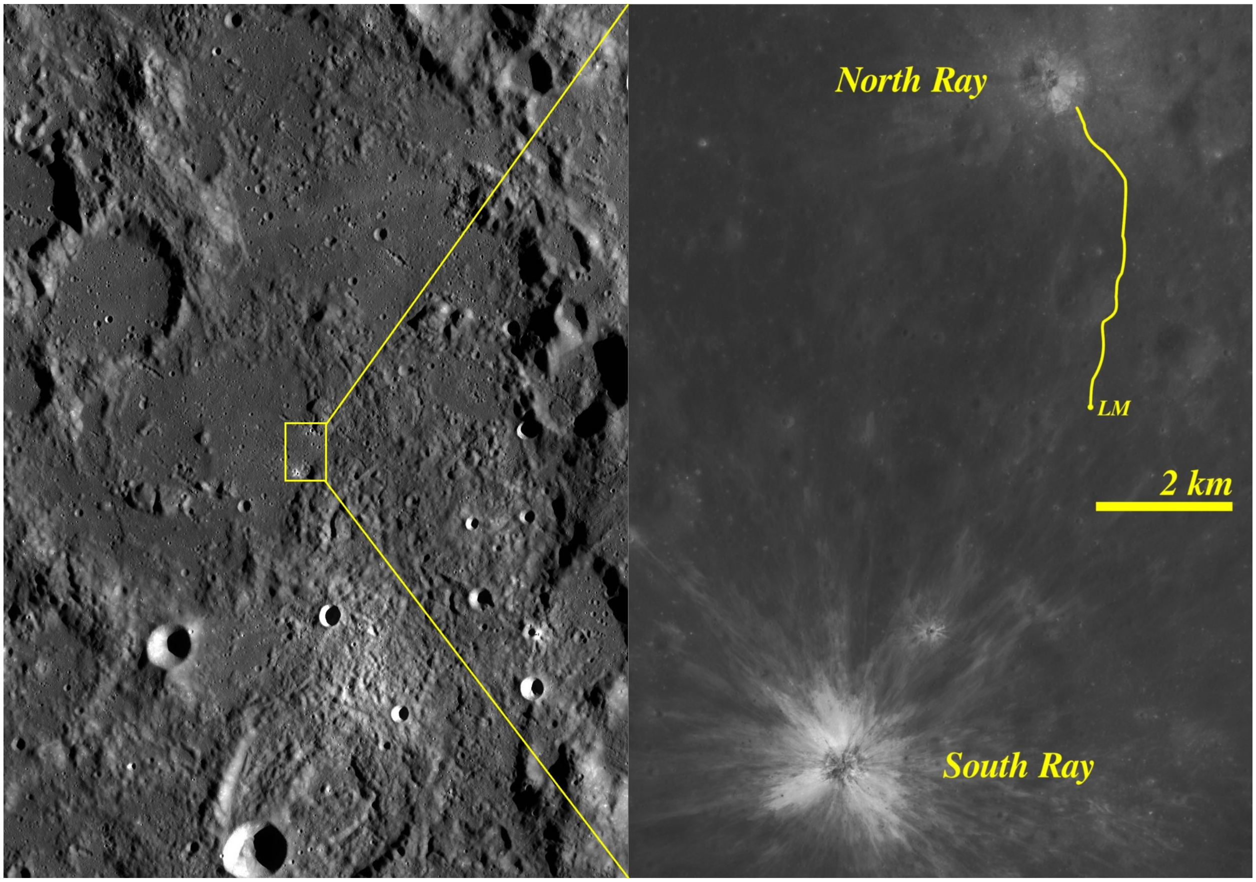

Figure 7.3: (Left) Detail of the Apollo 16 site on the edge of the Descartes formation. (Right) Close-up of the landing site, showing the route of the third EVA to the rim of the North Ray Crater. LROC NAC M106777343R/L [NASA/GSFC/Arizona State University].

Figure 7.4: Frames from the television transmission showing the mission Commander John Young examining the sample 67015 [NASA].

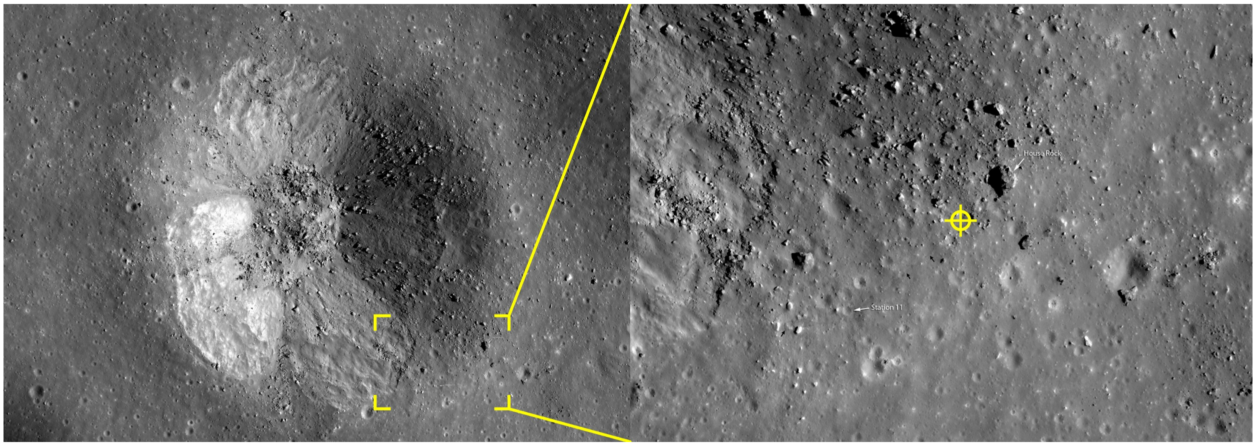

Figure 7.5: (Left) Close-up of the North Ray Crater. (Right) Detail of the southern rim, showing the approximate collection site of sample 67015. LROC NAC image M175179080LR [NASA/GSFC/Arizona State University].

regolith. The second EVA used a crater to the south (South Ray Crater) to drill into the Cayley formation, while the third EVA drove north onto the Descartes formation, to sample the rim of the 890-meter-diameter, North Ray Crater (Figure 7.3).

Like all of the earlier Apollo 16 sampling locations, the rim of North Ray Crater was dominated by impact breccias. The astronauts' descriptions of the rocks were basically variations of *very light-colored breccias with dark clasts*. A sample that is typical of the site (and the mission) is a softball-sized breccia that mission Commander John Young documented (Figure 7.6), described, and collected just inside the south rim of North Ray Crater (Figure 7.5):

> `167:09:11` **CDR**: Okay, Houston. The black clasts in this rock are really black material. It's either a very fine-grained black breccia...I'll tell you what it looks like. It looks like that black breccia, fine-grained that had that white clasts in it on Apollo 15. Although here, the matrix is white, and the clasts are black.
>
> `167:09:54` **CAPCOM**: Okay, understand.
>
> `167:09:55` **CAPCOM**: How large are the clasts?
>
> . . .
>
> `167:10:03` **CDR**: Three centimeters ...
>
> . . .
>
> `167:10:10` **CDR**: It could be a very dense, basalt-like rock. It is. It's cleavaged; I mean it looks like it has a 90-degree cleavage on it, and I'm hard put to tell that. That's just the way it breaks. But it's sure shocked. It's too big to go in the bag, but I'm going to put it in there anyway.

This sample, a 1.2 kilogram light-colored matrix breccia with dark-colored clasts, was assigned the sample number `67015` (Figure 7.6).

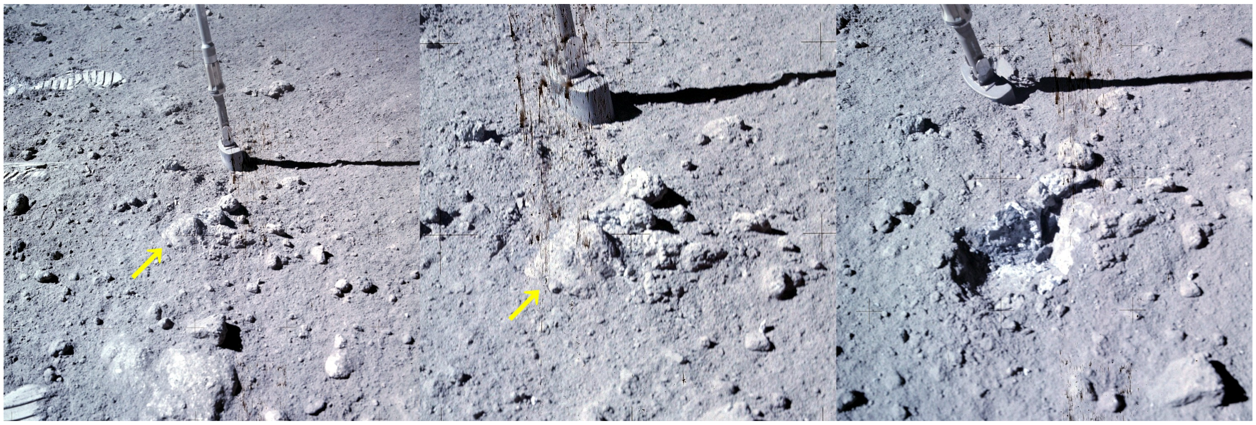

Figure 7.6: The documentation of the collection of sample 67015. (Left) The sample 67015 *in situ*. The sample is marked by the yellow arrow [NASA AS16-116-18621]. (Center) A close-up of the sample before collection [NASA AS16-116-18622]. (Right) The sample site after the collection of the sample 67015 [NASA AS16-116-18622].

