SECTION 3: THE MOON (4 lectures)

The Moon is our closest neighbour in space, and the extra-terrestrial body we know most about. It shows only one face to the Earth, and so until the 1960's, we knew nothing about the farside of the Moon. We are in a similar situation with Mercury today. Scientists who study the Moon are very fortunate. We have data from telescopic observations from the ground, photographic data from a host of unmanned spacecraft, returned soil and rock samples from manned and unmanned missions and field observations from the astronauts themselves. However, most of this data was collected in the 1960's and 70's, and we had to wait 20 years before another lunar mission returned to the Moon. Since 1994 we have seen two spacecraft sent to the Moon and another is planned for launch next year. So lunar science is enjoying a revival, and we are certain to learn a lot more about our neighbour over the next few years.

3.1 Lunar Volcanism and Tectonism

The Moon can be split into two distinct provinces, the maria and the highlands. The maria are basically large lava sheets, filling in impact basins which formed much earlier. They cover a large area on the nearside, approximately 30%, but only 2% on the farside. Samples returned from the Moon confirmed their volcanic origin and basaltic composition, characterised by relatively low SiO_2 content (45-55%) and by relatively high MgO and FeO contents.

3.1.1 Lava Flows

The events that resulted in the mare floods must have had high temperatures, high eruption rates and low viscosities in order to travel such long distances before cooling. Flows in the Imbrium basin for instance appear to originate from the south-west basin edge and travel for hundreds of kilometres, the largest extending 1200km into the basin. We know these flows were of low viscosity because of the thickness of the flow scarps seen. They average just 35m in thickness. Flows have also been identified in other areas, including the site of Hadley Rille, where at least three layers have been cut through by the rille. Lava flows did not occur all at the same time. In some cases they were separated by sufficient time to have significantly different crater densities, implying different exposure ages to space.

The most prominent basalt eruptions appear to have occurred between 3.9 and 3.1 billion years ago as determined from dating of lunar samples. A small amount of volcanism probably occurred as little as 2 billion years ago on the basis of crater density studies, and it is likely that volcanism may have started a lot earlier than 3.9 billion years ago with the lava's from those eruptions having been covered over by subsequent events.

Whilst no accurate start or termination date for lunar volcanism can be given, it is clear that any activity occurring in the last 3 billion years contributed only a small amount to the volume of basalt we see today. Although the extensive mare regions are the most obvious form of volcanism we see on the Moon, there are many others that have been found.

3.1.2 Sinuous Rilles

Sinuous rilles are basically meandering channels formed by the action of flowing lava moving downslope. They vary in size from 10's of metres to 3km wide, by a few to 300 kilometres long, but their sides remain remarkably parallel throughout their entire length, apart from a slight narrowing further from the vent. Lunar sinuous rilles have often been compared to terrestrial lava channels. However, it is important to note that lunar sinuous rilles are an order of magnitude larger than the terrestrial lava channels, and often have smoother morphologies. The three most popular hypotheses of the formation of sinuous rilles used to be 1) collapsed lava tubes or open lava channels, 2) erosion by pyroclastic flows, 3) erosion by water. Since no pyroclastics or water were found near the Apollo 15 landing site at Hadley Rille, their origin had to be due to basaltic lava flows, and indeed they are found everywhere where there are mare deposits, but they do have a higher concentration near the edges of mare basalts.

The width of the rilles imply that high effusion rates were necessary to form the sinuous rilles. Turbulent lava flows are more likely to be capable of causing these features, which in turn would require fairly fluid lava's with low yield strength and low viscosity. Hulme (1982) reviews the possible formation processes of sinuous rilles. An example he gives is the following:

FIGURE 3.1a-f (Formation of a sinuous rille)

Sinuous rilles often begin in depressed source areas, looking very much like craters. These source depressions may have been caused by a lava fountain erupting lava which would build up around a vent to the point lava would start to flow. The vent vicinity would be the point where the lava would have been at its hottest and most erosive and from this would probably produce the depressions (see Wilson & Head 1980, 1981 for more information on this).

