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.

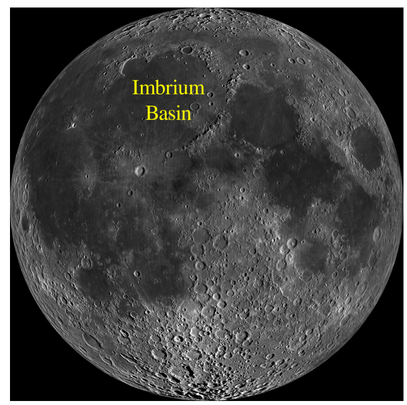

Figure 5.1: Image of the full Moon with the Imbrium Basin labeled. LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

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.

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.[49] 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.

[49] Wilhelms (1993)

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.[50]

[50] A slightly more cynical, but more realistic, reason for the increasing role of science was suggested by Don Wilhelms [Wilhelms (1993), 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.”

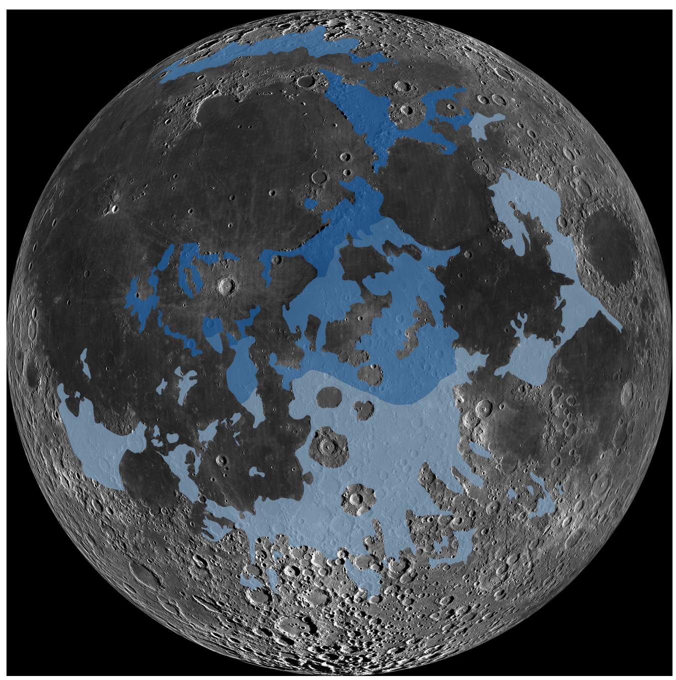

Figure 5.2: The extent of material ejected from the Imbrium Basin (blue). Image of the Moon from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University], overlay of Imbrium ejecta adapted from Wilhelms et al. (1987), plate 8A.

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.)

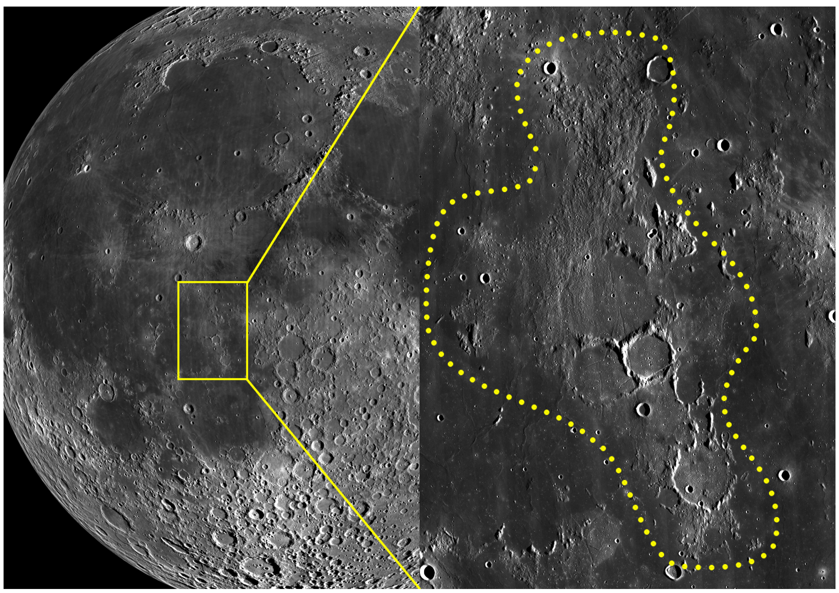

Figure 5.3: The Fra Mauro formation. (Left) Location of the Fra Mauro formation. (Right) Detail of the Fra Mauro formation (the boundary is only approximate). Both images are from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

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 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.

