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[61]:

[61] Bain and Hershey (1971)

> "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,[62] 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.[63]

[62] The geological field training of the Apollo 15, 16, and 17 astronauts is covered in great detail in Wilhelms (1993) as the author of that book played a large role in the training.

[63] Wilhelms (1993), page 269

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.

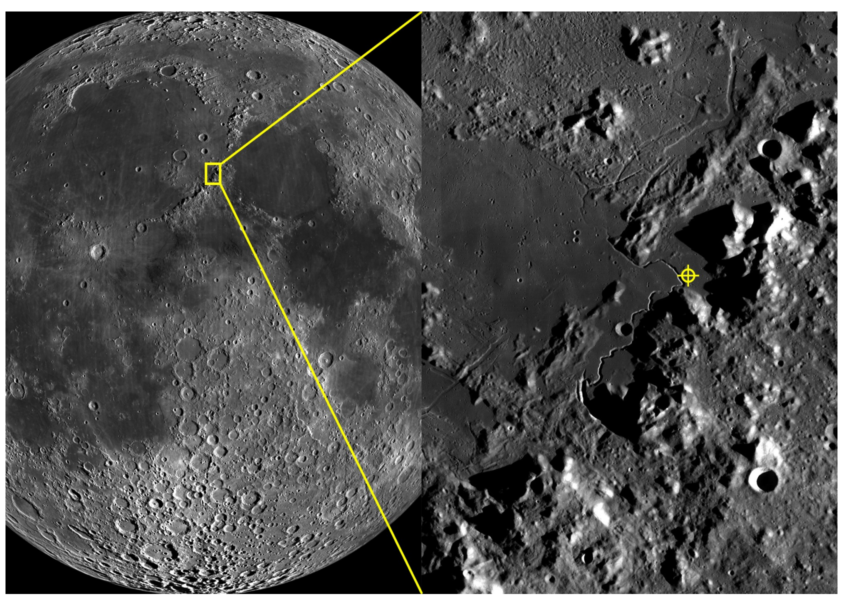

Figure 6.1: The landing site of Apollo 15 on the rim of the Imbrium Basin. Images from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

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.