Sample Appearance

Superficially, sample 67015 looks a lot like the sample from Fra Mauro (14321), big, angular clasts embedded in a fine-grained matrix (Figure 7.7). However, the two samples have different compositions, and these differences are what are important. The light color of 67015 — and of nearly all of the Apollo 16 samples — is due to the high abundance of plagioclases such as anorthosite. Apollo 16 found that this material is a major component of the lunar highlands.

In the previous chapter, we saw that the anorthosite sample 15415 represented a piece of the original lunar crust. It makes sense that the oldest surfaces of the Moon (the highlands) would be rich in this material. In fact, anorthosites are often used as the calling card of the highlands. For example, when we see anorthosite particles in the regolith of Apollo 11 and 12, we interpret it as highland material that has been tossed onto the younger mare surfaces by more recent impacts that occurred in the highlands. The high abundance of anorthosite in the highlands is the reason for the relatively high albedo of the highlands compared to the mare surfaces.

The other major components of 67015 are the centimeter-sized dark clasts. The dark clasts look a lot like basalt — fine-grained, dark — and the elemental composition even shows a negative europium anomaly. However, there is a very important difference between the dark clasts and the basalts. Basalts, such as the Apollo 11 sample 10022, are rocks formed from magma heated by internal processes (hot Moon: volcanism). The dark clasts in 67015 are not basalts, but *impact melts*. Impact melts are material formed from magma melted by external processes (cold Moon: impact crater formation).

In the end, basalts and impact melts are both materials that have cooled from molten rock.

Figure 7.7: Image of the Apollo 16 sample 67015 at the Lunar Receiving Laboratory [NASA S72-37216]. The cube is one inch high.

Chemistry of 67015 vs. 10022

The impact-melt clasts in 67015 and the entirety of 10022 both cooled from molten rock. The differences in chemistries between these two samples provide clues to the different origins of the material that formed these samples.

Table 7.1 highlights the major differences in the chemistries between 10022 and the impact-melt clasts of 67015. The high iron (Fe) and titanium (Ti) content of 10022 is characteristic of the higher-density material that originated in the lower, KREEP-rich layers of the lunar magma ocean. As this material erupted onto the lunar surface, it formed the lunar mare, covering up the ancient original crust. By contrast, the chemistry of 67015 is poor in these higher-density materials but rich in the low-density element aluminum (Al). Impact melt with this chemistry was originally referred to as *very high alumina* (VHA) *basalt* before the impact nature of its origin was understood. VHA impact melt is very common in the clasts of breccias collected on the rim of North Ray Crater.

Aluminum is major component of anorthosite. The high alumina content of the 67015 clasts indicates that they were formed from material that was part of the upper layers of the lunar magma ocean, the ancient lunar crust. The VHA clasts of 67015 are also rich in KREEPy material. This implies that the ancient crustal material was somehow mixed with deeper, KREEP-rich layers, during its formation. The obvious mechanism for mixing and melting ancient crust with material from deeper layers is an impact event.

	10022	67015
Al_2O_3	8.6	21.2
TiO_2	12.2	1.14
FeO	18.9	7.78

Table 7.1: 10022 vs. 67015 Chemistry [wt.%]. 10022 chemistries from [69], 67015 chemistries from [53]

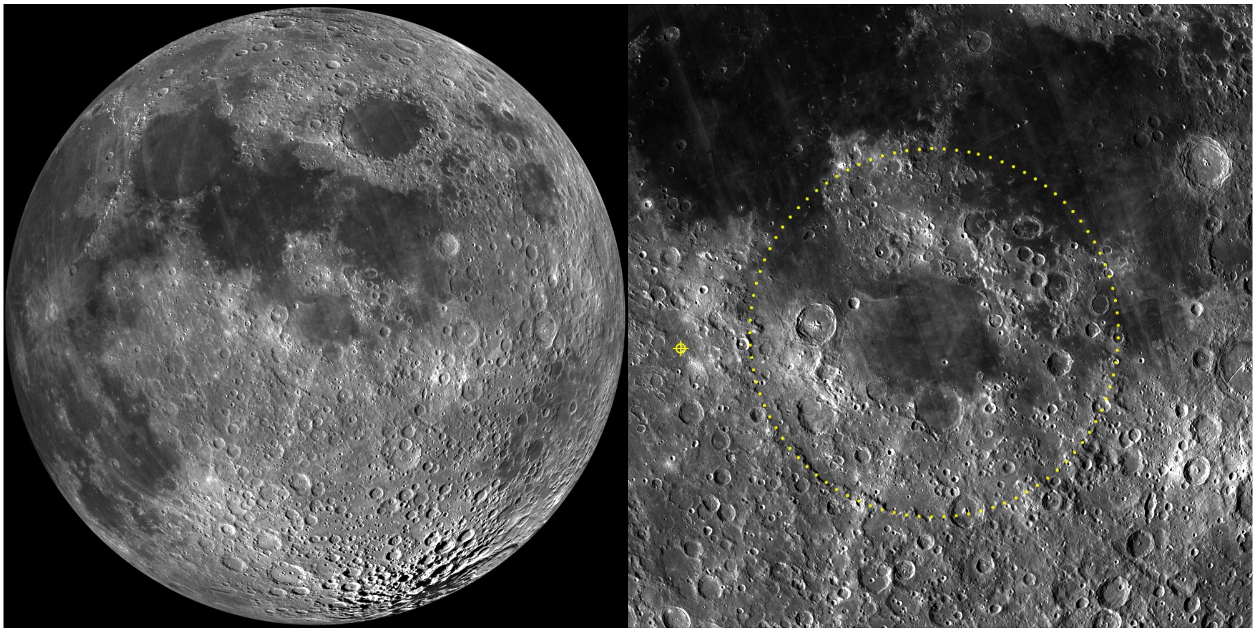

Figure 7.8: The Nectaris Basin. (Left) Image of the Moon centered on the Nectaris Basin. (Right) Close-up of the Nectaris Basin, showing the approximate location of the outer rim. The location of the Apollo 16 landing site is shown near the left edge of the image. Images from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

The Nectaris Impact Basin

The near-complete lack of volcanic materials at the Apollo 16 site meant that the pre-mission interpretation of the site was incorrect. Based on the samples, a new interpretation was needed, an interpretation where impact processes play the major role.

Most modern interpretations are a variation on the theme that the slightly younger Cayley formation is material ejected from the Imbrium impact event (essentially the same thing as the Fra Mauro formation explored by Apollo 14), and the Descartes formation is the ejecta from an older impact basin.[75] [43]

The most obvious candidate is the nearby giant impact basin named *Nectaris*. The Nectaris impact basin is 860 km in diameter and is one of the older basins on the near side of the Moon (Figure 7.8). The rim of the basin has been covered by more recent material, so is not nearly as sharp and well defined as the rim of the Imbrium Basin. The nearest rim of the Nectaris impact basin is about 100 km from the Apollo 16 site, and it is older than the Imbrium basin. This makes it the best candidate for the source of the material at the Descartes formation. The Nectaris Basin is large enough to have evacuated deep-seated KREEPy material, which makes it a likely source of the VHA impact melt in the 67015 sample. If this is the case, then the age of the 67015 melts will date the Nectaris impact event.

It should be noted that the connection between the Descartes formation and Nectaris Basin is not universally accepted. In fact, many scientists believe that the samples from the rim of North Ray Crater do not actually sample the Descartes formation, but are pieces of the Cayley formation instead.[3]

The time of the formation of the Nectaris Basin is an important event in the history of the lunar surface. Like the ejecta from the Imbrium impact, the ejecta from Nectaris can be traced across the near side of the Moon, so it is an important age marker. Since it is one of the oldest impact basins on the Moon, its age is used to mark the beginning of the time of large bombardments of the lunar surface. The formation of the Nectaris Basin marks the beginning of the *Nectarian* era of the lunar geological time scale. The end of the Nectarian era is set by the formation of the Imbrium Basin, one of the younger basins. The Nectaris Basin is the oldest landmark in the lunar geological time scale; everything older is referred to as *pre-Nectarian* in age (the *Genesis Rock* 15415 is pre-Nectarian in age) (Figure 7.9).

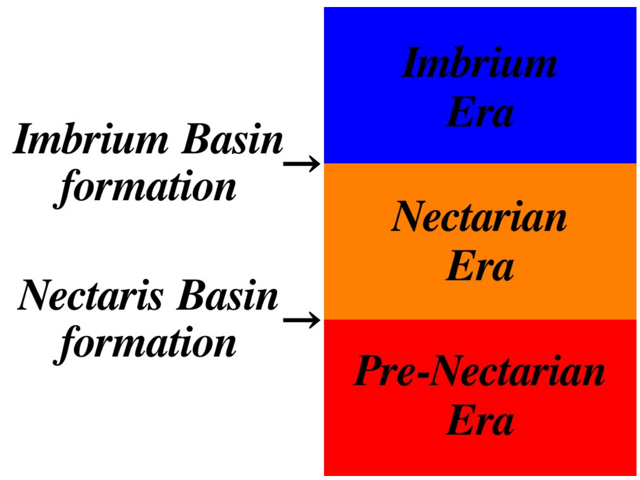

Figure 7.9: A simplified diagram of the earliest lunar eras.

The VHA melt clasts in 67015, as well as similar clasts in breccias collected on the rim North Ray Crater, have been dated using the Argon-40/Argon-39 technique.[53] [43] All of the melts have a narrow age range, with a strong cluster of ages at 3.92 billion years old.[75] This age is now accepted by most studies as the age of the formation of the Nectaris impact basin.