On slopes typical at mare edges (~0.004) and with the eruption rates necessary for turbulent flow ($\sim 10^5 m^3 s^{-1}$, Hulme 1982), the lava would flow once it reached a critical depth (he quotes 20m for his model). With thicknesses and effusion rates such as these, the width of the flow would be several km, and Hulme suggests that a channel within the flow would have a width of 1500m. In his model, the lava in the channel would be turbulent, whilst the rest of the flow was not. (Fig 3.1a).

The meandering may be the result of this turbulence, which can be considered as a series of eddies superimposed on the mean flow (Fig 3.1b). Of course local topography will also have some influence too. While these meanders were forming, the flow would have been heating up the ground beneath it. At some point, erosion of the bed would begin and the channel would become fixed in position (Fig 3.1c). Once the channel depth became larger than the floor depth, the width of the channel would become fixed (Fig 3.1d). Ground erosion would occur along the entire length of the rille, but less so further from the vent.

Once the flow has cooled enough to prevent the flow from proceeding, the rille has reached its final form (Fig 3.1e). Now the rille will undergo ageing, just as any other feature on the Moon. Eventually, the sides of the rille will slump under the influence of gravity, filling the floor with the slumped material and giving the rille a V-shaped profile as opposed to the U-shape of fresher rilles (Fig 3.1f). As a result of this the channel rims would have widened (just as slumping of crater rims during modification will act to widen the transient crater diameter). This is the form we see on the Moon today.

3.1.3 Domes, Cones and Shields

Although large volcanoes do not exist on the Moon, there are small volcanoes found in many areas. Domes are broad, convex landforms more-or-less circular-oval, found on the lunar maria. On Earth, the term “dome” would imply a silicic lava being involved - this is not the case on the Moon, as far as we know. Lunar domes range in diameter up to 24km, rising only 100 to 250m above the surrounding terrain, so really they are shields, in the correct sense of the word.

Lunar cones are very different to those found on Earth. They are more often found associated with rilles on the Moon and have a very low albedo. Most are small and some are irregular in shape, rising only 100m from the ground and only 2-3km diameter at the base. Some have summit craters, less than 1km in diameter.

3.1.4 Dark Halo Craters

Dark halo craters, as their name suggests are crater-like forms with a dark halo around them. They are usually found along basin margins or along rilles and lineaments. Most show rim deposits 2-10km in diameter. The existence of dark halo craters has been used to support the theory that lunar cones may have been formed by the same process as on the Earth, i.e. explosive ejection of sprays of molten rock which are deposited around the vent.

Apollo 17 visited a dark halo crater named “Shorty” to see if it was indeed a volcanic form. Shorty turned out to be an impact crater and not volcanic at all. However, its ejecta, the low albedo material, turned out to be pyroclastic material of volcanic origin. It appears that Shorty crater penetrated a layer of deposits from an explosive volcanic event some time in the past. Whether all dark halo craters are the same or whether some are actually volcanic forms themselves is unknown. The most likely volcanic candidates are those found along the rilles or in a straight line. In any event, the discovery of these pyroclastics is clear evidence that explosive volcanism did occur at some time in lunar history, although how much and for how long is unknown.

3.1.5 Tectonism

Tectonism has clearly played a role, albeit a relatively minor one, in the history of the Moon. Graben and ridges are seen radial and concentric to impact basins, indicating that perhaps some kind of loading stress induced the activity due to the weight of the mare material within the basins. Tidal stresses may also cause tectonic activity, even today, but not enough to modify the thick lunar lithosphere by producing graben or ridges. Some of the Apollo missions carried seismometers to measure “moonquakes”, and although several were detected, they were much, much less energetic than those we experience on Earth. It seems from the data returned from Apollo that, unfortunately, we can’t hope to see surface tectonics in action on the Moon today.

3.2 Lunar Highlands and the Lunar Timeline

3.2.1 Lunar Highlands

The lunar highlands have a high albedo relative to the maria, due to a higher content of refractive minerals. The highlands make up the majority of the surface of the Moon, so it is surprising that relatively little work has been carried out on these regions. They consist entirely of impact craters, in fact the surface is saturated with impacts of varying degrees of degradation from the very freshest to those barely discernible from the surrounding terrain.

