The Moon

Moon consists of a variety of igneous rock types that differ widely in their mineralogy, composition and age.

The most visible evidence of these differences is the existence of two distinct terrains on the Moon:

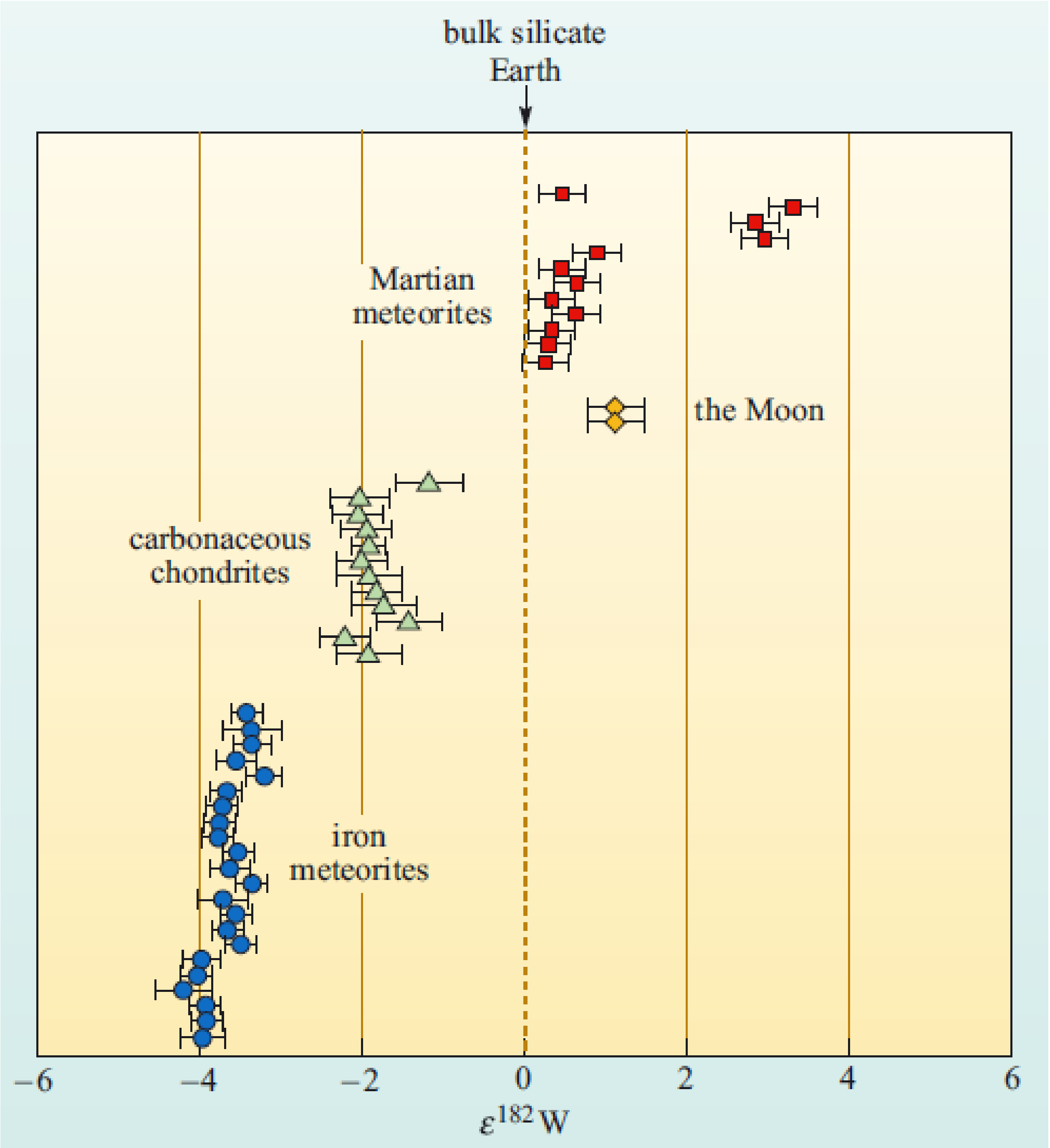
- the light-coloured feldspathic rocks of the highlands
- the dark basalts of the maria

Both rock types are igneous and indicate that at some time during its history the Moon was extensively molten.

Indeed the anorthosites, which are also very old, are thought to have formed by a process of floatation on a magma ocean, their dominant mineral, plagioclase, being lighter than the iron-rich basalts from which they crystallised.

It is possible to use Hf–W model ages to date the age of the Moon. One lunar basalt yields a positive ε182W, i.e. it has more radiogenic W than the bulk silicate Earth.

However, the Moon is also thought to possess a higher Hf/W ratio than Earth, so the derived age is similar to that of the bulk silicate Earth, and ages for Hf/W fractionation in the Moon range from between 30 Ma and 45 Ma after the start of the Solar System.



bulk silicate Earth
Martian meteorites
the Moon
carbonaceous chondrites
iron meteorites
−6
−4
−2
0
2
4
6
ε^{182}W

Structurally, the Moon contrasts with the Earth in that it has a very small core and is totally solid – there is no convecting outer core and hence no magnetic field.