In Chapter 5, the age of sample 14321 was used to set the age of the formation of the Imbrium Basin at 3.87 billion years ago. This age is not that different from the age of the Nectaris Basin at 3.92 billion years. This means that the Nectarian era only lasted about 50 *million* years (0.05 billion years). In this short span of time, at least twelve large impact basins formed on the lunar surface. Apparently this was a time of intense bombardment of the lunar surface. This brief episode of large objects impacting the Moon is called the *Late Heavy Bombardment*.[80]

It should be noted that the 3.92-billion-year-old age of the Nectaris Basin, as well as the

[3] See chapter 9 of [88] for a summary of the arguments.

whole idea of the *Late Heavy Bombardment*, is not universally accepted. Many recent studies[4] have pointed out that most samples used to determine the age of the other eleven impact basins have been collected at sites contaminated by Imbrium ejecta. (This is certainly the case at the Apollo 16 site.) These studies propose that the narrow cluster of impact basin ages is due to contamination by Imbrium ejecta, and that the actual age of many of the basins may be much older.[5] In this model, large impact basins were forming all throughout the early history of the Moon.

[4]See [64] for a summary of the arguments

[5]For example, [64] put the age of Nectarin at about 4.1 billion years old

The History of 67015

For over 500 million years, the original anorthosite-rich crust of the Nectaris region was fractured, heated, and reformed by countless impacts. 3.92 billion years ago (or earlier), the large Nectaris Basin formed during an impact event. The energy from this event created a large amount of heated and completely melted material that later cooled. The resulting anorthosite-rich breccia with impact-melt clasts was thrown all across the near side of the Moon. A large deposit of this ejecta landed about 100 km from the western rim of the Nectaris Basin, forming what would become the Descartes formation.

A short time after this event (about 80–200 million years later), the Imbrium impact (more than 2,000 km away) ejected material that partially covered the Descartes formation, and intermixed with original material. This Imbrium material formed the Cayley formation.

For the next 3.8 billion years, a thick layer of regolith accumulated over these features due to the the continuous bombardment of the lunar surface.

50 million years ago, a small bolide impacted into the base of the Descartes formation, forming the 890-meter-diameter North Ray Crater. The formation of this crater dug up material from the underlying Descartes formation and deposited it on the rim of the crater.

On April 23, 1972, the two Apollo 16 astronauts, on their third EVA, drove the Lunar Rover 5 km to the north of the Lunar Module to the rim of North Ray Crater. Here they collected many impact breccias from the Descartes formation, including the sample that would become `67015`, and returned them to the Earth.

Chapter 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.[1]

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.[2] 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.

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):

> `128:12:4` **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

[1]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* [87].

[2]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.

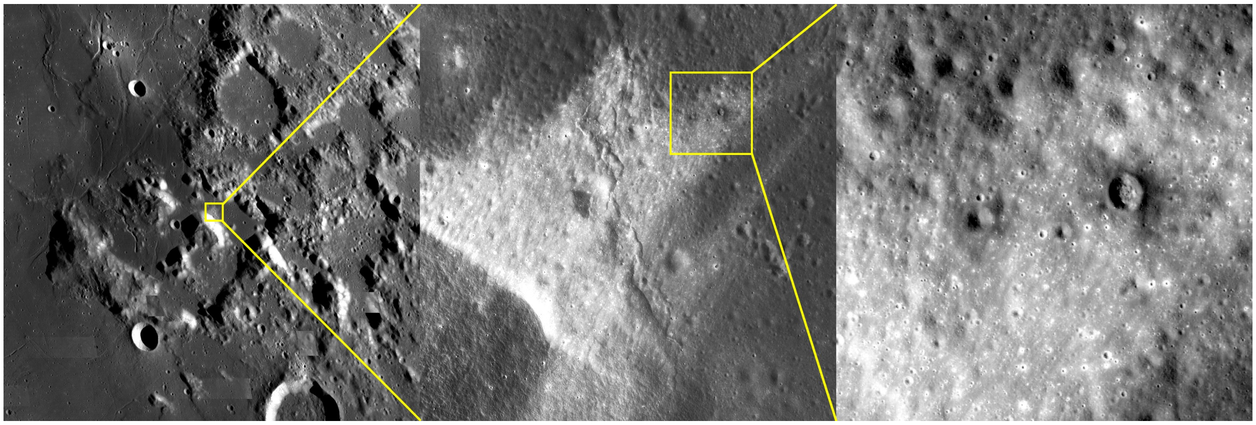

Figure 8.1: Dark halo craters in the Taurus-Littrow valley. (Left) The southeastern rim of the Serenitatis Basin. LROC near side mosaic [NASA/GSFC/Arizona State University]. (Center, Right) Close-up of the landslide in the Taurus-Littrow valley, showing the dark craters reported by Al Worden. LROC NAC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

> 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

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.

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

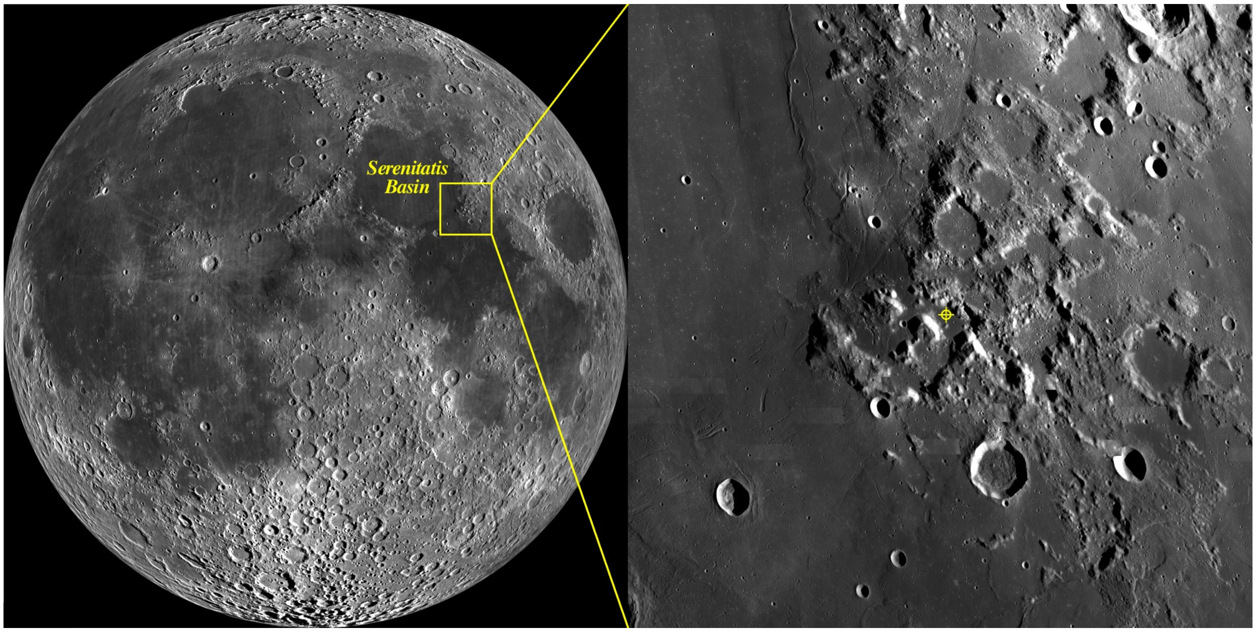

Figure 8.2: The location of the Serenitatis Basin and the landing site of Apollo 17 on the southeastern rim of the Serenitatis Basin in the Taurus-Littrow valley. LROC WAC near side mosaic [NASA/GSFC/Arizona State University].

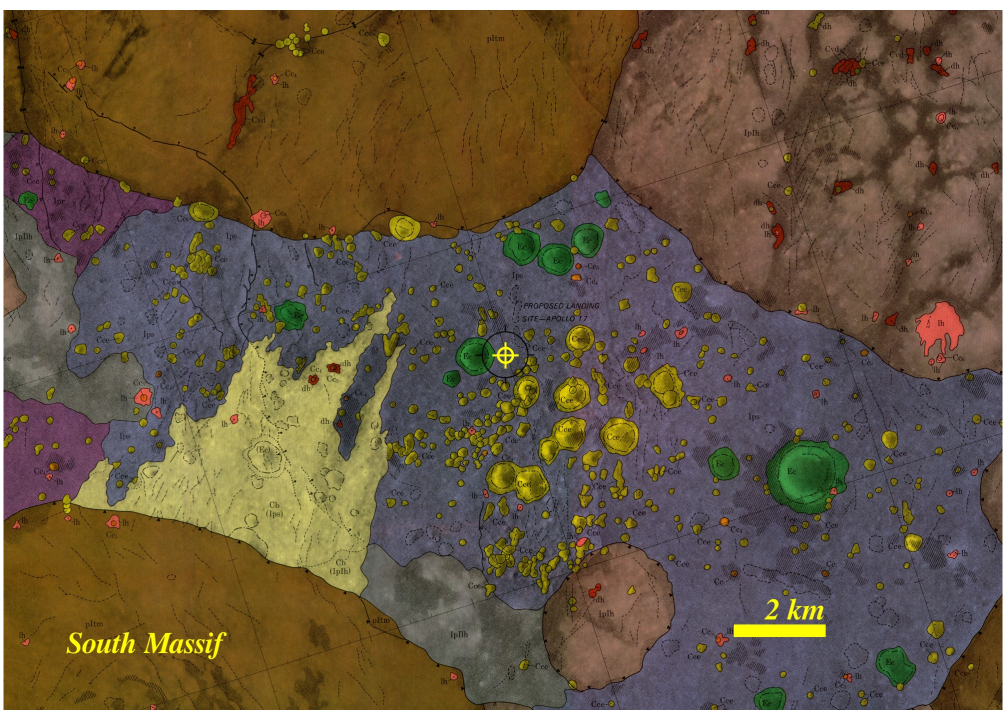

Figure 8.3: Detail from the pre-mission geological map of the Apollo 17 landing site [49].

