

Lecture 33

Growth and Differentiation of Planet Earth – Formation of the Core and Moon

Reading this week: White Ch 11 (sections 11.5 – end)

Today – Guest Lecturer, Greg Ravizza

1. Core Formation imprint on the mantle
2. origin of the moon
3. Earth Accretion summary

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Core Formation continued... Chemical indicators from the Mantle

Recalling the discussion at the end of last lecture...

Two things are apparent:

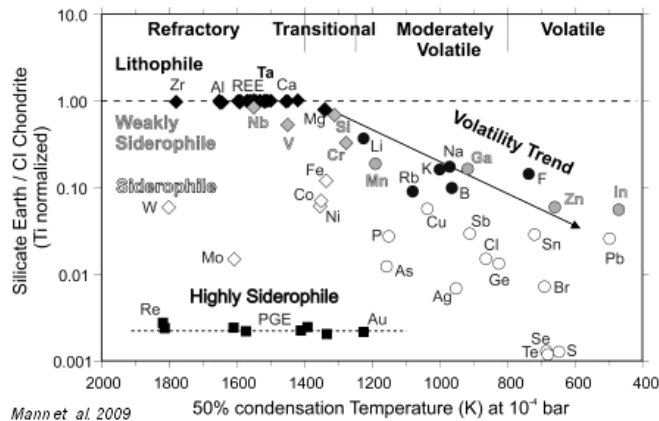
- a) **Sideophile elements** are **not as low in the mantle** as would be expected from pure metal-silicate equilibration.
 - They are **5-350 times more enriched** than expected for **complete equilibrium** between silicate and molten iron.
 - **Volatile siderophiles** appear to be **even more enriched** than **non-volatile** ones.

These facts **could** argue for **incomplete equilibration** (e.g., a kinetic or spatial effect), an impure Fe phase (e.g., a chemical effect) and/or addition of a volatile rich component **after** core formation.

- b) **Chalcophile elements** are depleted in the silicate Earth relative to chondrites, but not as depleted as many of the siderophiles are.

This **could** argue against much **S** in the core.

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Element abundances of the Earth's mantle normalised to CI chondrite and Ti (data from Palme and O'Neill, 2003). Siderophile elements have metal-silicate partition coefficients that are >1 and were therefore depleted from the mantle relative to CI during core formation. They can be divided into three basic groups, weakly siderophile (grey symbols), siderophile (unfilled symbols) and highly siderophile (black squares). Lithophile elements are not depleted from the mantle as a result of core formation (all other black symbols). An additional depletion trend affecting both lithophile and siderophile elements results from volatile behavior (circles) which is considered to be a broad function of the elements' 50% condensation temperatures from the solar nebula at 10^{-4} bar (data from Wasson, 1985).

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Chemical indicators of core formation from the mantle

Before we interpret the data further, let's look at how we might estimate the siderophile content of the early mantle.

Direct Method:

1. analyze actual samples of mantle (e.g., xenoliths in lava flow)

Indirect Methods:

1. analyze a siderophile element in a mantle-derived lava, and then apply a melting model to estimate the element's concentration in the unmelted mantle source of that lava.
2. Analyze a "melting invariant" trace-element ratio of one siderophile element and one non-siderophile, refractory element in a mantle-derived lava, and then use some fancy footwork to estimate the concentration of the refractory element using the chondritic primitive mantle model.

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Chemical indicators of core formation from the mantle

Each method has assumptions and inherent weaknesses.

Direct # 1

Xenoliths are rare, and even rarer are xenoliths that haven't either reacted with their host magma or don't show evidence of prior high-temperature modification in the mantle (recrystallization, secondary phases, etc).

Indirect # 1

Melting models, as we'll discuss in the near future, are good at predicting *relative* abundances of trace elements in the source but **are not as good at predicting absolute concentrations**.

Indirect # 2

For the most part, **this is the most accurate and most widely used approach** because it depends on compositional characteristics that are well known. However, assumptions about the constancy of a trace element ratio during melting still result in some large uncertainties.

Let's look at this method in more detail.