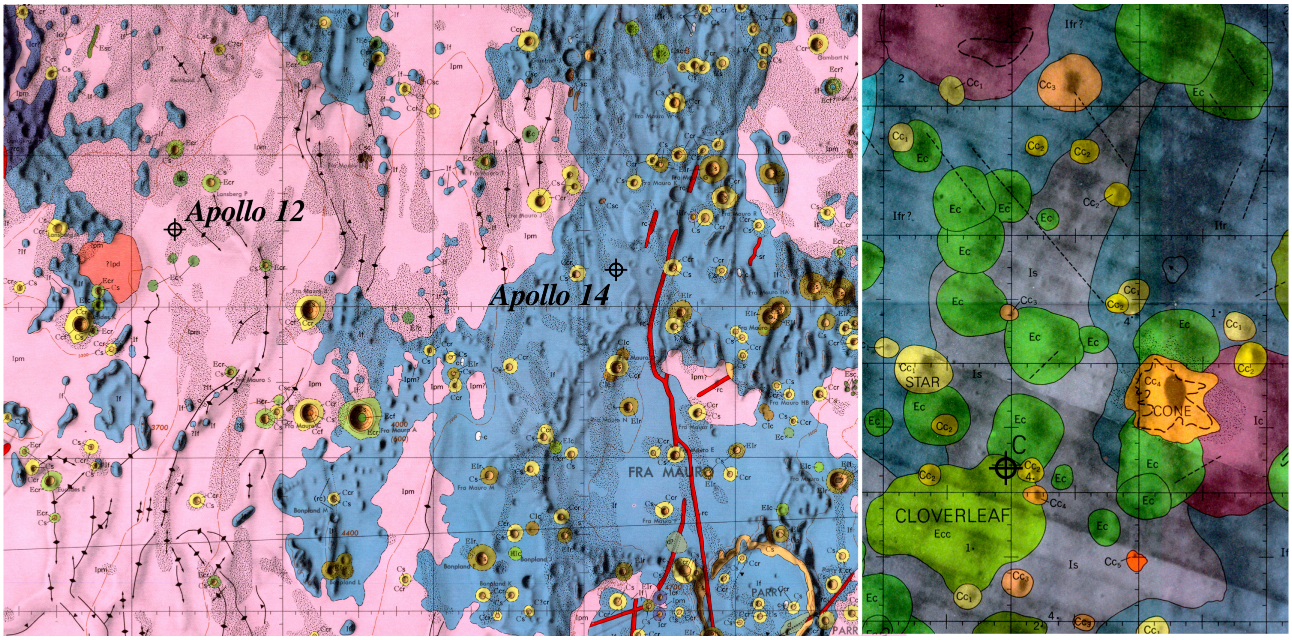

Figure 5.4: (Left) Detail of the geological map of the Fra Mauro region (Eggleton, 1965). The landing site of Apollo 12 and 14 are indicated. (Right) A detail of the immediate vicinity of the Apollo 14 landing site (Offield, 1970).

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.[51] In the case of

[51] H. J. Melosh's monograph *Impact Cratering: A Geological Process* (Melosh, 1989) is pretty much the go-to references for all aspects of impact cratering

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[52] made an extensive study of this crater in the early 1960s.[53] 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.

[52] 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 (1993).

[53] Shoemaker (1963)

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.

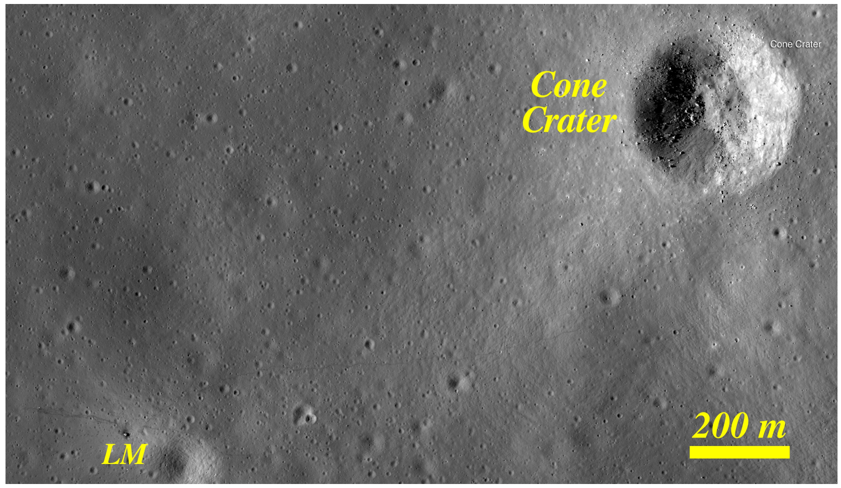

Figure 5.5: Landing site of Apollo 14. The footprints of the astronauts leading from the lunar module to the rim of Cone Crater are visible. LROC NAC image M150633128LR [NASA/GSFC/Arizona State University].