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.

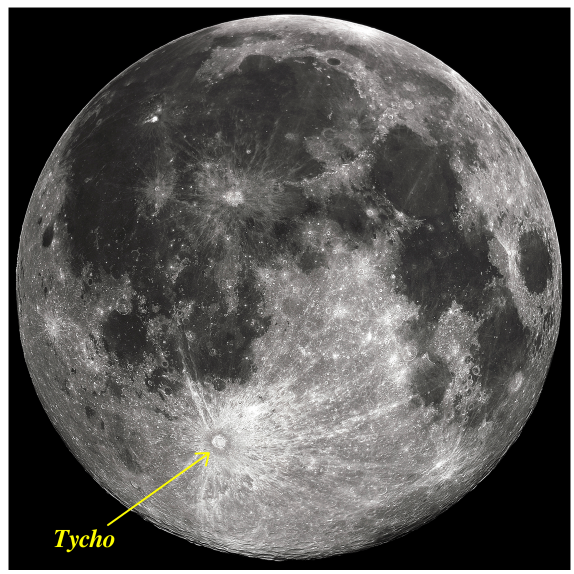

Figure 8.4: Image of the full Moon, showing the location of the Tycho impact crater [Image from Gregory H. Revera].

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.[49]. 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.

Studies published immediately after the Apollo 17 mission added further support to the Tycho connection.[3] These studies noted the alignment of the central cluster of craters,

[3] See [60], [38], [48]

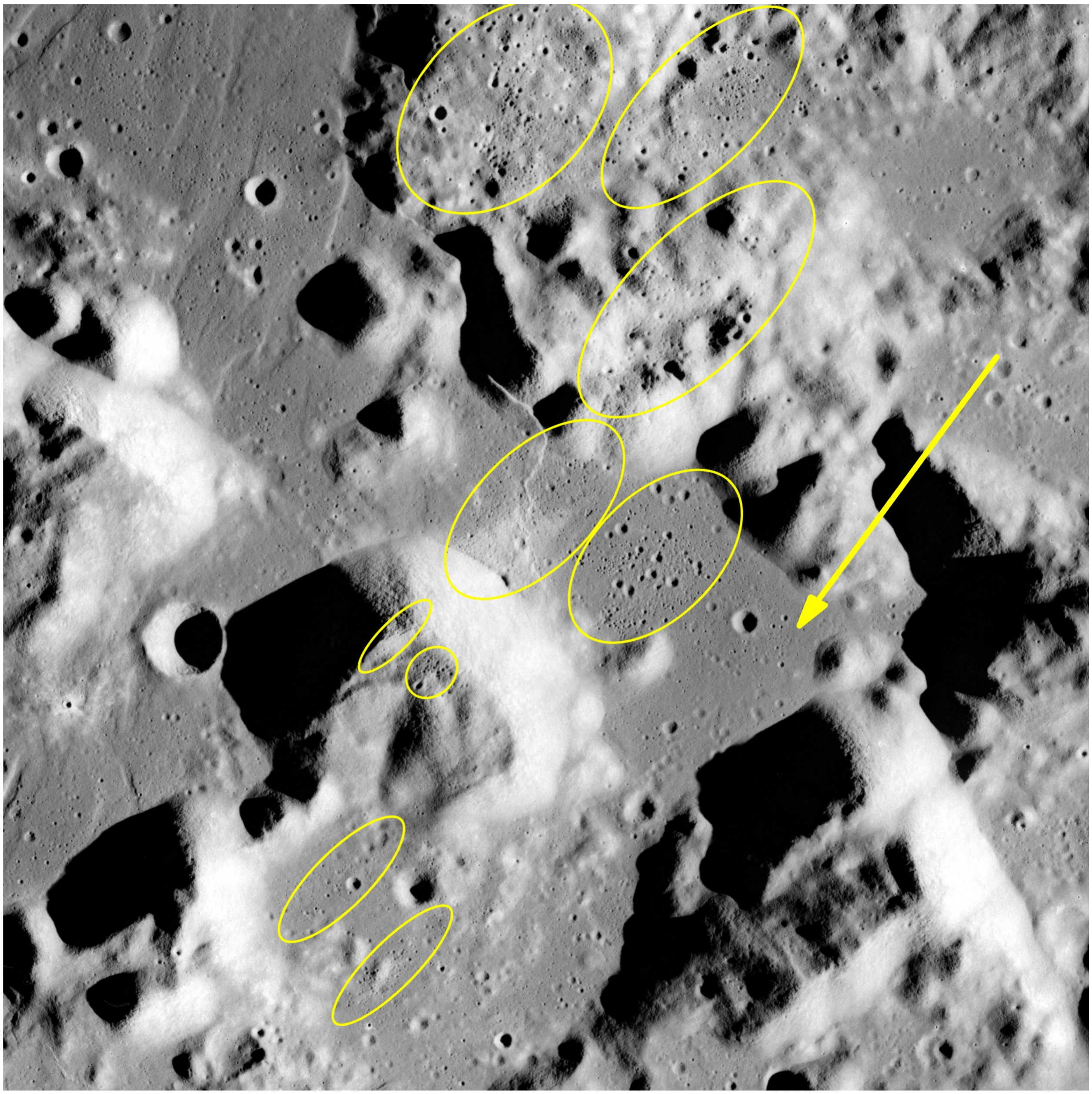

Figure 8.5: Image of the Taurus-Littrow valley [NASA AS17-M-0447]. The yellow ellipses mark recent impact craters on the site (adapted from [48]). The arrow indicates the direction to the Tycho impact crater.

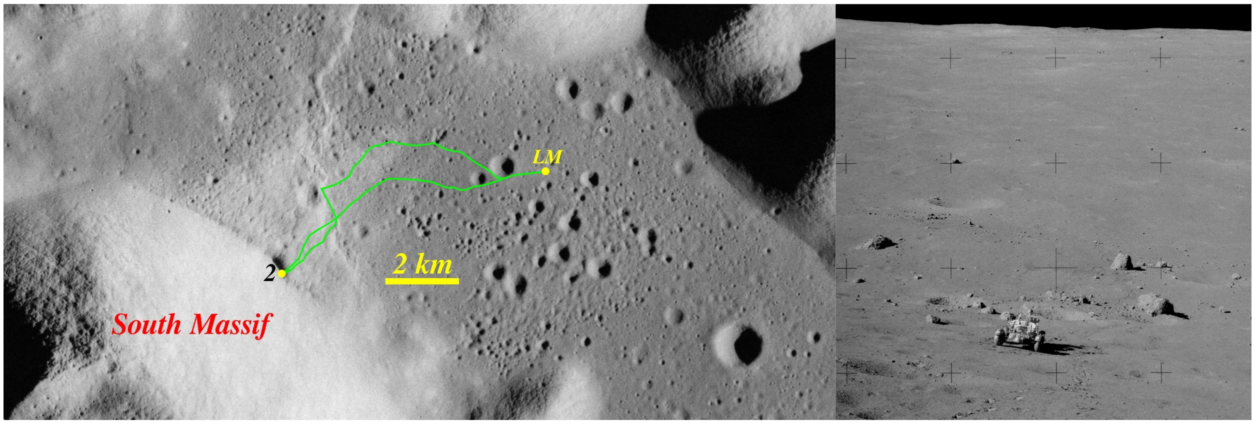

Figure 8.6: The second EVA of Apollo 17. (Left) The route of the second EVA across the Taurus-Littrow valley floor [NASA AS17-M-0447]. The stop at the base of the South Massif is labeled with a **2**. (Right) The Lunar Rover at the base of South Massif [NASA AS17-138-21072]. The view is toward the top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

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 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.[4] 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

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 [4].

in diameter. The goal of the rake was to remove any bias in the collection of samples. Instead of collecting only rocks chosen 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.

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.