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Chemical indicators of core formation from the mantle

Indirect # 2

This method has 3 steps, outlined below.

Henry's Law, applied to equilibrium between a melt and one or more solids, says that for an element A:

$$^A K_d = \frac{[\text{modal conc. of A}]_{\text{solids}}}{[\text{conc. of A}]_{\text{melt}}}$$

Some siderophile elements have low K_d values (<1) during melting of mantle rock to produce basalt, so that very little of such elements will remain in the solid phases in equilibrium with a basaltic melt.

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Chemical indicators of core formation from the mantle

Indirect # 2 (continued).

1. *invariant ratios* allow rely on analogous behavior to “see through” the chemical effects of processes.

These involve **elements** that **behave very similarly** during a process, such as melting of the mantle.

Non-siderophile example: K and U behave very similarly during mantle melting, such that $K/U \approx 12,000$ in many mantle-derived rocks on Earth (i.e., K/U ratio is a nearly invariant ratio for most mantle melting systems).

${}^U K_d \approx {}^K K_d$ (note: we used this invariance when we talked about formation temperatures of planetary surfaces because K is more volatile than U)

To calculate the siderophile content of the mantle, we want invariant ratios that include a siderophile element. For example, Mo/Nd. Mo is moderately siderophilic. Nd is a lithophile.

${}^{Mo} K_d \approx {}^{Nd} K_d$ so $(Mo/Nd)_{\text{basalt}} \approx (Mo/Nd)_{\text{mantle}}$

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Chemical indicators of core formation from the mantle

Indirect # 2, continued.

2. Refractory elements give absolute concentration:

Nd is a refractory element, so it was **not redistributed** significantly during the **high temperature processes** that occurred **during accretion**.

Al is another refractory element. Since it is a major constituent of the high temperature materials that formed the Earth's mantle, **the Al content of the mantle is very well known**.

Al content is a good thing to pin absolute concentration of our siderophile element to (in this case, the element Mo).

It turns out that $Nd_{\text{volatility}} \approx Al_{\text{volatility}}$, meaning they condense similarly during the condensation sequence.

Therefore, it is safe to assume that

$(Nd/Al)_{\text{early mantle}} \approx (Nd/Al)_{\text{chondrites}}$

Remember, assuming that the early mantle formed from chondritic material is a very good approximation for the refractory elements.

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Chemical indicators of core formation from the mantle

Indirect # 2, continued.

3. Absolute Siderophile Concentration Calculation

We can use the following equation to calculate the absolute concentration of our siderophile element (Mo) in the mantle:

$$(\text{Mo/Nd})_{\text{old basalt}} \times (\text{Nd/Al})_{\text{chondrites}} \times \text{Al}_{\text{mantle}} = \text{Mo}_{\text{mantle}}$$

Note that this final equation utilizes three well-known facts to determine a fourth:

- ✓ similar behavior of Mo and Nd during formation of a basalt from the mantle
- ✓ similar volatility of Nd and Al during condensation and accretion.
- ✓ the absolute concentration of Al in the mantle.

The same procedure can be applied to other siderophile elements too. For instance, for W, one would use the invariant W/U ratio and the fact that

$$\text{U}_{\text{volatility}} \approx \text{Al}_{\text{volatility}} \text{ to calculate } \text{W}_{\text{mantle}} \text{ from } \text{Al}_{\text{mantle}}$$