After the first few Apollo missions to mare regions were completed, some more adventurous targets for landing sites were made. Apollo 16 was sent to a highland site close to Mare Nubium. Its objective was to sample two units within the highland region which were smooth, dark and had the appearance of being volcanic in origin. However, when the samples were returned, no evidence for volcanism was found, and an alternative explanation of it being impact ejecta was then accepted. It may well have come from the young impact basin Imbrium, which is a large distance away. So some of the highland regions do still hold surprises for us.

FIGURE 3.2 (Crustal dichotomy)

Why the farside has so little mare material is still unknown. Many point to the fact that the farside crust is very much thicker than the nearside (Fig 3.2). However, some volcanism has occurred on the farside, notably in the crater Tsiolkovsky. The floor of this 180km diameter crater has been flooded with perhaps several generations of lava flows. It also has a dark halo crater nearby, possibly indicative of more ancient volcanism having occurred. We are, of course, lacking any samples from the farside, volcanic or otherwise. Samples from the nearside have opened up our understanding of the processes and events that have occurred there. Samples from the farside would undoubtedly do the same, particularly where volcanism is concerned.

3.2.2 Lunar Timeline

On the Moon, craters are most readily degraded by the impact of another crater on it or close by (space weathering over thousands and millions of years also causes degradation). As well as "ageing" adjacent craters, the overlying of fresh crater material on an older crater (or other feature) gives us a relative timeline for those two events, i.e. the crater doing the overlaying is younger than the one being overlaid. This simple "law of superposition" has enabled a timeline to be established for events on the Moon, and isotopic dating of returned lunar samples has enabled tentative anchor points in time for that timeline.

Lunar history is split into five periods, named according to major events occurring within those eras.

Table 3.1 Lunar stratigraphic systems (taken from *The Lunar Sourcebook*)

Period	**Typical Units**	**Approximate Age**
Pre-Nectarian	Basins and craters; volcanic and intrusive igneous rocks; megaregolith and crust	Before 3.92 b.y.
Nectarian	Nectaris and 12 other basins; many degraded craters; some light plains	3.92 - 3.85 b.y.
Imbrian	Imbrium and Orientale basins; Cayley plains; degraded craters; most maria	3.85 - 3.2 b.y.
Eratosthenian	Slightly degraded craters; significant maria	3.2 - 1.2 b.y.
Copernican	Fresh, rayed craters; minor maria	1.2 b.y. - present

Pre-Nectarian: This period encompasses all event that occurred before the Nectaris impact event. Whilst a lot of the features from this period will have been destroyed, there is still clearly a lot observable, including the heavily cratered highland regions and many ancient basins. This period of lunar history was surely a very interesting one - it must have encompassed the chemical differentiation that the Moon underwent, melting, solidification of the crust, in fact the "Moon" as a structural body was formed in this period. No evidence for this remains today however, and we have to study to the rocks themselves to work out what actually happened in the very early times.

Nectarian: A very short period, but obviously very busy judging by the number of impact basins and craters which occurred during this time. This indicates a period of very heavy bombardment by meteorites which was not repeated to such a degree at any subsequent point in lunar history. The crust must have undergone a substantial reworking during this period, and perhaps even very early volcanism may have begun. Rocks from this era were returned from the Apollo 17 site which may be ejecta from one of the impacts of the time.

Imbrian: The Imbrium impact was a very important event in lunar history. Its ejecta sheet dominates the lunar globe and represents an important stratigraphic marker. Possibly only one other basin impact occurred after Imbrium itself (Orientale), but intense cratering did still happen during this period. Many rocks from this era were returned with some of the Apollo missions, and it represents the period when most of the lunar volcanism occurred.

Eratosthenian: Now we're getting a bit closer to home. Volcanism probably ceased during the early part of this period and although some impact craters did still form, there were nowhere near as many as in earlier times. This was also the period where some of the basins subsided due to the weight of the mare material filling them - extensional and compressional features were formed, giving us the wrinkle ridges and graben we see associated with impact basins.