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

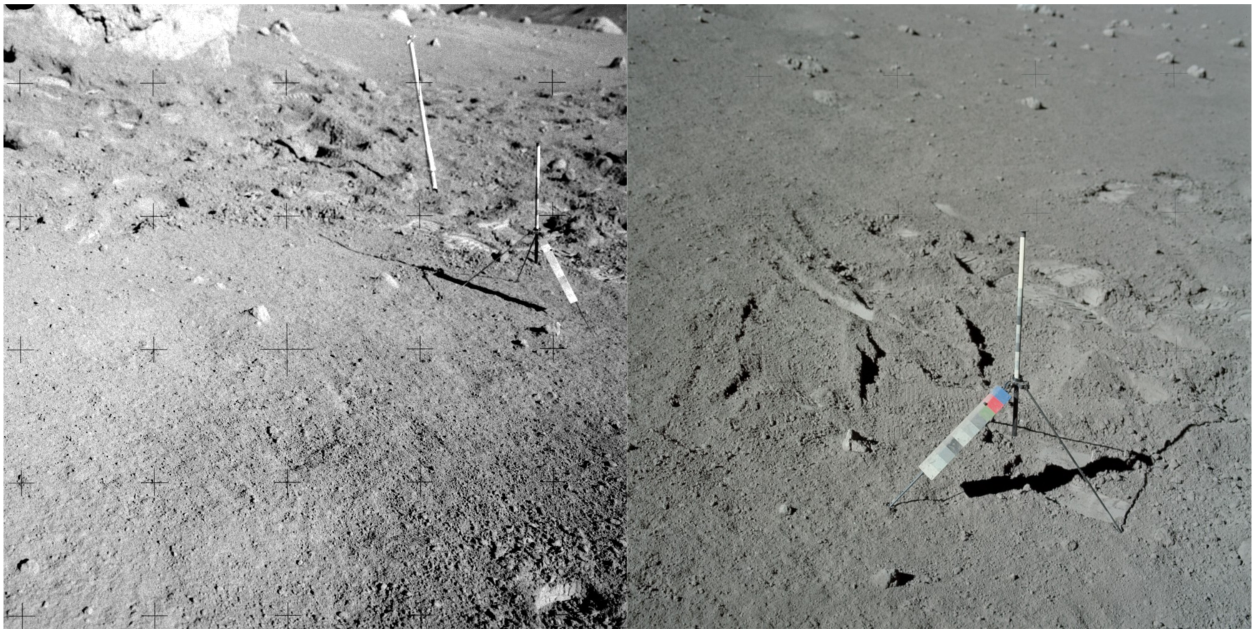

Figure 8.8: The before and after images of the rake sample collection site at the base of the South Massif [NASA AS17-138-21046 (left), AS17-137-20962 (right)].

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)[14]. The largest of these impact-melt breccias was the 221-gram, baseball-sized rock 72535.

All of the samples were chemically similar to the nearby boulders,[46] suggesting that the small, rake-sample rocks had once 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.[17]

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

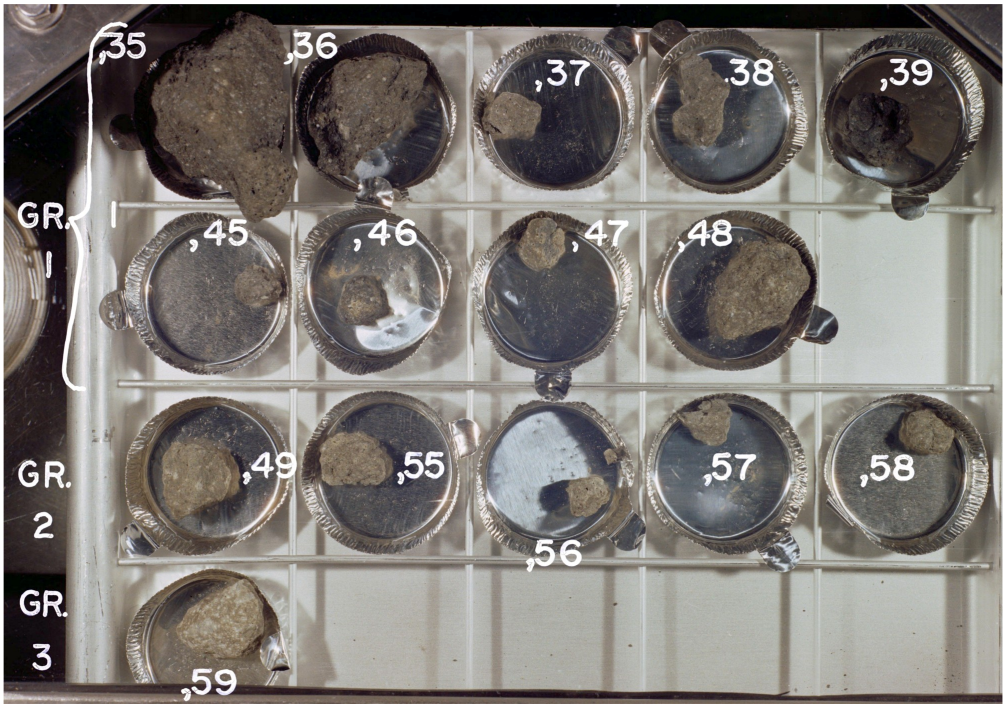

Figure 8.9: The larger rocks from the rake sample collected in bag 501 [NASA S73-19605]. The sample 72535 is the largest sample, in the upper left corner. The round aluminum sample trays are about 2 inches across.

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

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.[76] This would imply that the age of 72535 does not date 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.[24] 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.

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.[7] 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 $\pm$ 4 million years old.

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 $\pm$ 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

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

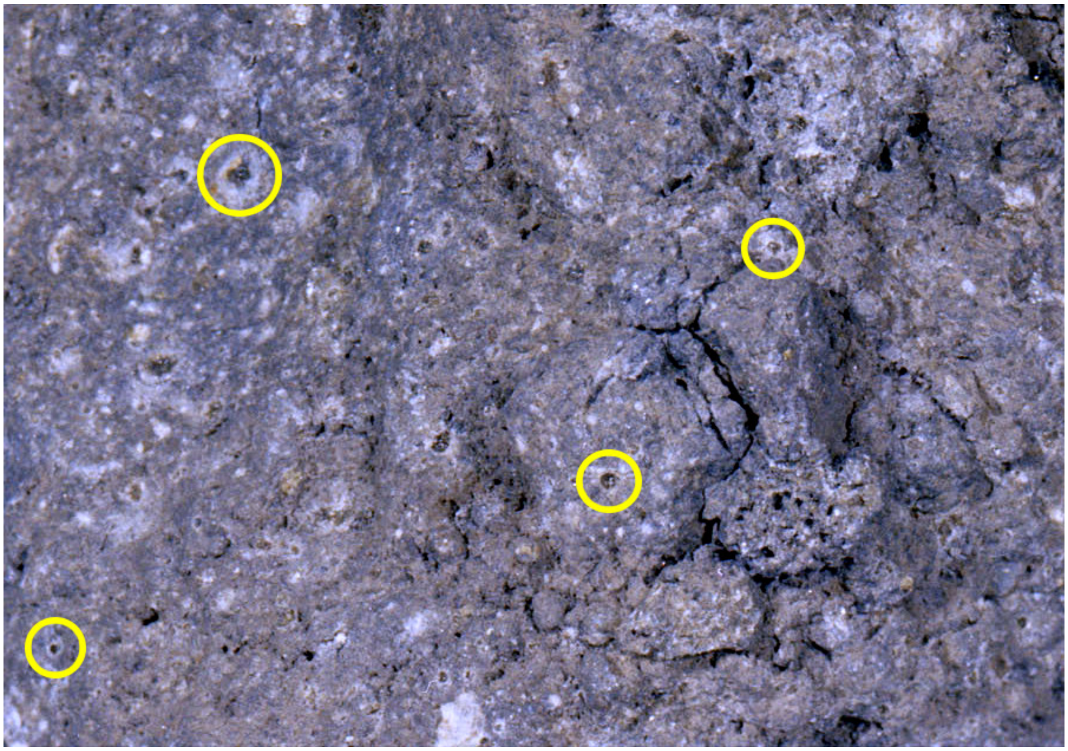

Figure 8.11: Close-up of the sample 72535 at the Lunar Receiving Laboratory. A few of the micro-meteorite craters are circled [NASA S73-19581].

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.[36] Over time, these impacts will reduce the rocks to a powder, creating the lunar regolith (see Chapter 4).

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.[9] 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.[35]

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, [37] so that means that they will last a few million years before they are

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)].

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.

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 upwelled 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.

Chapter 9

History of the Moon

2,415 samples weighing a total of 382 kg (842 lbs) were returned from the Moon by the six Apollo missions. In this book we have investigated the story of only six of these samples, a mere 11.2 kg of material, an infinitesimal fraction of the total haul. These six stories are each a small piece of a larger work. This larger work is the history of the lunar surface.

Themes and Variations

When you take a look at a summary of the six samples (Table 9.1), two themes are readily apparent.

Sample	Mass [g]	Sample	Source	Radiogenic Age [billion yrs]
10022	95.6	Basalt	Mare Tranquillitatis	3.59
12033	450	Regolith	Copernicus Crater	0.80
14321	8,998	Impact Breccia	Imbrium Crater	3.87
15415	269.4	Anorthosite	Ancient Lunar Crust	4.15
67015	1194	Impact Breccia	Nectaris Crater	3.92
72535	221.4	Impact Melt	Serenitatis(??) Crater	3.89

Table 9.1: Summary of the six samples in this book.

The first apparent theme is their radiogenic age: the samples are ancient. Five of the six samples are older than 3.5 billion years old, older than >99.9% of the Earth's surface. The history of the Moon is the history of an ancient surface. Most of the significant change of the lunar surface happened a long time ago, long before the current crust of the Earth was formed. The history of the first billion years of the solar system cannot be found on the Earth; those surfaces are long gone. If you want to know what happened in the first billion years of our solar system, you have to look to the Moon.

The second theme is that the energy that created the samples came predominately from impact processes. The history of the lunar surface is mainly a story of objects raining down on the Moon and modifying its surface. Volcanism played a very minor role in the global history of the lunar surface. The mare surfaces may cover a large part of the lunar near side, but the mare are a relatively recent, thin veneer of material over an extensive, impact-modified ancient surface.

Putting these two themes together, we can surmise that the history of the early solar system is a history of impacts. It is a history that is shared by all of the surfaces in the inner solar system.

Not all of the events witnessed by the samples are ancient. From the exposure age of three of the samples, (Table 9.2), scientists were able to determine that three small, local impacts events happened relatively recently. These events are important since they demonstrate that impacts are still modifying the surface of the Moon.

Sample	Exposure Source	Exposure Age [billion yrs]
14321	Cone Crater	0.025
67015	North Ray Crater	0.047
72535	Tycho Crater	0.096

Table 9.2: Age of recent craters from samples' exposure ages.

