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.

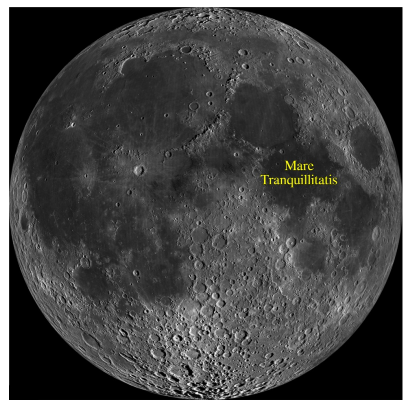

Figure 3.1: Location of Mare Tranquillitatis [NASA/GSFC/Arizona State University].

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 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.

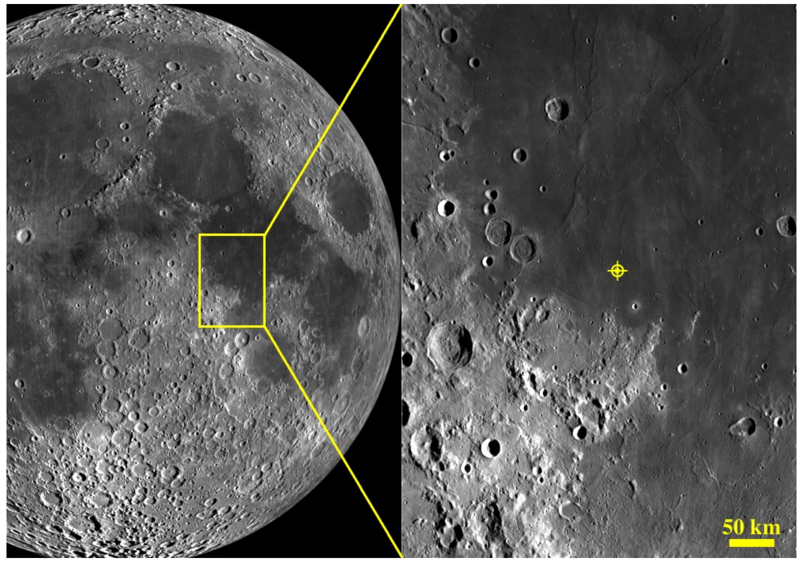

Figure 3.2: The context of the Apollo 11 landing site in the Sea of Tranquility. Both images are from the LROC WAC mosaic of the lunar near side [NASA/GSFC/Arizona State University].

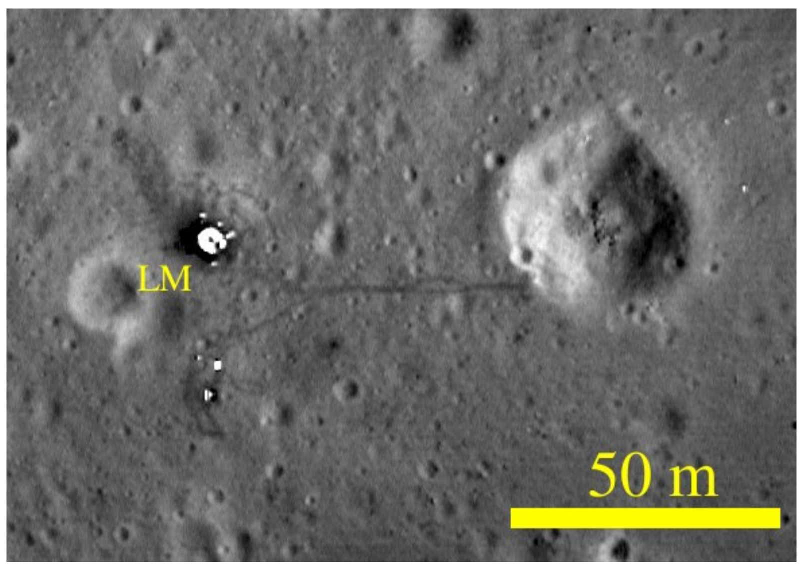

Figure 3.3: A high-resolution, recent (Nov 5, 2011) image of the Apollo 11 landing site. The lunar module is labeled `LM`. The footprints of the astronauts are clearly visible. The patch of disturbed ground to the upper left of the lunar module is where the astronauts spent most of the EVA. LROC M175124932R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

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.

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.

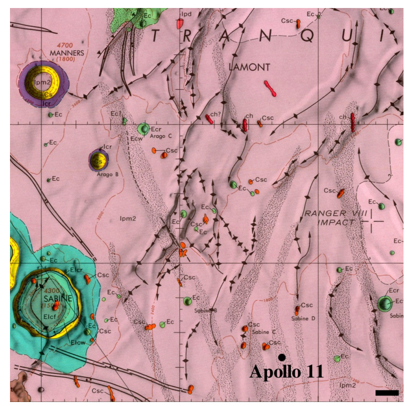

Figure 3.4: A detail of the geological map of the Apollo 11 site (Morris and Wilhelms, 1967). The black bar is 10 km.