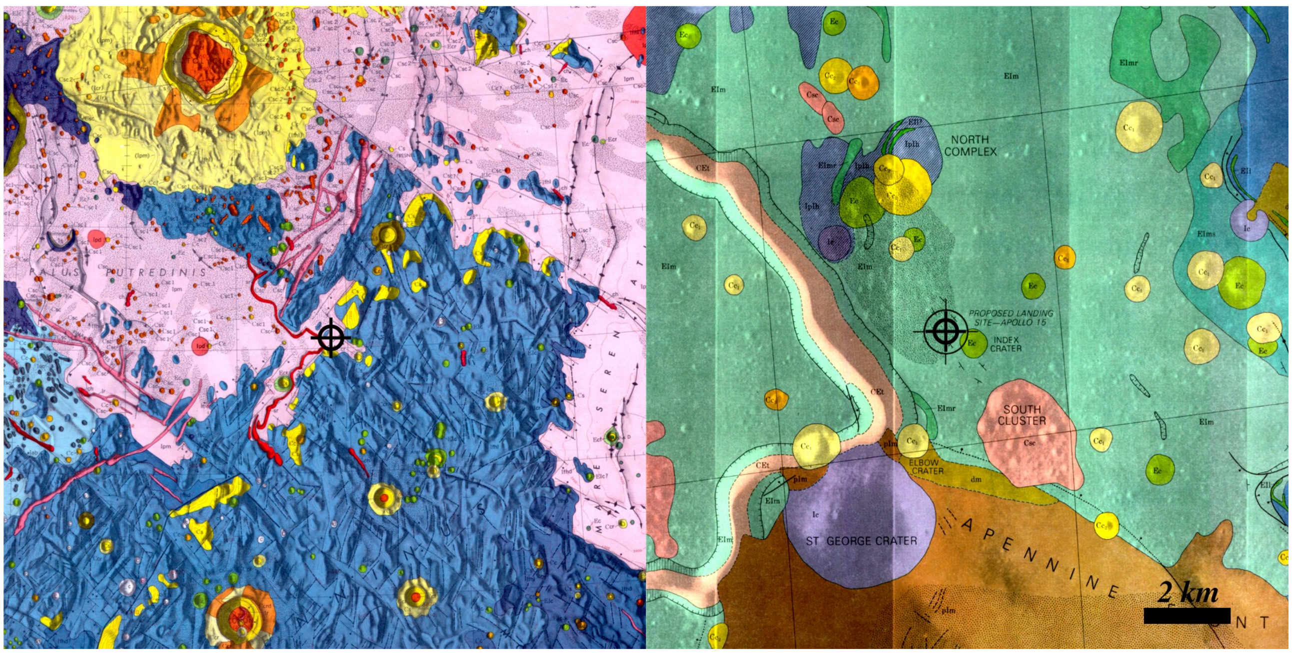

Figure 6.2: Geological maps of the regions of the Apollo 15 landing site. (Left) A detail of the large-scale geological map of the Apennine Mountains (Hackman, 1966). (Right) A detail of the geological map of the immediate vicinity of the Apollo 15 landing site (Howard, 1971).

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. 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.

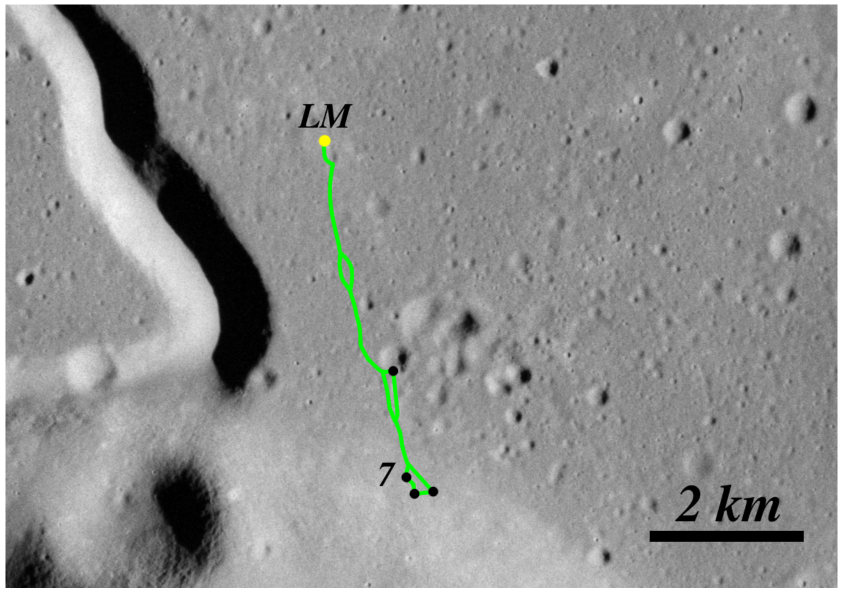

Figure 6.3: The path of the second EVA of Apollo 15. The point labeled with a "7" is Station 7, the location of Spur Crater [background image: NASA AS15-M-0585]

The 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.

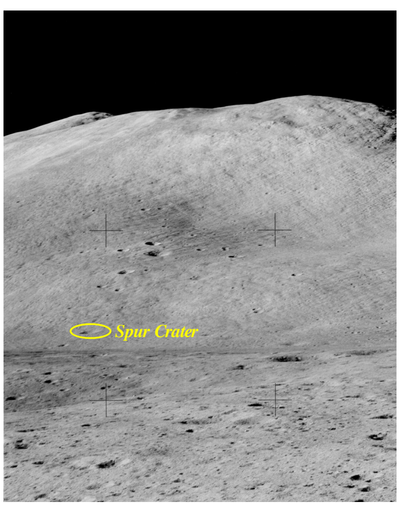

Figure 6.4: A view of the Apennine Mountain front as seen from the lunar module [NASA AS15-85-11377]. The route of the second EVA is essentially straight from this spot to the Spur crater.

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...

145:24:20 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.