In Situ

At the very beginning of this book, I said that one of the most important characteristics of the Apollo samples is that they have a **Context**. In the chapter that followed, we saw that establishing the context of the samples is not a simple problem.

The specific context (the collection site) of the sample is usually easy. Most of the Apollo samples were documented on the surface of the Moon. Some were documented in great detail, some by just a single photograph. There is little controversy about where the samples were collected.

The tricky part is to relate a sample to a particular geological unit. Sometimes this is pretty straightforward. There is little controversy that sample 10022 represents a piece of Mare Tranquillitatis or that 14321 is a piece of the Fra Mauro formation and was created by the Imbrium impact event. The connection of the ropy glass in 12033 with the Copernicus impact event is pretty solid, but there is certainly room for other interpretations. The connection between 67015 and the Nectaris impact is fraught with controversy. So, too, is the connection between the impact melt 72535 and the the Serenitatis impact event. We have no idea where 15415 began its life or even if the measured radiogenic age really represents when it formed.

I believe that the story of the context of our six samples is representative of the entire collection of Apollo samples. Many samples have strong connections to specific geological

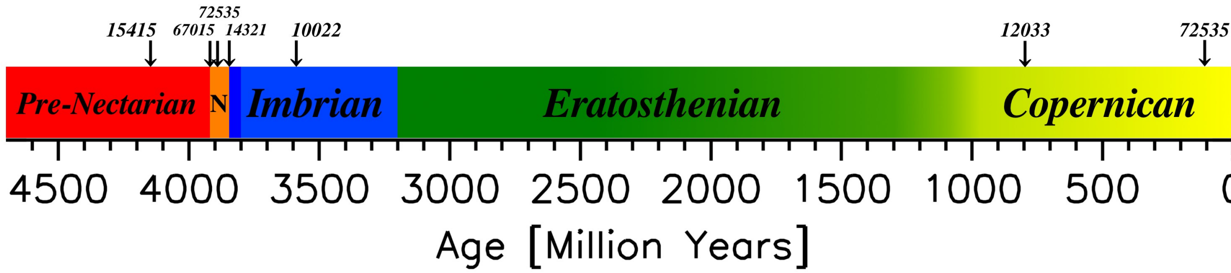

Figure 9.1: Lunar Geological Time Scale

units with well-defined histories. Some samples may have a good connection to a unit, but the history of that unit may be problematic. And some samples have weak connections to geological units whose histories are a mess or completely unknown.

From Local to Global

The story the Apollo samples tell covers an area far larger than the area explored by the Apollo missions. Scientists can relate well-known local samples with global features. The Apollo lunar samples can give us insight into the stories of places far away from where the samples were collected.

Way back in Chapter 3, we saw that the relative age of overlapping surfaces can be determined by using stratigraphy. (Young features overlie older features.) The samples allowed us to turn those relative ages into absolute ages. The samples *calibrated* the local stratigraphy.

Throughout this book, I have talked about the importance of determining the age of certain events. Some events, like the formation of the Imbrium impact basin, have left a signature across the surface of the Moon. Knowing the age of these far-reaching events allows us to determine the ages of surfaces all over the Moon, and to see how distant surfaces are related. When scientists determined the age of the Imbrium impact event by finding the formation age of sample 14321, the age of an important time maker was then known: it has been **calibrated**.

The Lunar Geological Time Scale

In Chapter 4, we were introduced to the lunar geological time scale as way to relate the ages of features across the Moon. The sample from that chapter, 12033, was instrumental in determining the age of the Copernicus Crater. Other samples we looked at played equally key roles in establishing important time markers in other eras (Figure 9.1).

With the lunar geological time scale calibrated, features across the surface of the Moon, including places not visited by the Apollo missions, can be placed into geological eras and constraints can be placed on their absolute ages. For example, Figure 9.2 shows the

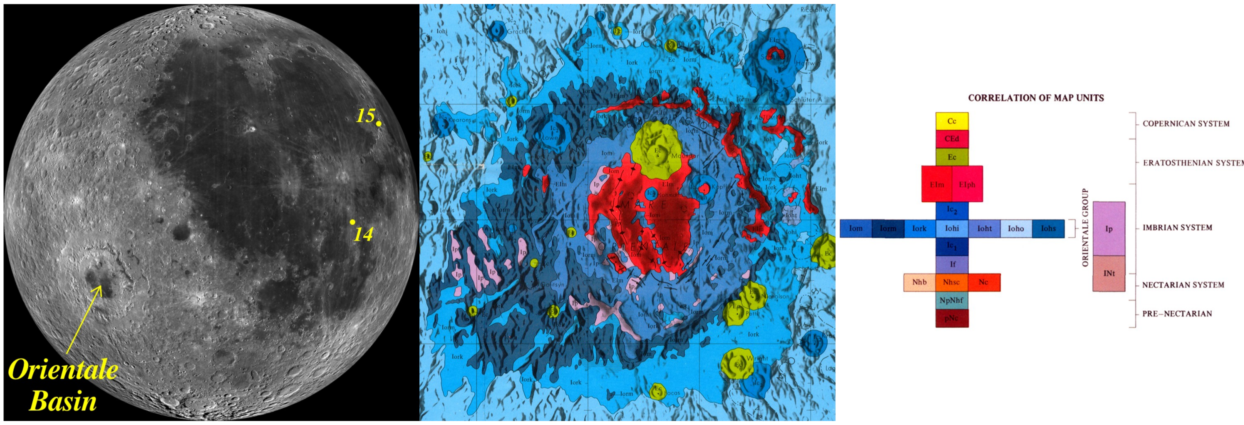

Figure 9.2: The Orientale impact basin. (Left) The location of the Orientale impact basin on the western edge of the near side. The landing sites of Apollo 14 and 15 are shown for reference. LRO mosaic [NASA/GSFC/Arizona State University]. (Center) A detail of the geological map of the center of the Orientale impact basin[71]. (Right) The key for the geological map, indicating the geological eras.

geological map of the region surrounding the Orientale impact basin, a feature on the very western edge of the lunar near side. This basin is the youngest and freshest of the large impact basins on the Moon. It is way outside of the Apollo landing zone of the Moon, so Apollo did not explore it. We do not have any samples from this region.[1] Even without samples, however, broad absolute ages can be determined for features in this region using the calibrated geological timescale. For example, in the very center of the basin sits a mare surface (red, labeled `EIm`) that scientists have assigned to the very end of the Imbrium Era or the beginning of the Eratosthenian Era. This means that this mare most likely has an age in the range of about 2.8 billion to 3.4 billion years. This is most likely a rather young mare surface.

The ages of features determined using the lunar geological time line can be very approximate, particularly in the Copernican and Eratosthenian Eras. There is a far more accurate method available, a method, like the geological time scale, that was calibrated by the Apollo samples.

Crater Counting

A glance at the Moon's surface shows that the number of impact craters is not uniform. The younger surfaces have far fewer impact craters than the older surfaces (Figure 9.3. The number of craters in a given area of lunar surface (number of craters per square kilometer) is called the *crater density*. The relative ages of surfaces can be established by comparing the crater densities: the surfaces with more craters are older.

[1]This may not be entirely true; some have argued that the Apollo 16 samples contain material ejected from the Orientale Basin.

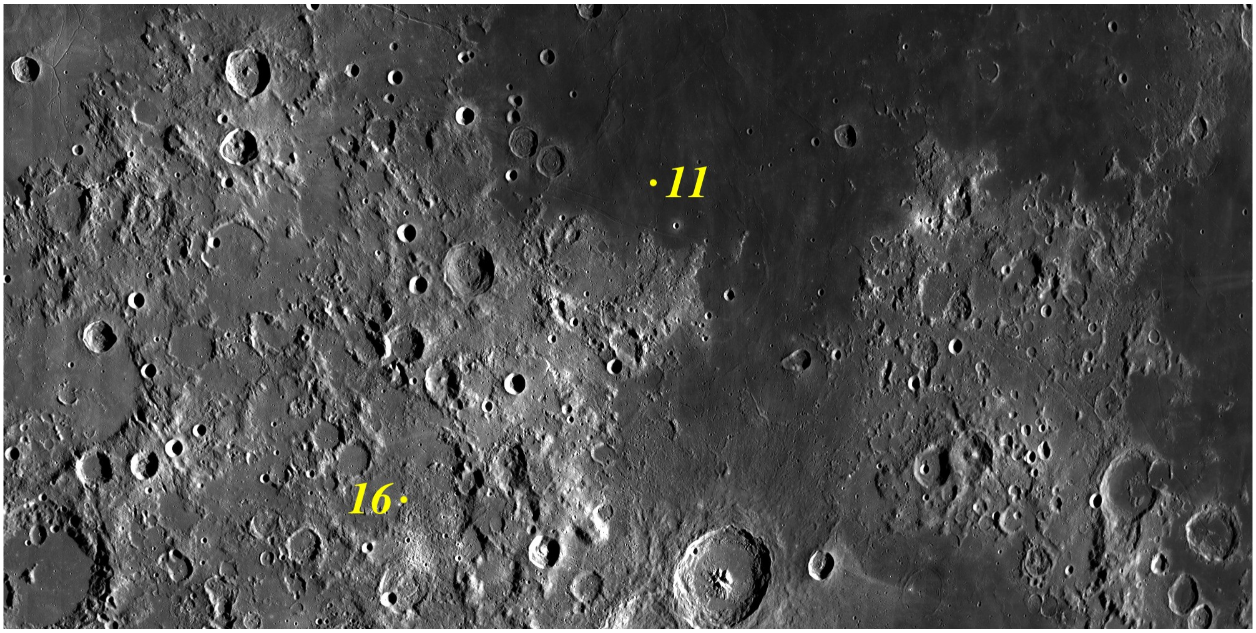

Figure 9.3: The equatorial region of the lunar near side, illustrating the contrast in crater densities between the younger mare landing site of Apollo 11 and the older highlands site of Apollo 16. LRO near side mosaic [NASA/GSFC/Arizona State University].