Copernican: We are in the Copernican period now, and have been for the past billion years, approximately the time of the impact creating the crater we now know as Copernicus. The rays and ejecta of Copernicus cover almost every other unit on the Moon, and very few impacts greater than 50km diameter are younger. No volcanism younger than Copernicus has been discovered, although a small amount of tectonism may have occurred.

3.3 **Elemental abundances**

While we have already talked about the two main provinces of the Moon, the maria and the highlands, nothing has been said about the composition of these two units nor of the abundance of elements there. Before we get to look at the lunar rocks, the stuff of which the Moon is made, we need to review things on a finer scale - rocks are made from minerals which in turn are made from elements and its here that we start.

The major elements on the Moon are oxygen, sodium, magnesium, aluminium, silicon, calcium, titanium and iron. Of these, oxygen is by far the most abundant, making up 60% of all the atoms which make up the lunar rocks. There is no free oxygen however; all of the oxygen is bound up with other elements. The next most abundant element in terms of atoms is silicon, taking up another 16-17%, then aluminium (10% in highlands 4.5% in mare), then calcium, magnesium, iron, titanium and sodium in that order make up the rest. Normally, when you see the concentration given of these elements, it is in terms of the element as if it were in a simple oxide (i.e. FeO or TiO_2).

Incompatible trace elements are generally unable to fit easily into the crystal structure of major minerals (hence the name “incompatible”) and have a very low abundance (hence the name “trace”). Often, some of the most important elements in terms of what they can tell us are not the major elements, but those which are much rarer. For instance, they may be able to tell us more about the igneous processes that formed the lunar rocks (i.e. inferring the compositions of source melts). They have too low an abundance to form minerals themselves, and during chemical differentiation the incompatible trace elements partially separated and became concentrated in early silicate melts, in some cases to form rocks known as KREEP (potassium [K], rare earth elements [REE], phosphorus [P]) rocks. Although highly enriched in these elements, they still constitute only trace amounts by weight of the rock itself (<0.1% wt.).

KREEP rocks are mostly associated with the highland regions, and are strongly correlated with one another in those areas. Mare KREEP rocks do exist although the range of concentrations in the mare are much smaller than those in the highlands.

3.4 Lunar Minerals

Lunar rocks are made up of minerals and glasses. Over 90% of the volume of these rocks are made of silicate minerals, the most abundant of which are pyroxene, plagioclase feldspar and olivine. After silicates, the oxide minerals are most abundant, chiefly concentrated in the mare regions, where they can make up to 20% of the rocks there.

3.4.1 Silicate Minerals

These are by far the most abundant mineral in both the mare and highland regions. Meteoroid impacts over time have pulverised the topmost layer of these rocks to form the regolith layer (fragmented, unconsolidated rock debris). The regolith extends several metres deep and gives useful samples of several different rock types. There are many kinds of silicate mineral, the most common of which are pyroxene, plagioclase feldspar and olivine.

Pyroxenes $(Ca,Fe,Mg)_2Si_2O_6$: This may well be the most complex of the major silicates and is the most abundant dark mineral found on the Moon. It comes in two general varieties in the lunar environment, the low-Ca and high-Ca. The high-Ca variety makes solid solutions of $Ca_2Si_2O_6$, with contributions from Mg and Fe, whilst the low-Ca varies between the endmembers $Mg_2Si_2O_6$ (enstatite) and $Fe_2Si_2O_6$ (ferrosilite). The mare regions generally have a higher concentration of pyroxenes, and are mainly of the high-Ca type. These often have a lower magnesian and higher iron content than those in the highlands.

Plagioclase Feldspar $(Ca,Na)(Al,Si)_4O_8$: Most of the lunar feldspars come from the plagioclase series, with very few potassium feldspars being found. There is also a lower content of sodium relative to terrestrial feldspars, which highlights the overall depletion of alkali elements in the lunar crust. The plagioclase feldspars vary from the most dominant form, anorthite ($CaAl_2Si_2O_8$) to that of albite ($NaAlSi_3O_8$) which represents only a few percent of the rocks sampled.