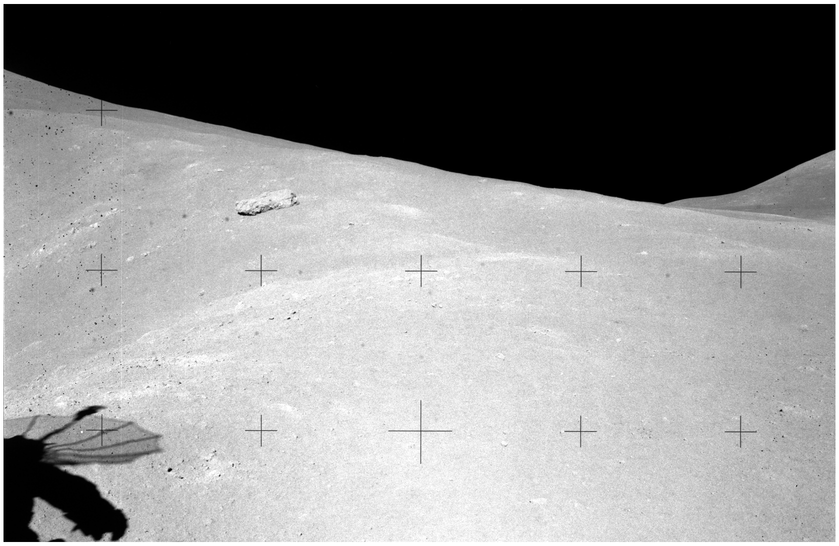

Figure 6.5: The northern rim of Spur Crater. The large boulder is easily visible just inside the rim of the crater [NASA AS15-90-12201].

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

145:40:43 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.

...

145:42:41 LMP: Oh, man!

145:42:41 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?

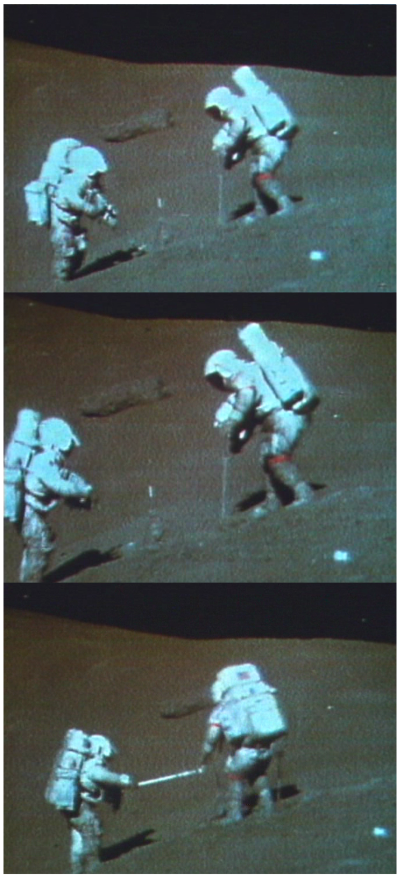

Figure 6.6: A series of frames from the television video of the astronauts at work on the rim of Spur Crater, showing the collection of the sample 15415 [NASA].

145:42:55 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:

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.