This technique is very powerful, since it allows us to compare surfaces that are far apart, even if the surfaces have no common features that would allow us to determine their stratigraphic relation. Many mare surfaces on the near side are isolated and do not overlap other mare surfaces, making stratigraphic relations hard to determine. In such cases, we can use crater densities to determine their relative ages.

An extreme example is the case of the mare in the Tsiolkovskiy impact crater on the far side of the Moon (Figure 9.4).[2] The Tsiolkovskiy crater location means that there is absolutely no physical overlap with any near side mare surfaces, so comparing crater densities with near side mare surface is the only way to determine its relative age. Crater counts on the Tsiolkovskiy mare determined that it has a slightly higher crater density than the Imbrium mare at the Apollo 15 site, but not as high a crater density as Mare Tranquillitatis at the Apollo 11 site.[82] This result is important as it established that the mare on the far side formed in the same era as the mare on the near side. The formation of mare surfaces happened at about the same time all across the lunar surface.

[2]The Tsiolkovskiy crater mare was Jack Schmidt's favorite candidate landing site for Apollo 17. The very complicated logistics of a far side site, including the need for a communication satellite in lunar orbit, ruled it out early in the selection process (see Chapter 7 of [87]).

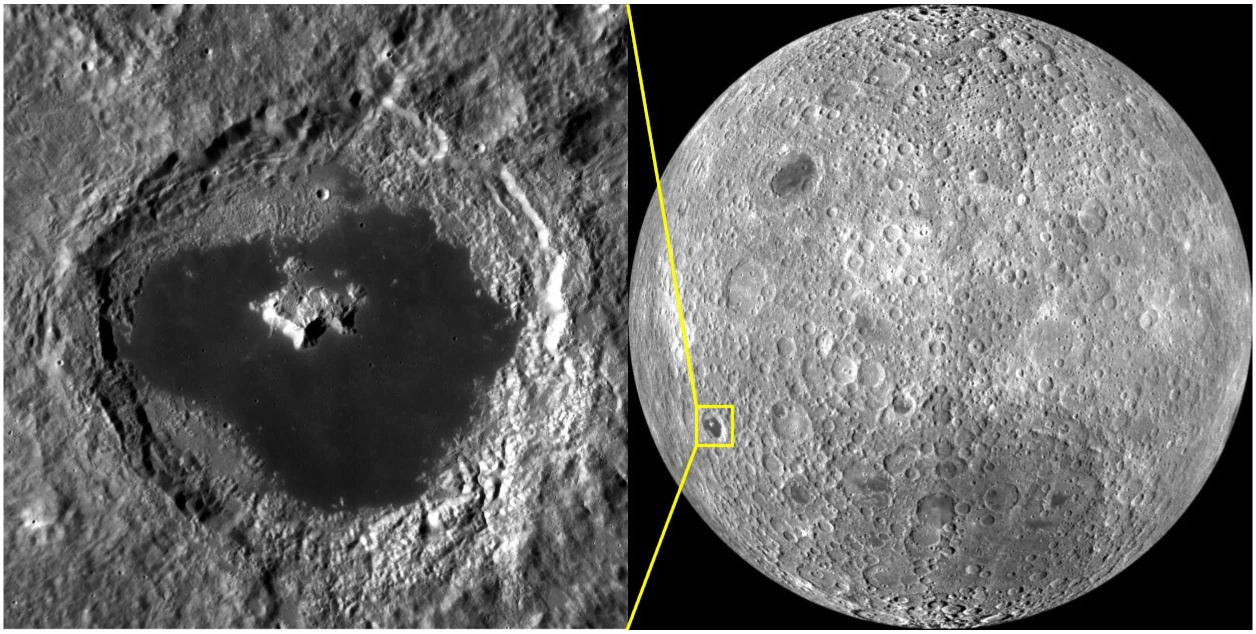

Figure 9.4: Tsiolkovsky impact crater on the lunar far side. LRO mosaic [NASA/GSFC/Arizona State University].

From Relative to Absolute Ages

There are many different ways to quantitatively represent the crater density of a surface. One of the most commonly used representations is called the *cumulative size-frequency distribution*. In this representation, we choose an area and count the total number of craters larger than a diameter D. In its simplest form, the cumulative size-frequency distribution of a surface can be reduced to a single number by choosing a specific diameter and a specific amount of surface area. This allows us to easily compare the crater densities between two surfaces by simply comparing two numbers.

One of the most commonly used values for cumulative size-frequency distributions are a 1 km for the crater diameter (D) and 1 km^2 for the area. The resulting number is usually represented as N(1), and is read as *the total number of craters that have a diameter equal to or greater than 1 km per square km.*

Table 9.3 lists the N(1) $\times$ 10^{-4} values for the lunar surfaces that our six samples came from.

The data in Table 9.3 is very powerful since it allows us to turn relative ages into absolute ages across the entire lunar surface. We can use the crater density measured on surfaces with well-established absolute ages (the Apollo landing sites) to calibrate crater densities across the surface of the entire Moon.

Figure 9.5 plots the values for the Age vs. N(1) from Table 9.3. The red line is a fit to the data from *all* of the lunar samples.[3] Finding the absolute age of a surface can now be

[3] The six Apollo missions were not the only missions to return samples from known locations on the lunar

Sample	Source	Age [billion yrs]	N(1)	Ref
10022	Mare Tranquillitatis	3.59	64 ± 20	NI94
12033	Copernicus Crater	0.80	6.68 ± 1	H12
14321	Imbrium Crater	3.87	370 ± 70	NI94
14321	Cone Crater	0.025	0.21 ± 0.05	NI94
15415	Ancient Lunar Crust	4.15	$3{,}600 \pm 1100$	NI94
67015	Descartes Formation (Nec?)	3.92	340 ± 70	NI94
67015	North Ray Crater	0.047	0.39 ± 0.17	H12
72535	Serenitatis Crater (Imb??)	3.89	100 ± 30	NI94
72535	Tycho Crater	0.096	0.6 ± 0.17	H12

Table 9.3: Cumulative crater densities of the surfaces sampled. References: NI94 [62], H12 [33].

reduced to finding the total number of craters larger than 1 km on the surface, dividing that number by the total area of the surface, and then using the fit in Figure 9.5 to find the absolute age.

A concrete example: The relative age of the Tsiolkovskiy mare (Figure 9.4) was established by comparing its crater density to that of the Apollo landing sites. Since the crater densities have been calibrated, the absolute age of the Tsiolkovskiy mare can be estimated. Recent crater counts of the Tsiolkovskiy mare, using high-resolution data from the Lunar Reconnaissance Orbiter, have determined that the crater density [N(1)] is 33×10^{-4}.[89] Using Figure 9.5, we can see that this value of N(1) corresponds to an age of about 3.2 billion years. That is how old the Tsiolkovskiy mare is.

Cratering Rate

The data in Figure 9.5 reveals another very important part of the story of the lunar surface. The green dashed line in the plot is what you would expect the crater density to be if the rate of impactors hitting the Moon *today* were representative of the rate for the entire history of the lunar surface. The green dashed line fits pretty well for about the most recent 3 billion years of lunar history. This implies that the current rate of impactors hitting the Moon today has been pretty much the same over the last 3 billion years.

The story before that was much different. Prior to 3 billion years ago, the rate of impactors hitting the Moon was much higher than it is today. The first 1.5 billion years of lunar history was a time of an extremely high rate cratering. The initial anorthosite-rich crust of the Moon was section*ed to a very high rate of impacts and this high rate continued as the last of the large impact basins were formed. The impactor rate started to lessen as the first mare surfaces started to form, and the impactor rate dropped to the current rate as

surface. The Soviet Union landed three robot missions on the Moon (Luna 16,20, and 24) that returned samples from surfaces that were not visited by the Apollo missions. A nice summary of the Luna missions can be found on Wikipedia: `http://en.wikipedia.org/wiki/Luna_programme`.

