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.[77] All of the previous Apollo sites had been on or near lunar mare (the Fra Mauro site of Apollo 14 is technically a highlands site, but it is surrounded by and partially overlapped by mare). Another

[77] The story of how NASA chose the Apollo 16 landing site is a fascinating story and cautionary tale. See chapter 16 in Wilhelms (1993).

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.

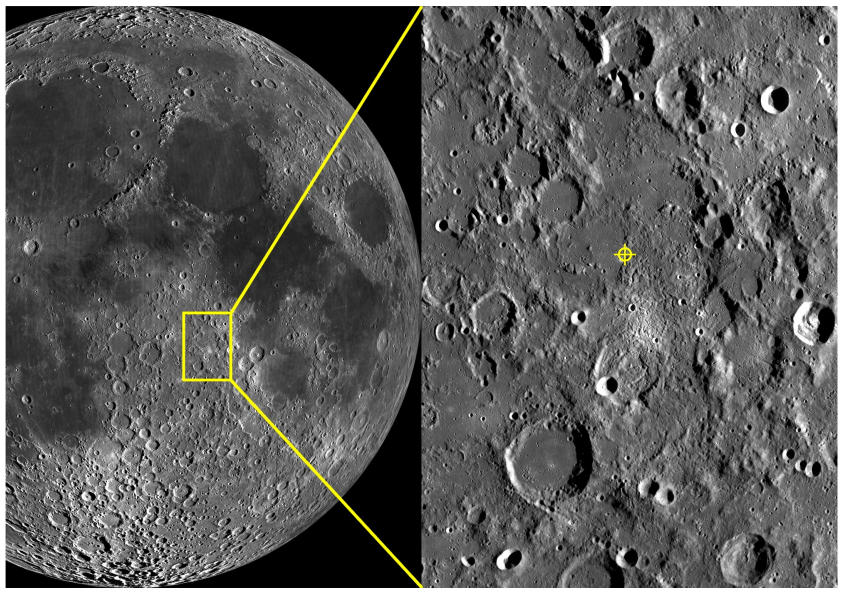

Figure 7.1: The landing site of Apollo 16 in the lunar highlands. The Descartes formation is the hilly patch of material to the immediate right of the Apollo 16 landing site. Images from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

The 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.

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.

Figure 7.2: Geological maps of the region of the Apollo 16 landing site. (Left) Detail of the large-scale map (Milton, 1968). 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 (Hodges, 1972).

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:[78]

[78] (Milton, 1968)

> "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."[79]

[79] (Hodges, 1972)

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.[80]

80 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 Wilhelms (1993).

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 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?

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

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.

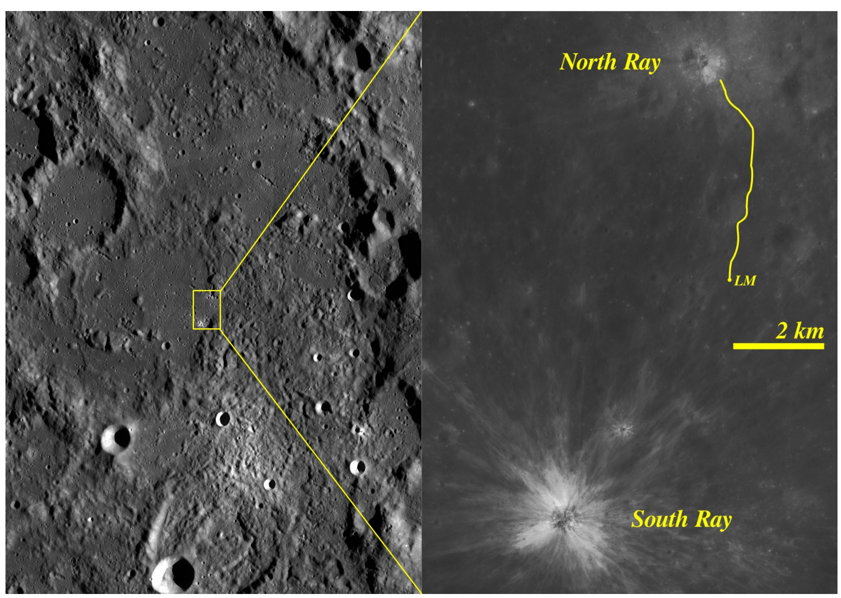

Figure 7.3: (Left) Detail of the Apollo 16 site on the edge of the Descartes formation. (Right) Close-up of the landing site, showing the route of the third EVA to the rim of the North Ray Crater. LROC NAC M106777343R/L [NASA/GSFC/Arizona State University].