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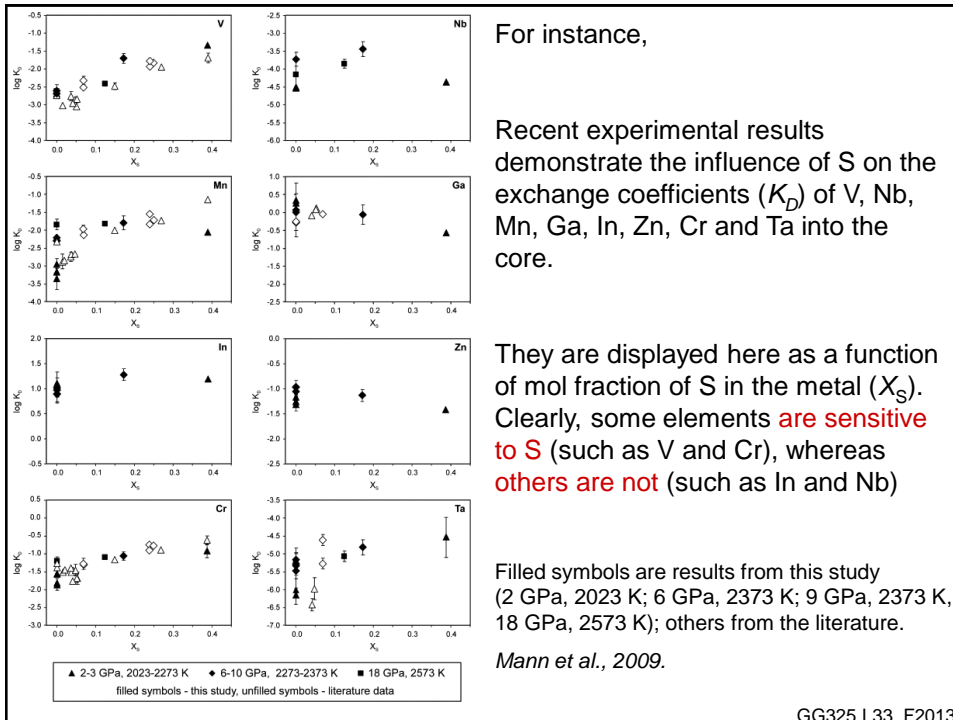
Chemical indicators of core formation from the mantle

Some Results of Indirect # 2

Both Mo and W are considered "moderately" siderophile. Applying the above procedure, we find that:

Mo_{mantle} and W_{mantle} are somewhere in between what would be expected from complete equilibrium with molten Fe and no equilibrium with molten Fe.

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Core Formation Chemistry and Homogeneous Accretion

This topic is very much an area of ongoing research, but it looks like at least some volatile-rich chondritic material was added to the mantle after the core was formed to explain the moderately siderophile/very volatile element abundances.

This means that core formation occurred before accretion was complete.

In general, the mantle can be considered to have been ~90% equilibrated with pure molten Fe, which implies the Earth had built up to at least 90% of its current size when core formation occurred.

Other evidence for this late chondritic veneer being added material to Earth after core formation comes from estimates of $\text{Fe}^{+3}/\text{Fe}^{+2}$, CO_2/CO and $\text{H}_2\text{O}/\text{H}_2$ in the mantle.

All are slightly higher than expected for homogenous accretion, yet lower than expected for heterogeneous accretion.

Earth Accretion Summary

Both **homogeneous** and **heterogeneous** accretion fail to explain all observations, but the **homogeneous** model **is better** at predicting the distribution of materials within the early Earth.

Most geochemists now prefer a *modified homogeneous accretion model* (i.e., mostly homogeneous but with some funny business near the end).

1. Homogeneous accretion of perhaps 90% of the present mass.
2. Major part of the core forms, stripping highly siderophile elements from the mantle. Moderately siderophile elements (e.g., Mo and W) are not removed as effectively (possibly for kinetic reasons or because molten Fe is polluted by FeS, FeO or another contaminant; we don't know yet).
3. Most of the last ~10% of the Earth is accreted and the last few percent of the core forms, during which some additional stripping of siderophile elements (including moderately siderophilic ones) occurs.
4. A veneer of chondritic material is added, increasing all siderophile element concentrations, the relative proportion of volatile siderophiles to non-volatile siderophiles, and the abundances of other volatiles in the mantle.

As we'll see, this model requires further modification to account for our atmosphere.