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.

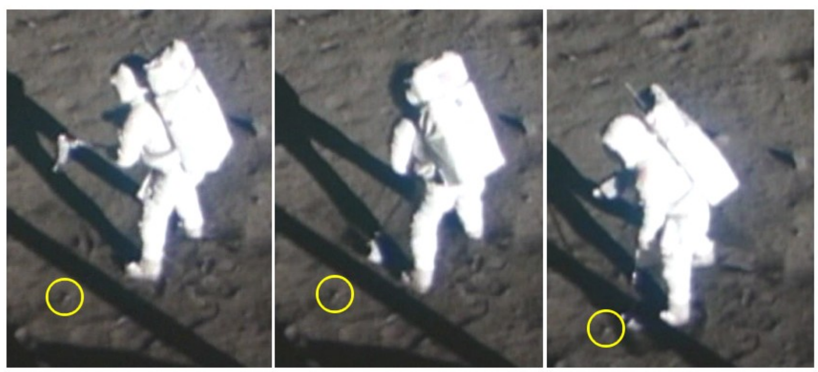

Figure 3.5: The collection of sample `10022`. The sample is indicated by the circle in each frame. The images are frames from the 16mm data acquisition camera mounted in the lunar module [NASA].

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. [11]:

[11] Shoemaker et al. (1969)

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

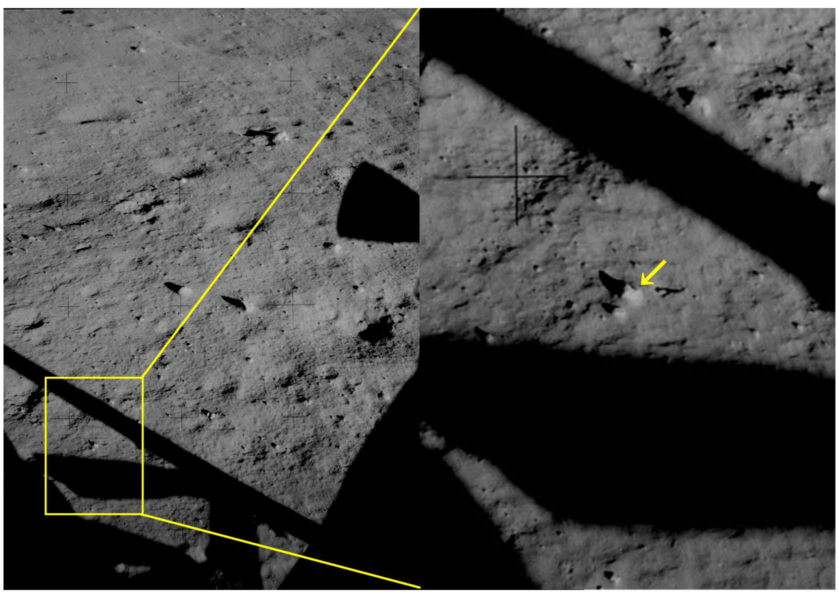

Figure 3.6: The location of sample `10022`. The arrow indicates the sample `10022` in its context on the surface of the Moon before collection. The shadows are caused by the legs of the lunar module. [NASA AS11-39-5777]

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

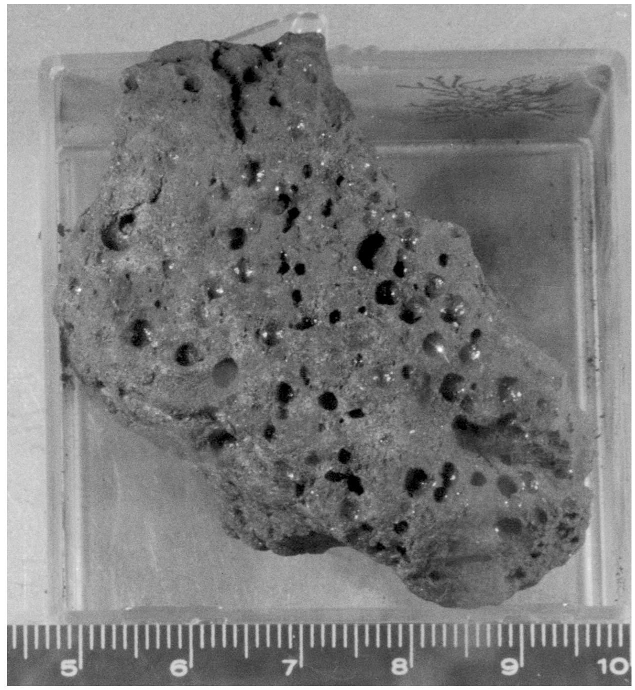

Figure 3.7: Photo of 10022 in the Lunar Receiving Laboratory. The scale at the bottom is in cm. [NASA S69-45209]

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 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[12], 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.*[13] This paper was the first study to determine the age of 10022.