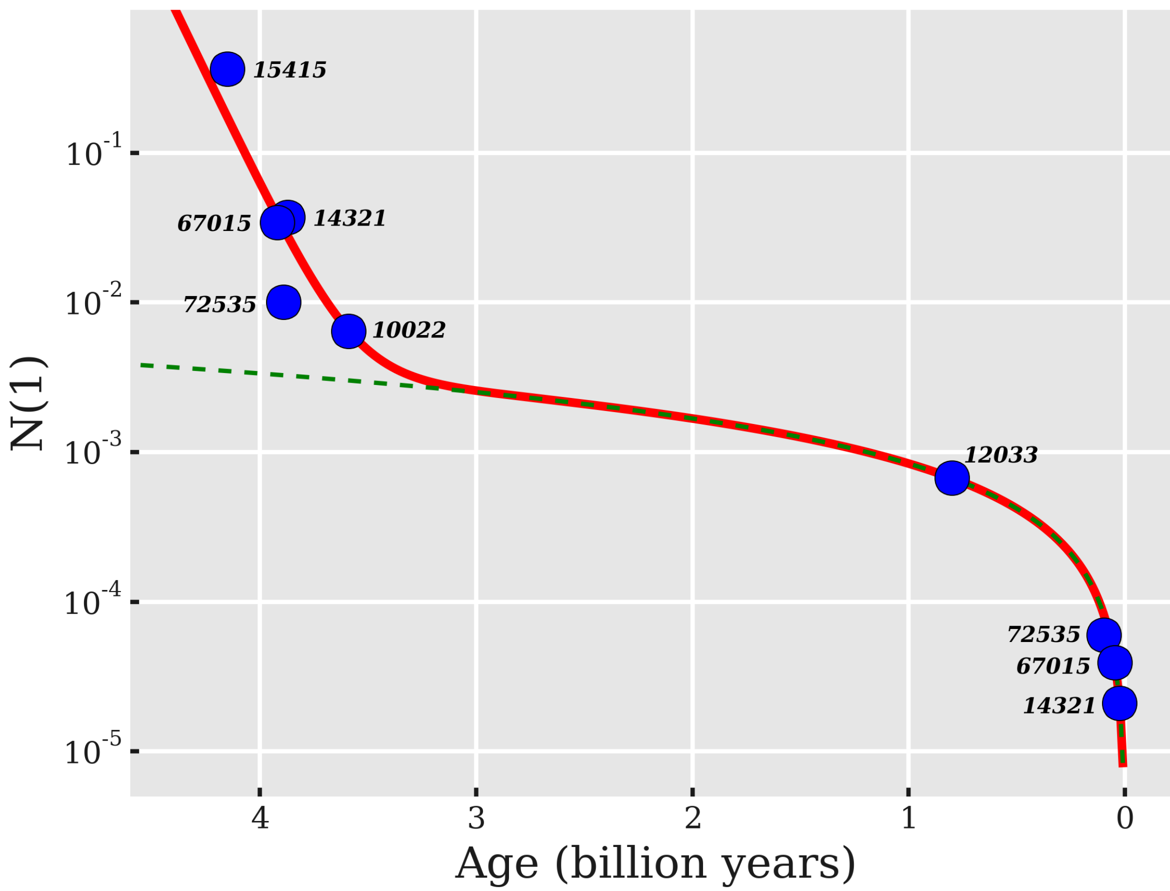

Figure 9.5: Lunar cratering chronology. A plot of Age vs. N(1) for the data in Table 9.3. The red line is a fit to all of the lunar sample data from [63] and the green dashed line is a fit for a constant cratering rate.

the last of the mare surfaces cooled.

The calibrated crater densities of the lunar surface are the best data we have for how the cratering rate in the inner solar system has changed over time. This cratering history is shared by all surfaces in the inner solar system. This has some important implications for the Earth's earliest history. The earliest evidence of life on the surface of the Earth dates back to about 3.5 billion years ago.[5] Data from the Moon is our best evidence that the earliest life on the Earth had to survive and evolve on a surface that was section* to an intense rate of impacts.

Crater Population

A slightly different way to describe the crater density of a surface is to group the measured crater sizes into a number of discrete size bins. This technique essentially creates a histogram of the craters counted on a surface. This way of describing the crater density is called an *incremental size-frequency distribution*. This distribution makes it easy to see the relative number of craters of different sizes.

Figure 9.6 (top) shows the incremental size-frequency distribution of the average crater densities of the highlands and mare on the lunar near side. Two facts are easily evident from the data:

- The highlands have at least 10 times more craters at *every* size range than the mare do.
- Small craters *greatly* outnumber larger craters on both surfaces. For example, on both surfaces there are about 100 times more 4-km craters than 40-km craters.

The relative number of craters of different sizes on a surface is called the *crater population* of the surface. The crater populations of the mare and highland surfaces are dominated by small craters. In fact, the crater population of the mare and highlands look very similar. The straight-line fits to the data for the mare and highlands have a very similar slope (Figure 9.6 (top)). However, if you look closely at the data you can see that the difference between the data points and the straight line looks slightly different for mare data than it does for the highland data.

A final type of crater distribution makes these differences easier to see. Instead of plotting the number of craters at different sizes, you can plot the *difference* between the number of craters measured and the straight-line fit. This type of plot is called an *R Plot*. An R plot provides a useful interpretation: The value of a point in an R plot tells you the fraction of the surface area covered by craters of a particular diameter. For example, Figure 9.6 (bottom) shows the R plots for the near side mare and highlands. The highlands are covered by mostly large craters, while the mare are covered by mostly small craters.

The R plots really emphasize the details of the crater population of a surface. The crater population of the highlands is different from the mare. The population of the impactors

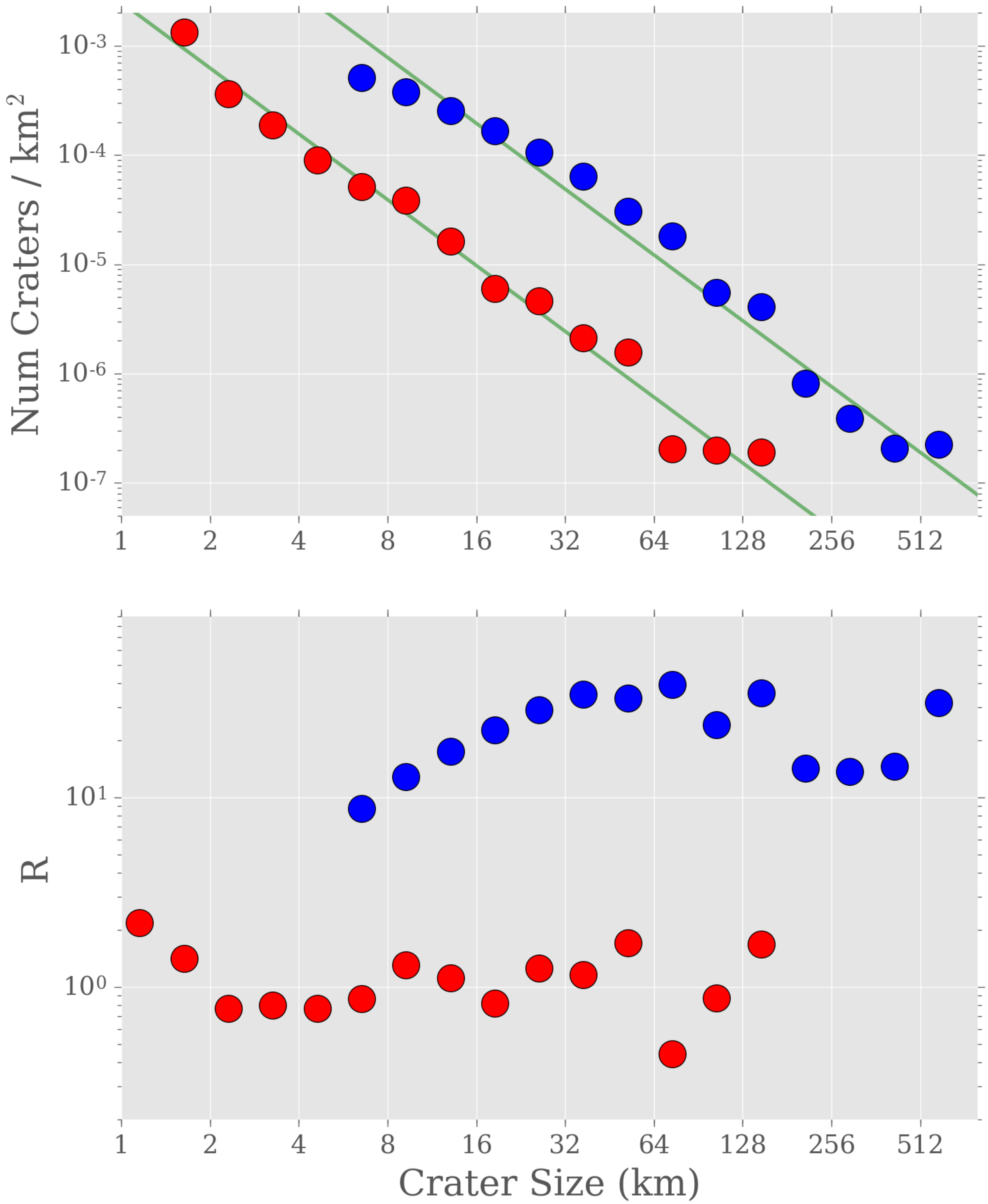

Figure 9.6: (Top) The crater densities of the lunar mare (red) and highlands (blue). The mare data is an average over the near side mare, and the highlands data is an average over the near side highlands. All data from chapter 8 of [12]. The green lines are a fit to the data. (Bottom) The R plot for the average near side mare (red) and highland surfaces (blue).

that formed the craters on the highlands had a much higher proportion of large impactors than the population that formed the craters on the mare surfaces.

This difference is important because it tells us that the *population* of impactors changed over time. Early in the history of the solar system, the population of impactors was dominated by large objects. Over time, the population changed to the point (today) where small objects make up a much larger fraction of the impactor population.

Putting all three of our crater distributions together reveals a story of the evolution of the objects raining onto the surfaces in the inner solar system.[4] Very early in the solar system's history there was a very high rate of bombardment from a population with a large fraction of big impactors. As time went on, the rate of impacts decreased and the population changed to one made up of a larger fraction of small impactors.

The only data we have of the history and evolution of the impactor population in our solar system is the calibrated crater densities of the lunar surface.

Our story started with learning about specific samples at specific places on the Moon. This knowledge led to insight into the entire history of the solar system. *Ex Luna, Scientia*.

[4]A detailed and very quantitative explanation of crater density distributions can be found in Chapter 10 of [54].

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