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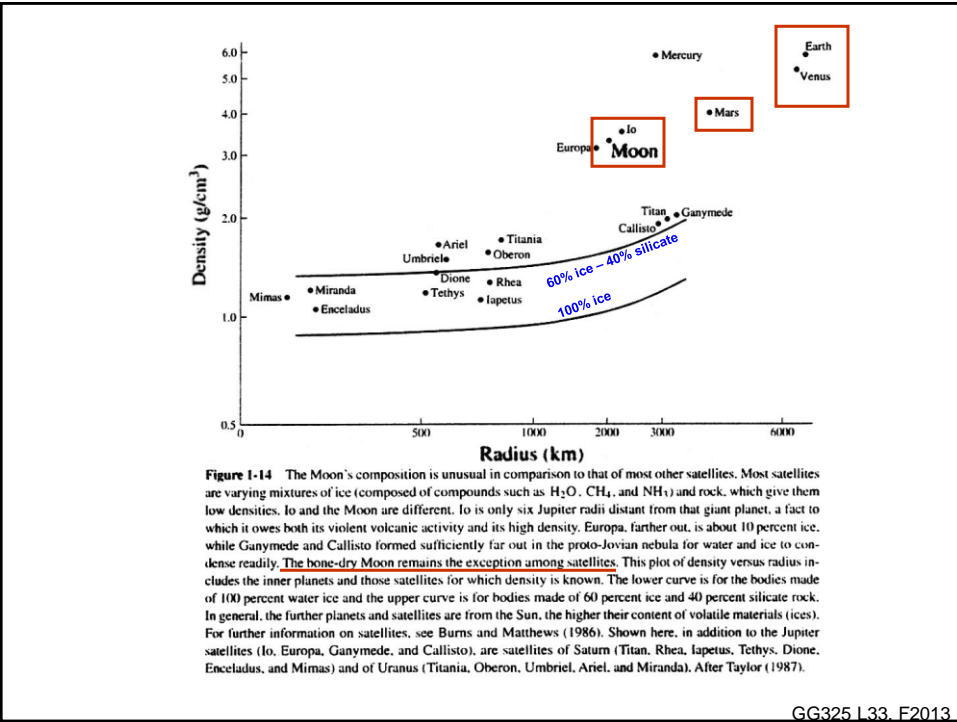
The formation of our Moon

Earth's moon plays a role in the story of our own accretion and differentiation.

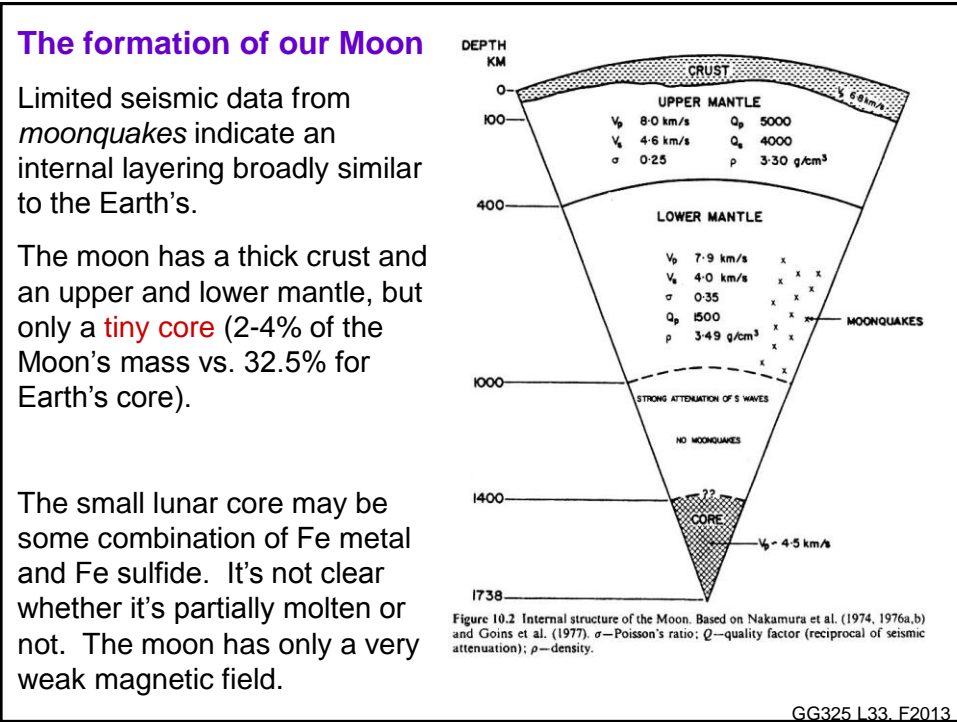
The moon is:

1. of relatively large mass for a planetary satellite
2. in an odd high inclination orbit
3. with Earth, retains a great deal of angular momentum
4. is much more dense than most moons and unique of all satellites in being essentially without "ice" components
5. compositionally very similar to Earth in some aspects.

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The formation of our Moon

Lunar sampling expeditions provide invaluable samples of the lunar crust.

Table 10.9. Comparison of the Compositions of the Earth and Moon

	Bulk Earth	Bulk Moon	Silicate Earth	Silicate Moon
SiO ₂	30.38	43.4	45.0	44.4
TiO ₂	0.14	0.3	0.201	0.31
Al ₂ O ₃	3.00	6.0	4.45	6.14
FeO	5.43	10.7	8.05	10.9
MgO	25.52	32	37.8	32.7
CaO	2.40	4.5	3.55	4.6
Na ₂ O	0.24	0.09	0.36	0.09
K ₂ O	0.02	0.01	0.029	0.01
Fe	28.43	2.166	87.5	
Ni	1.75	0.134	5.4	
S	1.62		5	
core%	32.5%	2.3%		
mantle	67.5%	97.7%		

Terrestrial composition from McDonough and Sun (1995), assuming the light element in the core is S. Lunar composition from Taylor (1992). *White, Geochemistry*

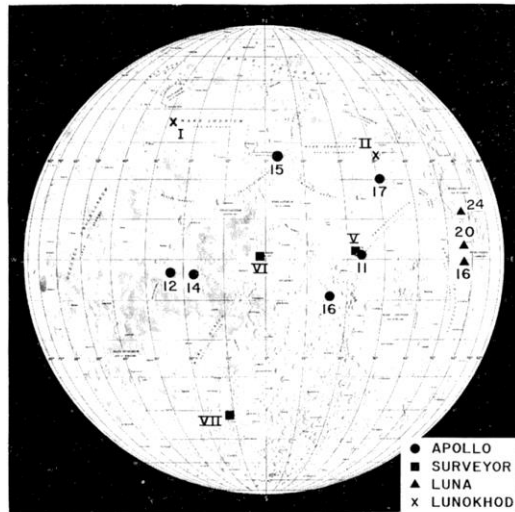


FIG. 3.1. The landing sites of the Apollo, Luna, Surveyor and Lunokhod missions. (After Taylor, 1975) *Henderson, Inorganic Geochemistry*

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The formation of our Moon

The moon is compositionally very similar to Earth in some aspects.

◆ oxygen isotopic composition

◆ bulk major element composition,
but in the moon's case there's much less of:

✓ metallic Fe (overall), although the silicate portion of the moon has more Fe²⁺ than the silicate Earth

✓ siderophile elements (e.g., Ga, Ge)

✓ moderately volatile elements (e.g., Na, K, Rb, Cs)

✓ highly volatile elements (e.g., Bi, Pb, As).