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 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).

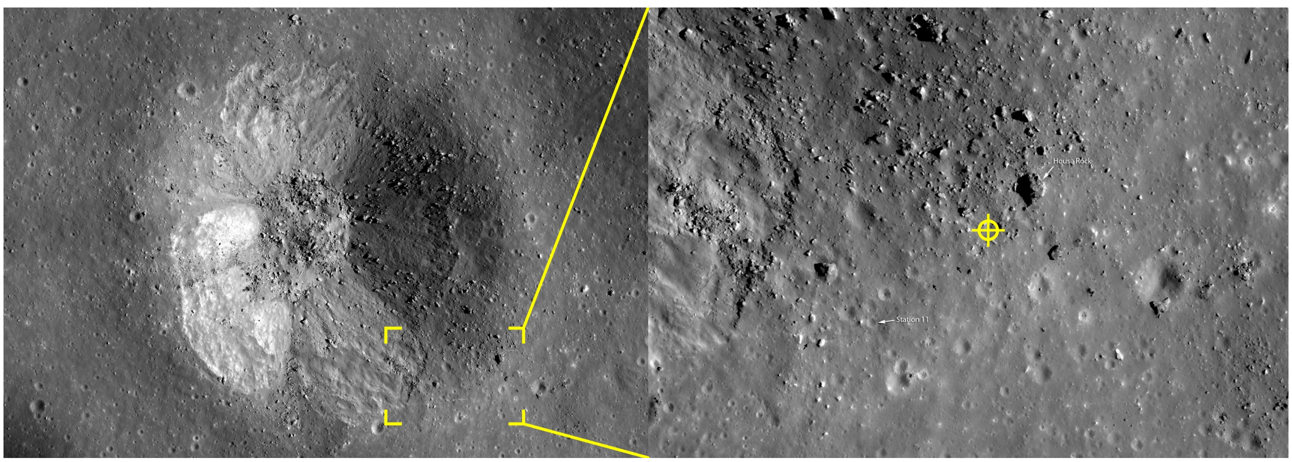

Figure 7.5: (Left) Close-up of the North Ray Crater. (Right) Detail of the southern rim, showing the approximate collection site of sample 67015. LROC NAC image M175179080LR [NASA/GSFC/Arizona State University].

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.

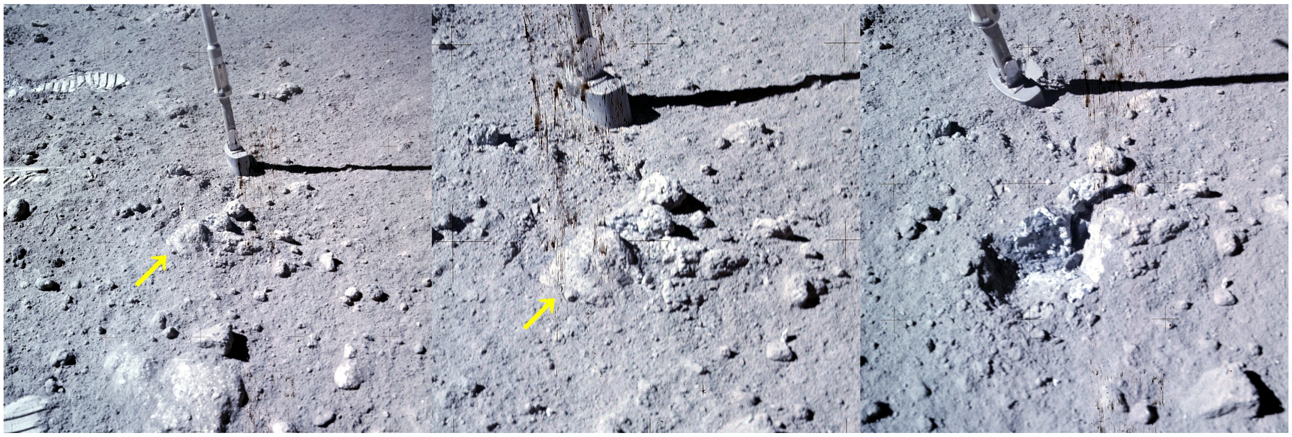

Figure 7.6: The documentation of the collection of sample 67015. (Left) The sample 67015 *in situ*. The sample is marked by the yellow arrow [NASA AS16-116-18621]. (Center) A close-up of the sample before collection [NASA AS16-116-18622]. (Right) The sample site after the collection of the sample 67015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

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

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.

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

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.

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.

	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 Rose et al. (1970), 67015 chemistries from Marvin et al. (1987)

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.