Plagioclase carries almost all of the lunar aluminium, and although plagioclase is found in both highland and mare regions, there is more found in the highlands. This correlates well with the remote sensing data which shows that there is a higher concentration of Al in the highlands relative to the mare. The higher plagioclase content (which is white) explains the brighter colour of the highlands.

Olivine $(Mg,Fe)_2SiO_4$: Just like the pyroxenes, olivines have a higher Fe content and lower Mg content in the mare than in the highlands. Olivines range between the solid solution endmembers of fayalite (Fe_2SiO_4) and forsterite (Mg_2SiO_4). Most mare basalt olivines vary between Fa_{20} and Fa_{70}.

3.4.2 Oxides

The oxides are far more distinct from terrestrial oxides than are the silicate minerals. They are particularly abundant in mare regions, commonly as ilmenite, and less so as spinels and armalcolite. Ilmenite ($FeTiO_3$) is the most abundant oxide. Most of the lunar titanium is found in ilmenite and related minerals.

3.5 Lunar Rocks

Now we reach the stuff that the Moon is made of - rocks. We have learned a lot about the Moon from the returned rocks, and certainly know a lot more about the composition of the Moon. The rocks of the Moon can be classified into four distinct types; 1) basaltic volcanic rocks, 2) pristine highland rocks, 3) polymict breccias and 4) lunar soil.

3.5.1 Basaltic Volcanic Rocks

These are formed by processes similar to those of the Earth are therefore probably the best understood of the lunar rocks. They are likely to have formed by the melting of the solid interior at 100-400km depth, followed by the rise of this molten rock to the lunar surface. There are two types of volcanic rock from the Moon which we know about. 1) Lava flows - these are much thinner than equivalent flows on the Earth, possibly due to the higher iron and lower silicon and aluminium content in the lunar basalt. 2) Pyroclastic deposits - these are glassy beads that appear to be the result of lava fountains and are similar to ash deposits found in terrestrial examples. Examples of such lunar soil are the orange soil found at the Apollo 17 site and green glass found at the Apollo 15 site. Dark halo craters, as discussed previously, are prime candidate sites for the future discovery of more pyroclastic deposits.

Lavas were produced by the partial melting of the lunar mantle. If this melting was in chemical equilibrium, then they will preserve the clues to the composition of the original source material. The minerals making up a rock will depend very much on the composition of the lava from which it formed and its mineralogy on the rate at which the lava cooled. Mare basalts are composed mainly of four major minerals: pyroxene, plagioclase feldspar, olivine and metal oxides and there is a wide variety of compositions of basaltic rock found on the Moon.

Mare rocks have a greater FeO and TiO_2 concentration and higher Ca/Al_2O_3 ratios than the highlands (i.e. the mare has less Al-rich plagioclase feldspar than in the highlands). The most identifiable compositional change between mare rocks lies in their TiO_2 content. The TiO_2 content is the basis for recognising three of the major basalt groups: high-Ti (>9%wt TiO_2), low-Ti (1.5-9%wt TiO_2) and the very low-Ti (<1.5%wt TiO_2). Each of these three groups may be sub-divided on the basis of other chemical variations. An important differentiation is made on the basis of the Al_2O_3 content. There are some low-Ti basalts that have a higher Al_2O_3 content than the others, and these are called the aluminous low-Ti basalts. The high-Ti basalts have been split into high-K (>0.3%wt) and low-K (<0.1%), based on their K_2O content.

High-Ti basalts: These were returned mainly from the Apollo 11 and 17 sites. The variation seen within this rock class is probably the result of the crystallisation and separation of early-forming minerals. All high-Ti basalts have low Eu contents relative to the other REE (known as the "negative Europium anomaly"). This is actually true for all mare basalts, as Eu tends to concentrate in Ca-feldspar (i.e. highland material - in fact, it is seen that highland rocks have more Eu relative to REE).

Low-Ti basalts: These were found primarily from the Apollo 12, 15 and Luna 16 sites. In general the REE are less abundant that in the high-Ti basalts. Some other incompatible elements are also lower in the low-Ti basalts.