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[54] 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.

[54] 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 (1993) and Jones and Glover (2013) for details and astronaut commentary.

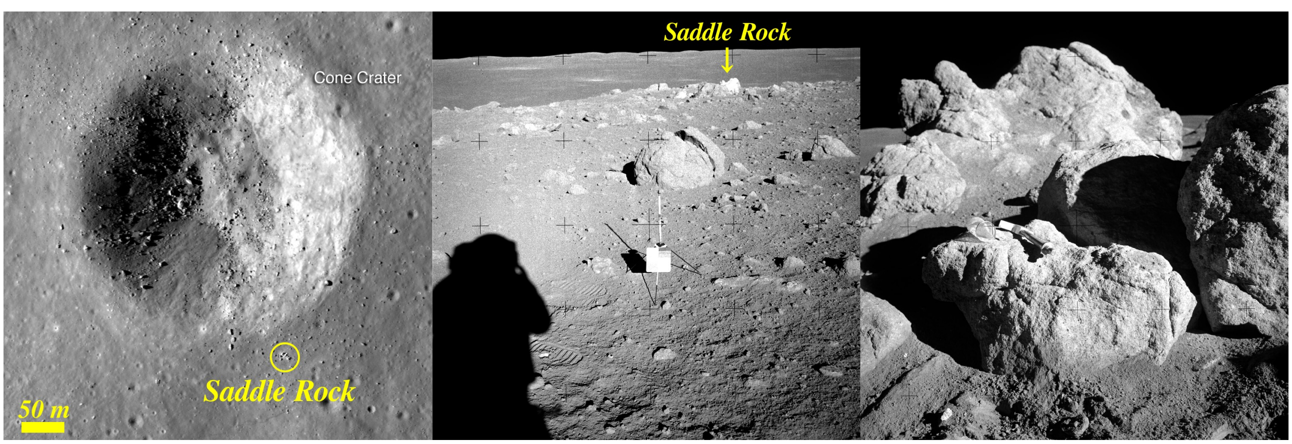

Figure 5.6: The sampling location on the rim of Cone Crater. (Left) Close-up image of Cone crater, showing the location of the boulder field (circled) on the southern rim. The northernmost boulder in that field is Saddle Rock (LROC NAC image M150633128LR [NASA/GSFC/Arizona State University]). (Center) 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].

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

> 133:37:39 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.
>
> ...
>
> 133:37:52 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:

> 133:40:24 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.
>
> ...
>
> 133:44:29 LMP: ... help with that one?
>
> 133:44:30 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.

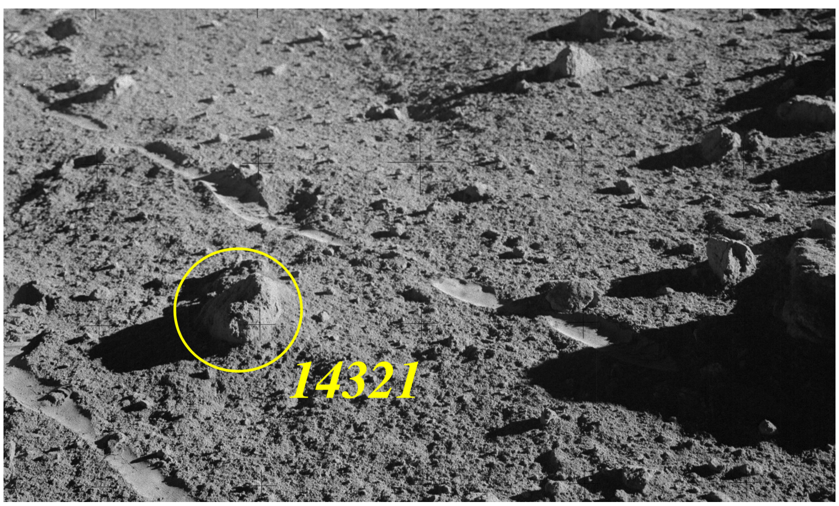

Figure 5.7: The football-sized sample 14321 near 'Saddle Rock' just before collection [NASA AS14-64-9128].