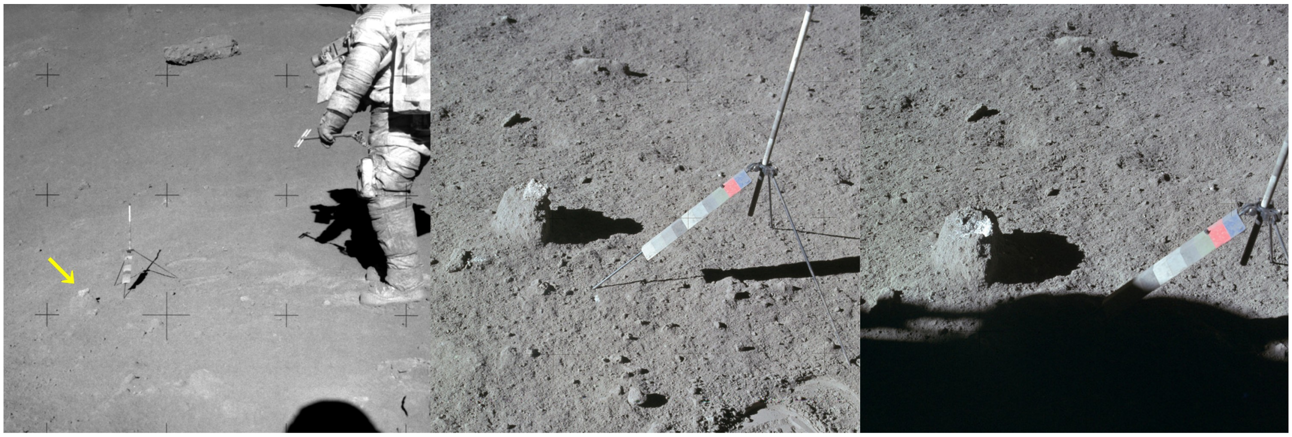

Figure 6.7: Documentation of the collection of sample 15415. (Left) The sample *in situ* on the rim of Spur crater (yellow arrow) [NASA AS15-90-12228]. (Center) Close up of the sample just before collection [NASA AS15-86-11671]. (Right) Close up of the site just after sample collection [NASA AS15-86-11672].

The notoriety[64] 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.

[64] Such is the notoriety of 15415 that it even got its picture on the front page of the *New York Times* Scott (1971)

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.[65] (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.

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

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.

"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.[66] 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.

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

Appearance

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

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*.

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." [67]

[67] Wood et al. (1970)

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, 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.[68]

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

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.

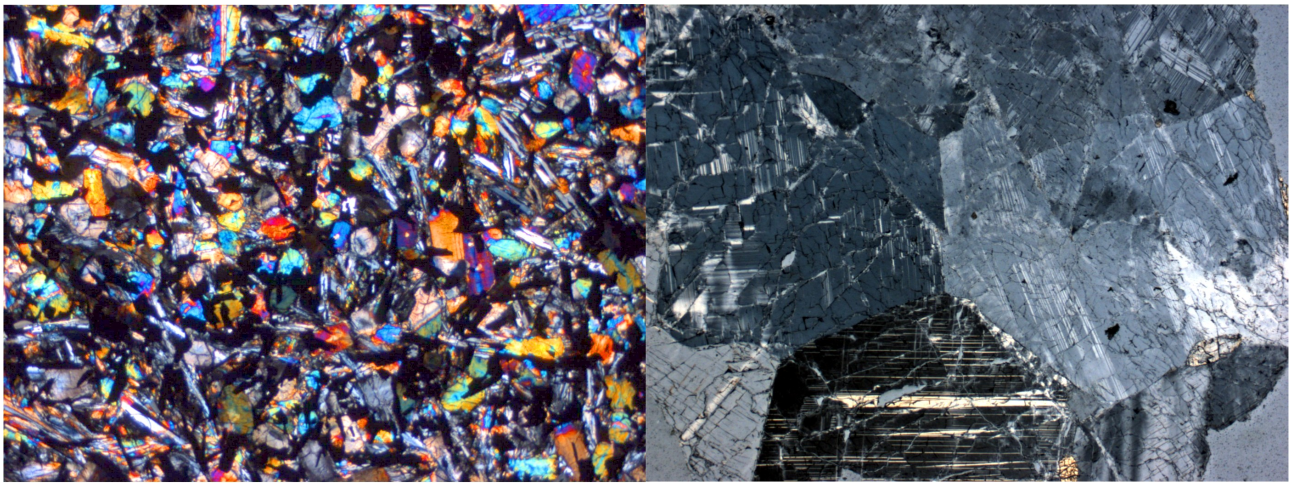

Figure 6.9: Thin sections of 10022 (left) and 15415 (right). Polarized light microscope images. The field of view for each image is approximately 2.85 mm wide. [NASA JSC01082 and JSC03885].

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 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.[69] 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.