12 Abelson (1970)

13 Turner (1970)

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.

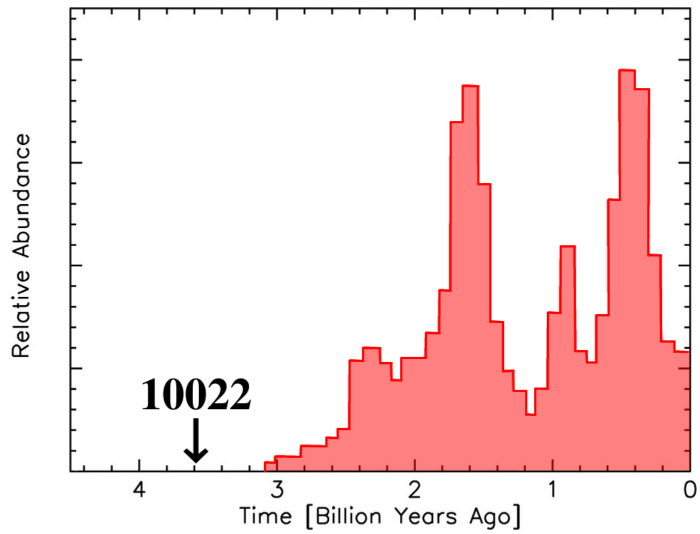

Figure 3.8: Histogram of the ages of the Earth's crustal rocks (red).

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 region...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[14]."

[14] Lunar Sample Preliminary Examination Team (1969)

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.[15]

[15] This is really just the barest overview of the chemistries on lunar basalts. Chapter 8 of the *Lunar Sourcebook* (Heiken et al., 1991) 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` are from Rose et al. (1970), lunar basalt ranges from Heiken et al. (1991), and terrestrial basalt ranges from Engel and Engel (1970).

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).[16] By contrast, the brighter lunar surfaces have albedos between 0.12 and 0.18.

[16] Evsyukov (1973)

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[17] (*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*.

[17] Whitford-Stark (1982)

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`.[18] 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.

18 Weill et al. (1971)

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*.

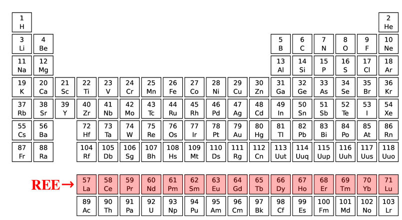

Figure 3.9: Periodic table of the elements. The rare earth elements are in red at the bottom of the table.

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*.[19] These meteorites are composed of materials that 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.

19 Anders and Grevesse (1989)

Figure 3.10 shows the abundance of rare earth elements in `10022` relative to the abundance in C1 chondrites.[20] A couple of things are quickly apparent in the plot. One, rare earth elements are about 100 times more abundant in `10022` than in

20 The abundances were taken from Haskin et al. (1970).

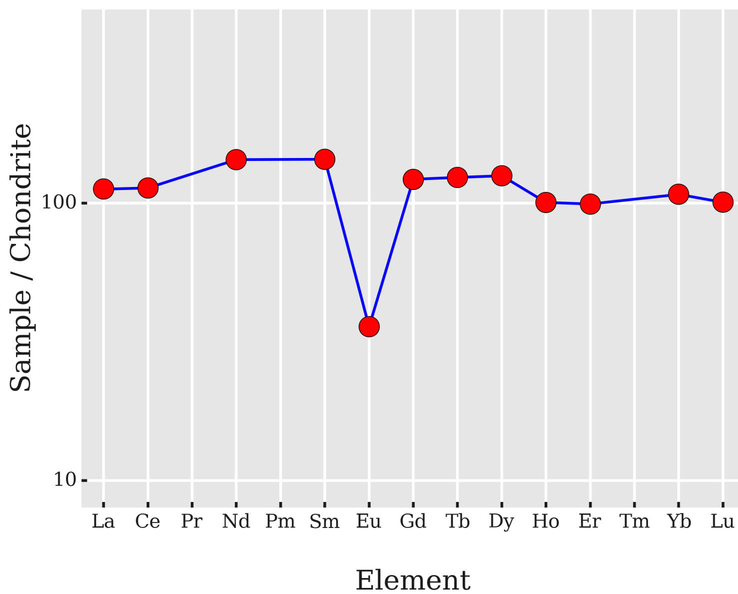

Figure 3.10: The abundance of rare earth elements in the sample `10022`. The abundances are plotted relative to the abundances in chondrite meteorites.

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 **??**.

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:[21]

> "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."

[21] Weill et al. (1971)