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.[81]

[81] Spudis (1984), and James (1982)

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

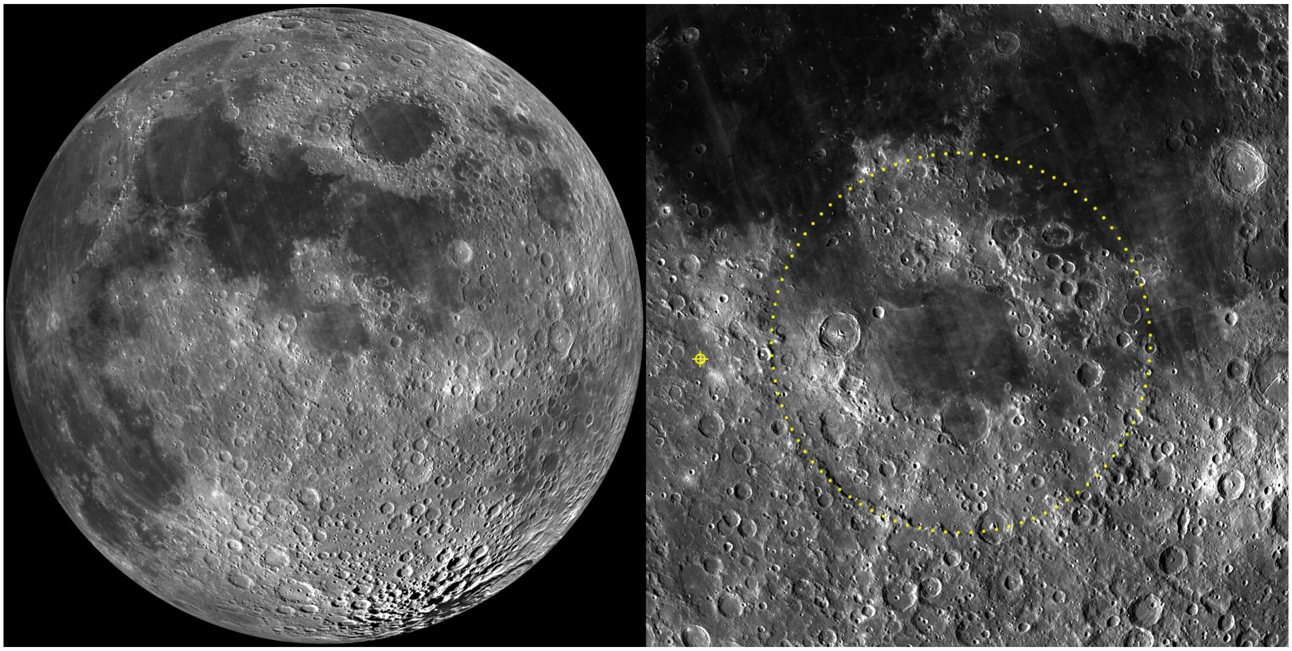

Figure 7.8: The Nectaris Basin. (Left) Image of the Moon centered on the Nectaris Basin. (Right) Close-up of the Nectaris Basin, showing the approximate location of the outer rim. The location of the Apollo 16 landing site is shown near the left edge of the image. Images from the LROC WAC mosaic of the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

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.[82]

[82] See chapter 9 of Wilhelms et al. (1987) for a summary of the arguments.

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).

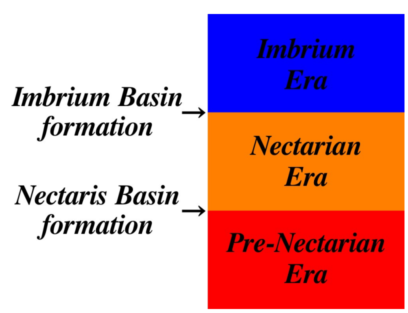

Figure 7.9: A simplifed diagram of the earliest lunar eras.

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.[83] All of the melts have a narrow age range, with a strong cluster of ages at 3.92 billion years old.[84] This age is now accepted by most studies as the age of the formation of the Nectaris impact basin.

[83] Marvin et al. (1987) and James (1982)

[84] Spudis (1984)

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*.[85]

[85] Tera et al. (1974)

It should be noted that the 3.92-billion-year-old age of the Nectaris Basin, as well as the whole idea of the *Late Heavy Bombardment*, is not universally accepted. Many recent studies[86] 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.[87] In this model, large impact basins were forming all throughout the early history of the Moon.

[86] See Neukum et al. (2012) for a summary of the arguments

[87] For example, Neukum et al. (2012) 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.