Aluminous low-Ti mare basalts: Three types of this basalt have been distinguished on the basis of their location and chemistry - from the Luna 16 site, from the Apollo 14 site and other from the Apollo 14 mission but which have high K_2O abundances. A suite of related aluminous basaltic rock fragments were found in a single breccia at the Apollo 14 site representing separate lava flows. Whilst these fragments show little variation in major elements, there is a huge variation in REE. Other Apollo 14 fragments have exceptionally high K_2O (0.6-1.2%wt) abundances and are called very high-K basalts. Very few of these have been found.

Very-low Ti basalts: These were found in drill cores at the Apollo 17 site. They have low REE and incompatible elements.

Twenty-five different volcanic glasses have been identified from the Apollo missions as being pyroclastic deposits. They have a wide variety of TiO_2 content from very low (0.26%wt.) to very high (16.4%wt.), but they tend to concentrate at the extremes, and few are found at midway abundances. The greatest chemical difference comes with the amount of compatible elements in the glasses. Like the mare basalts, pyroclastics also have a negative Eu anomaly.

3.5.2 Pristine Highland Rocks

Pristine highland rocks are rare. They represent rocks from the original crust which have not been pulverised by subsequent meteorite bombardment. Any pristine highland rock is extremely important to scientists as it gives us a direct view of the crust as it was when it originally formed. The difference between pristine rocks and others can sometimes be obvious just by looking at a thin film through a microscope, but this isn't always the case. Typically, there is no simple way to tell between the two, and mistakes have been made in their identification in the past. There are three major groups of pristine highland rocks: KREEP, ferroan anorthosites and Mg-rich rocks.

Ferroan Anorthosites: These are light coloured, rich in Al and Ca, and made mostly of plagioclase feldspar. It is the most common type of pristine highland rock. They are distinguished by an unusual combination of low-Na plagioclase feldspar with low-Mg pyroxene. Probably formed during the slow cooling deep below the surface. The "genesis" rock from Apollo 15 is a ferroan anorthosite. Usually pyroxene is the 2nd most abundant mineral, then olivine, and they have low abundances of REE. These rocks are very difficult to date.

Mg-rich rocks: These are more varied than the ferroan anorthosites, with several subclasses in the group, namely the gabbros and norites (made of pyroxene and plagioclase), troctolites (olivine and plagioclase) and dunites (nearly pure olivine). They are common at all Apollo sites and most are brecciated. Again, dating of these samples is very difficult, but when done give ages over 4 billion years.

KREEP rocks: these are highly enriched in KREEP, and only basaltic lavas have been identified as pristine. They appear to be older than most of the mare basalts and are most abundant around the Imbrium basin. Returned samples include small basaltic fragments found in the Apollo 15 and 17 breccias. Some rocks with enhanced KREEP are also known as Fra Mauro basalt because some of the rocks from the Apollo 14 site are almost exclusively KREEPy breccias (although these are not necessarily pristine examples). The location of the source bedrock for KREEP rocks is not known for sure, although they possibly come from the Apennine Bench Formation. They are easily found as they have an easily detectable chemical signature.

3.5.3 Breccias

Breccias are basically rocks made up of broken up fragments of other rocks. They are testimony to the intense bombardment that has taken place in the Moon's history. The majority of rocks brought back from the manned and unmanned Moon missions are breccias. They are composed of rock, mineral or glass fragments (called clasts) set in a fine-grained matrix (material between the larger rock and fragments). The fragments themselves may be a mixture of different materials of different ages which makes them difficult to classify. Two broad classification schemes can be used however:

Monomict breccias: These are made of only a single rock type, composed of broken and crushed fragments of the original lunar bedrock. They often have fragments with unaltered textures, and are therefore included with the pristine highland rocks. Monomict rocks appear to have somehow survived the period of bombardment with no contamination, mixing or alteration of its composition. Pure igneous highland rocks are rarer to find.

Polymict breccias: These contain many different rock types and materials (i.e. different bedrock, previous breccias, impact melts etc…) and constitute the highest proportion of returned rocks from the Apollo missions. They contain two components: broken rock fragments and melted material. Like all samples, none have been sampled directly from the bedrock, and so nothing is known about its parent unit. They naturally show a large compositional variation. There are several classifications of highland polymict breccias, and for those of you who are interested, take a look at the Lunar Sourcebook, Chapter 6, p.185.