And there's significantly more of

✓ refractory elements Al, Ca, Ti

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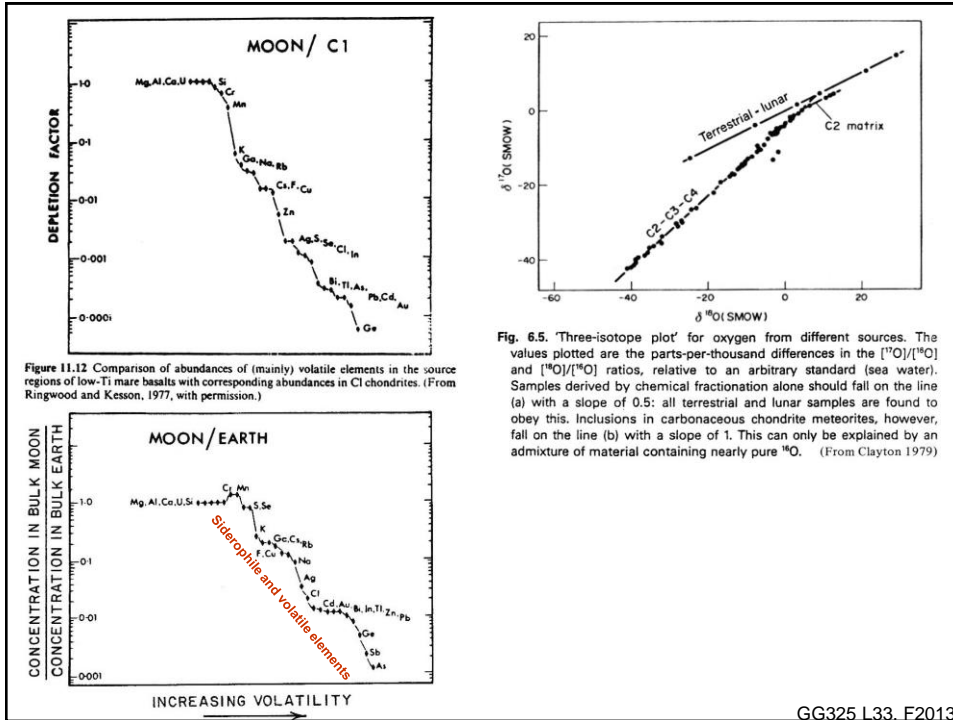


Figure 11.12 Comparison of abundances of (mainly) volatile elements in the source regions of low-Ti mare basalts with corresponding abundances in C1 chondrites. (From Ringwood and Kesson, 1977, with permission.)

Fig. 6.5. 'Three-isotope plot' for oxygen from different sources. The values plotted are the parts-per-thousand differences in the $^{17}\text{O}/^{16}\text{O}$ and $^{18}\text{O}/^{16}\text{O}$ ratios, relative to an arbitrary standard (sea water). Samples derived by chemical fractionation alone should fall on the line (a) with a slope of 0.5: all terrestrial and lunar samples are found to obey this. Inclusions in carbonaceous chondrite meteorites, however, fall on the line (b) with a slope of 1. This can only be explained by an admixture of material containing nearly pure ^{16}O . (From Clayton 1979)

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The formation of our Moon

Of the four likely scenarios for the formation of the moon:

- ☆ capture of an extra terrestrial body.
- ☆ "Auto" fission from the Earth
- ☆ Separate condensation near Earth
- ★ "Forced" fission from Earth, via impact ("collision")

the latter is the most commonly accepted, because it explains most of the observed facts.

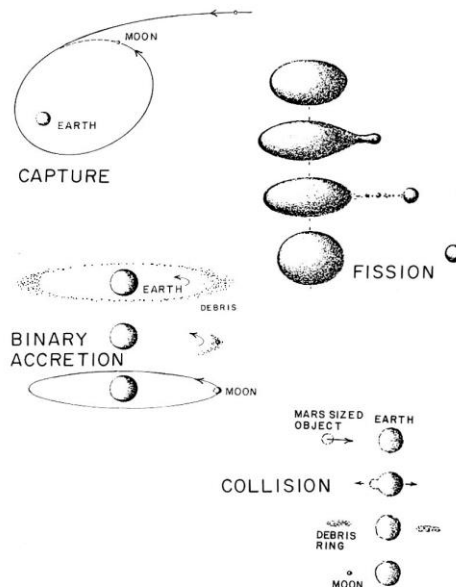


Figure 6-4. Drawings illustrating the four origins hypothesized for the Moon. Broecker, "...Habitable Planet"

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The formation of our Moon

The giant impact scenario is supported by:

- the relative proportions of refractory and volatile elements on the Earth and Moon
- the E-M homogeneity of refractory-element ratios
- and similar E-M oxygen-isotope ratios