[69] Kiefer et al. (2012)

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.[70]

[70] Papike et al. (1997)

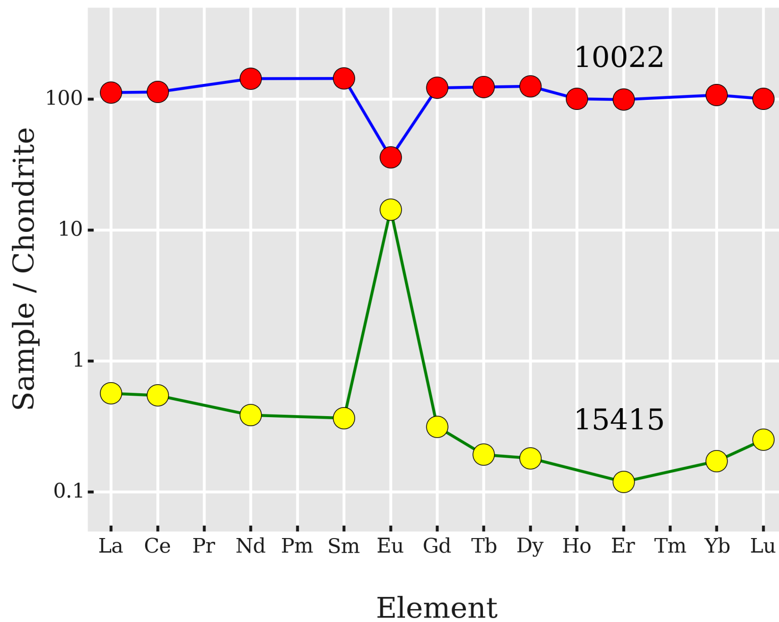

Figure 6.10: The abundance of rare earth elements in the samples 10022 (top) and 15415 (bottom). The abundances are measured relative to the abundances in chondrite meteorites. 10022 abundances are from Haskin et al. (1970). 15415 abundances are from Haskin et al. (1982), Hubbard et al. (1971a).

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.[71]

[71] 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 (Wood et al., 1970). However, the argument is exactly the same, and it fits in much more naturally with the discussion of 15415.

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).

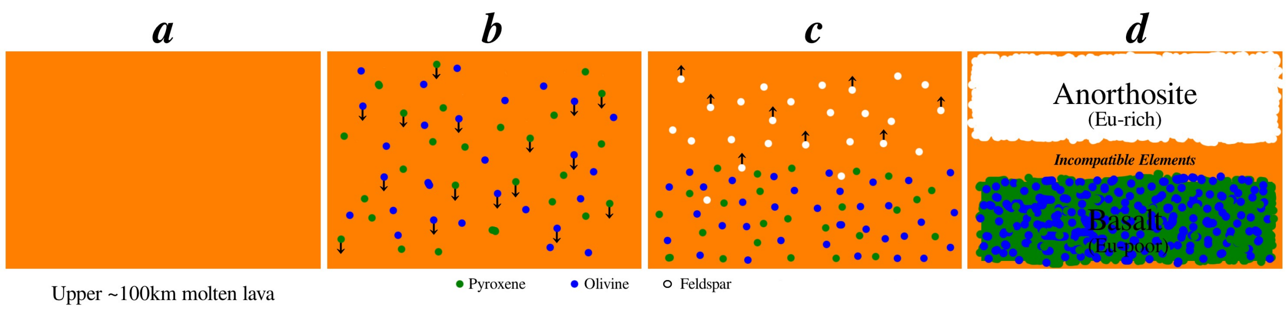

Figure 6.11: A schematic diagram of the global magma ocean model for the formation of the original lunar crust.

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.[72] To make a crust this thick, the

[72] Papike et al. (1997)

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.[73]

73 A summary of the age determination of 15415 can be found in Meyer (2011a)

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.[74]

74 Albarede (1978)

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.[75] In either case, 15415 represents a very ancient piece of the early surface of the Moon.

[75] See Warren (1985) and chapter 2 of Heiken et al. (1991)

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:[76]

[76] Wilhelms (1993), page 339

> "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.