3.6 Origin and Evolution of the Moon

One of the ultimate aims of lunar scientists is to work out how the Moon formed and how it evolved. The only evidence we have left from that early era are the rocks, and their composition and ages can provide important clues for us. However, much of the early history of the Moon is still poorly understood.

There are several theories about the lunar origin. The first suggests that the Earth and the Moon formed at the same time, accreting as separate bodies from the solar nebula (co-accretion theory). The second suggests that the Moon formed from the Earth - somehow the Earth's angular momentum increased, spinning the planet so fast that material was thrown off and accreted to form the Moon (fissure hypothesis). The third has the Moon forming in a different part of the solar system, then being captured by the Earth's gravitational field as it came past in it's unusual orbit (capture hypothesis). These three theories seem to have become less popular since the Apollo missions, in favour of a fourth hypothesis which has a large body (possibly Mars-sized) impacting off-centre with the Earth early in its formation. Material was thrown off and eventually accreted to form the Moon. This theory does have its pitfalls, but has less problems than all the others. It can explain the lack of volatiles on the Moon. During the impact, the material would have been heated, boiling off the volatile materials into interplanetary space, leaving only the material which could survive those temperatures as liquids or solids. Most of the heavy elements (such as Fe) would have been retained on Earth, leaving a relatively small amount to form the core of the Moon. Overall, the Moon is less abundant in Fe than the Earth and this seems to fit in well with the theory. In addition, the theory suggests that mostly the mantle of the Earth would have been flung off, and the bulk composition of the Moon does seem to be similar to that of the Earth's mantle.

What happened after that leads on to another topic of heated debate among lunar scientists. I would imagine that if you spoke to someone about the evolution of the early Moon, a "global magma ocean" would be mentioned. This theory first surfaced in 1970, in an effort to explain why there was such a clear dichotomy been the two major units on the Moon. In essence, the Moon was once molten to a depth of a few hundred to several hundred kilometres. This melt pool constituted the global magma ocean. Whilst molten, the light materials floated to the top, and the heavier elements sank, or at least did not float. The lighter material, once solidified, became the low density highland material we see today. The heavier regions became the source regions for the denser mare basalt lavas. Our current view of lunar magmatic evolution can therefore be summarised thus:

1. Formation of the anorthositic crust: the highlands are the product of plagioclase floatation, forming the first stable solid crust of the Moon. As the magma ocean crystallised, a residual liquid formed, rich in trace elements - these would have constituted the first of the KREEP regions. The crust would be continually bombarded and modified by the action of impact cratering events.
2. Formation of Mg-rich rocks: There is some debate as to when the Mg-rich rocks formed, but it seems that these magmas were the product of melting events that post-dated the magma ocean. As they formed, they assimilated anorthosite and KREEP material, although from which sources they formed is unknown.
3. Formation of KREEP basalts: After the majority of the magma ocean had crystallised, the residual material would have been enriched in several elements, including the trace elements. This would have found its way to the lower crust, and would have given rise to the KREEP basalts as the rising magmas assimilated the trace material.
4. Formation of the mare basalts: The Eu anomaly show that they formed from cumulates that developed after the plagioclase had crystallised (the europium mostly became locked up in the plagioclase). They formed at depth from sources rich in olivine and pyroxene. Most basalts made their way to the surface from around 3.9 billion years ago, and were then modified by impact cratering, just as the highlands.

<u>Reference List</u>

"The Lunar Sourcebook", Heiken G.H., Vaniman D.T., French B.M., 1995, Cambridge University Press

"A review of lava flow processes related to the formation of lunar sinuous rilles", Hulme G., 1982, Geophysical Surveys, 5, 245

"The formation of eroded depressions around the sources of lunar sinuous rilles: Theory", Wilson L., Head J.W., 1980, Lunar and Plan. Sci., 11, 1260

"Ascent and eruption of basaltic magma on the Earth and Moon", Wilson L., Head J.W., 1981, J. Geophys. Res., 86, 2971