Abundances of refractory and **volatile** elements in the Earth and Moon

	Earth	Moon	Moon/Earth
K ppm	150-200	100	0.50-0.67
U ppm	15-20	40	2.0-2.7
K/U	10,000	2500	0.25
Th ppb	57-76	152	2.0-2.7
Rb ppm	0.50-0.66	0.30	0.45-0.6
Sr ppm	16-21	40	1.9-2.5
Rb/Sr	0.031	0.0075	--
Na ppm	1200-1600	800	0.50-0.67

Source: Taylor, 1979



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Formation of our moon

The giant impact hypothesis: First proposed by R. Daly in the 1940s, and later by Hartmann and Davis (1974).

Current theory is that the Moon formed when the Earth (at >0.5 its present size) was struck at low angle by a slow-moving (~5 km/s) body **slightly larger than Mars** during the latest stages of accretion.

The impact would have occurred *after core formation* on both the Earth and the impacting body, which is sometimes called “**Theia**.”

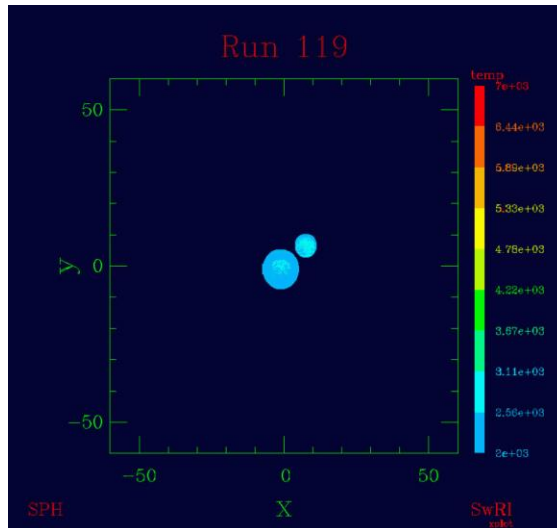
Theia is postulated to have accreted from material in roughly the same annulus of the solar nebula as the Earth (supported by the O-isotope data) and presumably was similarly depleted in highly and moderately volatile elements relative to the chondrites.

The collision **partially disrupted/melted the Earth’s mantle** and **completely disrupted/melted Theia**.



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Theia Impact Simulation



Simulation of the early stages of the Moon's origin by a giant impact.

(Canup, 2004).

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Formation of The Moon

Much of the resulting impact debris went into Earth orbit.

High temperatures after the impact evaporated the most volatile elements, leaving the moon very depleted in such material.

Most of the **core of the Theia** is believed to have accreted to the Earth and the **orbiting silicate material** slowly coalesced to form the Moon.

About 85% of the material forming the moon was derived from **Theia** and about 15% was from Earth's mantle.

The lunar siderophile element depletion is explained by prior core formation from **Theia** and Earth, and generation of the moon from the silicate fractions. A small core then segregated from the largely molten moon.



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Formation of our moon

Lunar rocks indicate **very extensive melting** occurred just after formation, probably producing a magma ocean >100 km deep (maybe more).

Melting produced a basaltic crust that was largely emplaced within 100-200 Myr after the Moon's formation. The very **oldest lunar rocks yet dated are nearly 4.5 Ga**.

Heavy impact bombardment continued until ~3.9 Ga.

From about 3.8-3.1 Ga, the large impact craters were flooded with immense outpourings of tholeiitic basalt, after which volcanic activity ceased.

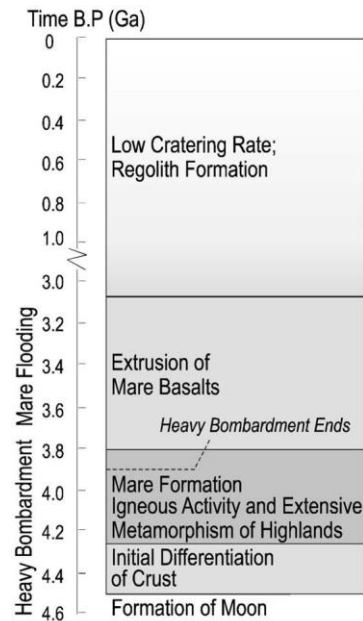


Figure 10.39 Highlights of lunar chronology modified from White, *Geochemistry*

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Formation of our moon

The Moon's basaltic crust contains a range of rock types. Two extreme compositions are found:

(a) a variety of basalt that is enriched in K, the lanthanide rare-earths, and phosphorus; this rock type is termed "**KREEP**".