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 (∼ 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

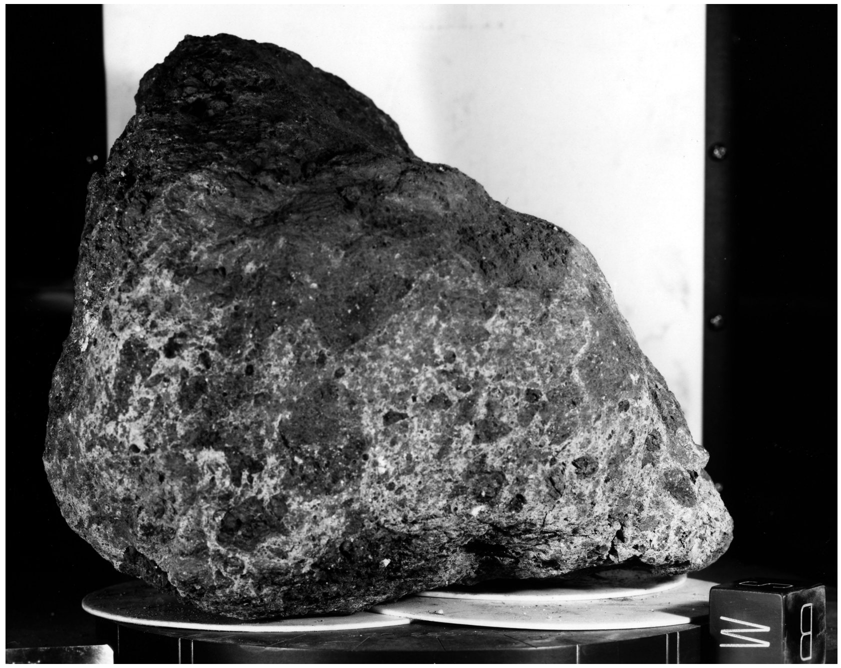

Figure 5.8: Image of 14321 at the Lunar Receiving Laboratory. The cube at the lower right is 1 inch across [NASA S71-28417].

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 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.

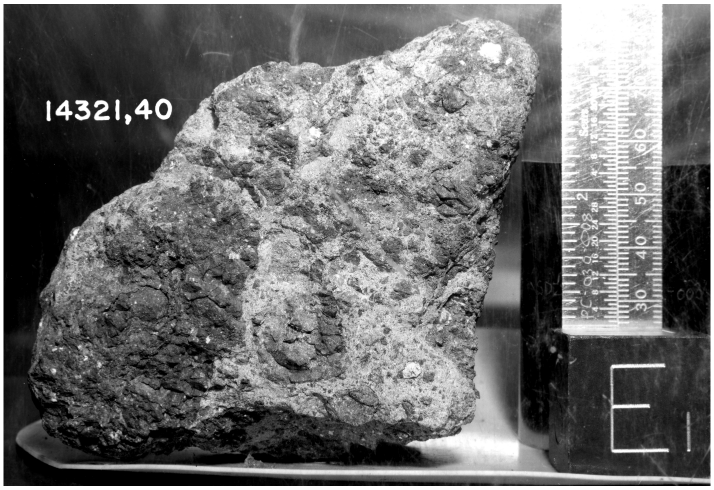

Figure 5.9: A piece of sample 14321 showing the nature of impact breccia [NASA S76-24007]. The cube is 1 inch across.

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. [55] 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. [56]

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.

[55] The studies were published as four papers in a single volume of the Journal *Geochimica et Cosmochimica Acta* (Duncan et al., 1975a,1975b, Grieve et al., 1975 and Morgan et al., 1975)

[56] Grieve et al. (1975)

The size and complexity of 14321 is matched by the number and complexity of the scientific papers it has generated. A recent (2009) compendium[57] 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!"

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

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 ??). [58]

[58] Stöffler and Ryder (2001)

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

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*.[59] This paper laid out a possible history of 14321. It goes something like this:

[59] Duncan et al. (1975a)

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.[60]

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.

60 The exposure age of 14321 was found to be 24 $\pm$ 2 million years old Arvidson et al. (1975). This is the accepted age of the formation of Cone crater.