(b) **anorthosite** (anorthite-rich rock) dominates the lunar highlands; it's thought to be produced by plagioclase that floated to the top of the magma ocean.

These two rock types form the upper and lower extremes of mirror-image normalized rare-earth element profiles, **suggesting that they separated from the same homogeneous reservoir**.

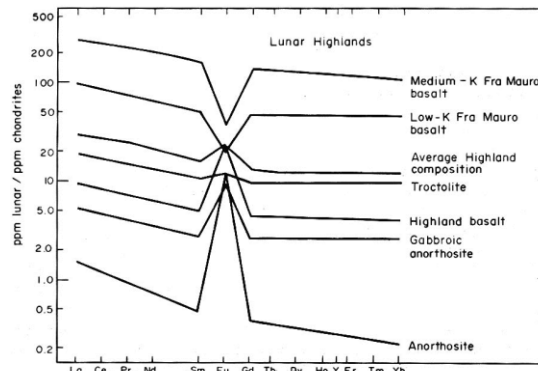


FIG. 3.5. Rare-earth element abundance patterns, normalized to abundances in chondrites, for highland rock types. (After Taylor, 1975) Henderson, *Inorganic Geochemistry*

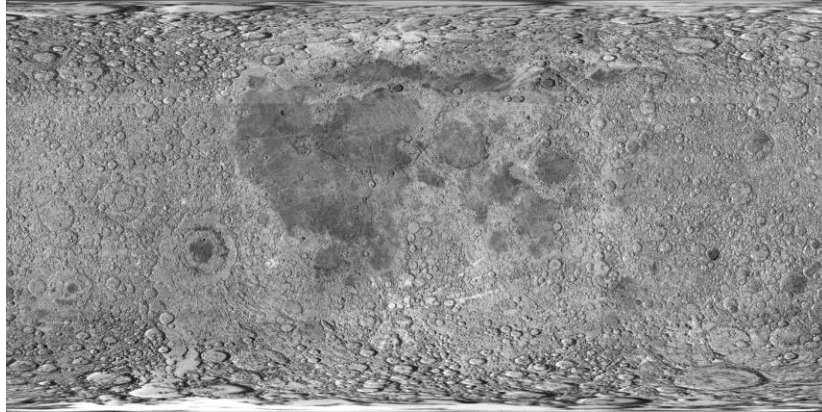
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Formation of the Moon

Other implications of lunar formation:

The total amount of energy released by accretion of the Earth was much greater than that released by the collision of Theia. Thus we expect that, like the Moon, the **early Earth melted extensively**.

This should have produced an early proto-crust rather similar to that on the Moon, and a partially depleted mantle.



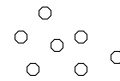
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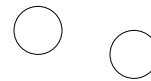
Terrestrial Planet Formation Summary

- Rapid collapse of molecular gas cloud; condensation; high-energy processing.
- Small (km size) bodies form quickly ($<10^6$ yr). Some of these bodies differentiate (for impact and radiodecay heating, i.e., of ^{26}Al , ^{60}Fe).
- Moon- and Mars-size bodies *may* also form nearly as quickly.
- Slower build up of larger bodies: time $\sim 10^7 - 10^8$ yr.
- Last stages of accretion occur in the *absence* of the solar nebula (i.e., after T Tauri stage).
- Mixing across $\sim 1\text{AU}$ or more likely (with chemical disequilibrium?) during later stages of accretion.

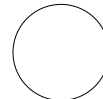
Rapid formation of kilometer bodies from dust



Rapid Formation of Moon sized bodies by runaway accretion



Slow (~ 10 Ma) Formation of Earthlike Planets



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