The Moon, being much smaller than the Earth and having a much larger surface to volume ratio, cooled very rapidly after formation.

The compositions of lunar rocks have been used to develop models of the bulk composition of the Moon, which can be compared with that of the bulk silicate Earth and meteorites.

	CI chondrite (primitive meteorite)	Earth (crust + mantle)	Moon (crust + mantle)	Ratio of trace element abundance Moon/Earth
Volatile elements				
K/ppm	545	180	83	0.46
Rb/ppm	2.32	0.55	0.28	0.51
Cs/ppb	279	18	12	0.67

	CI chondrite (primitive meteorite)	Earth (crust + mantle)	Moon (crust + mantle)	Ratio of trace element abundance Moon/Earth
Moderately volatile				
Mn/ppm	1500	1000	1200	1.20
Refractory elements				
Cr/ppm	3975	3000	4200	1.40
Th/ppb	30	80	112	1.40
Eu/ppb	87	131	210	1.60
La/ppb	367	551	900	1.63
Sr/ppm	7.26	17.8	30	1.69
U/ppb	12	18	33	1.83

One of the primary observations of the Moon is that it is depleted in the most volatile elements and enriched in refractory elements. This has been interpreted as relating to a very high temperature origin for the material that makes up the Moon.

	CI chondrite (primitive meteorite)	Earth (crust + mantle)	Moon (crust + mantle)	Ratio of trace element abundance Moon/Earth
Siderophile elements				
Ni/ppm	16500	2000	400	0.200
Mo/ppb	1380	59	1.4	0.024
Ir/ppb	710	3	0.01	0.003
Ge/ppm	48	1.2	0.0035	0.003

The extreme depletion of the siderophile elements in the silicate portion of the Moon strongly suggests that the material of which the Moon is made was already differentiated – it had already lost a metallic fraction and hence its inventory of siderophile elements.

any model of lunar formation must also take into account the following:

- Angular momentum is a property of rotating systems that depends upon mass and its distribution, angular velocity, and radius. The angular momentum of the Earth–Moon system is contained in the Earth’s rotation and the Moon’s orbital motion, and is unusually high compared with the other terrestrial planets

- The Earth and the Moon have indistinguishable oxygen isotope compositions, whereas most planetary bodies have different and distinct oxygen isotope compositions.

The formation of the Moon

The origin of the Moon has been debated for over a century, but particularly since the Apollo mission provided samples to study. Several theories of formation have been suggested.

Co-accretion

This theory proposes that the Earth and the Moon simply accreted side by side. The difficulty with this model is that it does not explain the angular momentum of the Earth–Moon system. This model explains neither the difference in density nor the difference in the depletion of volatile elements.

Capture
This theory proposes that the Moon was originally in a heliocentric orbit and was captured following a close approach to the Earth.

However, it is difficult to do this without the Moon spiralling into the Earth and colliding. It is also difficult to explain the indistinguishable oxygen isotope compositions of the Earth and Moon with this model.

Fission

-Moon split off as a blob during the rapid rotation of a molten Earth. George Howard Darwin (1845–1912), the son of Charles Darwin proposed that at one time (before the young age of the ocean floor was known) it was thought by some that the Pacific Ocean might have been the residual space vacated by the loss of material.

This model does have some attractive features: it explains why the Earth and Moon have identical oxygen isotope compositions. It also explains, for example, why the Moon has a lower density, because the outer part of the Earth would be deficient in iron due to core formation, and it explains why so much of the angular momentum of the Earth–Moon system is in the Moon’s motion. However, it is not clear why the Moon should spontaneously split away from the Earth without some large input of energy.

Impact models

Following the Apollo missions it was proposed that the Moon formed as a result of a major impact on the Earth that propelled sufficient debris into orbit to produce the Moon. Such models are now the most widely accepted

Information that came from sample-return was that more than 80% of the lunar crust was composed of anorthosite, indicating the presence of a magma ocean early in lunar history.

The presence of a magma ocean requires significant degrees of melting, which occurred in response to an impact – provided the accreting body was large and that subsequent lunar accretion was rapid (1–100 Ma).

Also, it is necessary to link the dynamics of the Moon with that of the Earth’s spin.

This led to the proposal of a series of single giant impact models in which the Moon was the product of a glancing blow collision with another differentiated planet.

A ring of debris would have been produced from the outer silicate portions of the Earth and the impactor (named Theia, the mother of Selene, the goddess of the Moon), which was roughly the size of Mars.

This model explains the angular momentum, the extensive early melting, the isotopic similarities and the density difference.

The most recent model simulations indicate that the giant impact that formed the Moon probably occurred at the very end of Earth's accretion, when the Earth was 90% of its present size.

Certain features of the Moon may be a consequence of prior differentiation of Earth and Theia, and of the giant impact itself. For example, the depleted volatile elements require that both Earth and Theia had already become at least partially differentiated due to earlier heating.

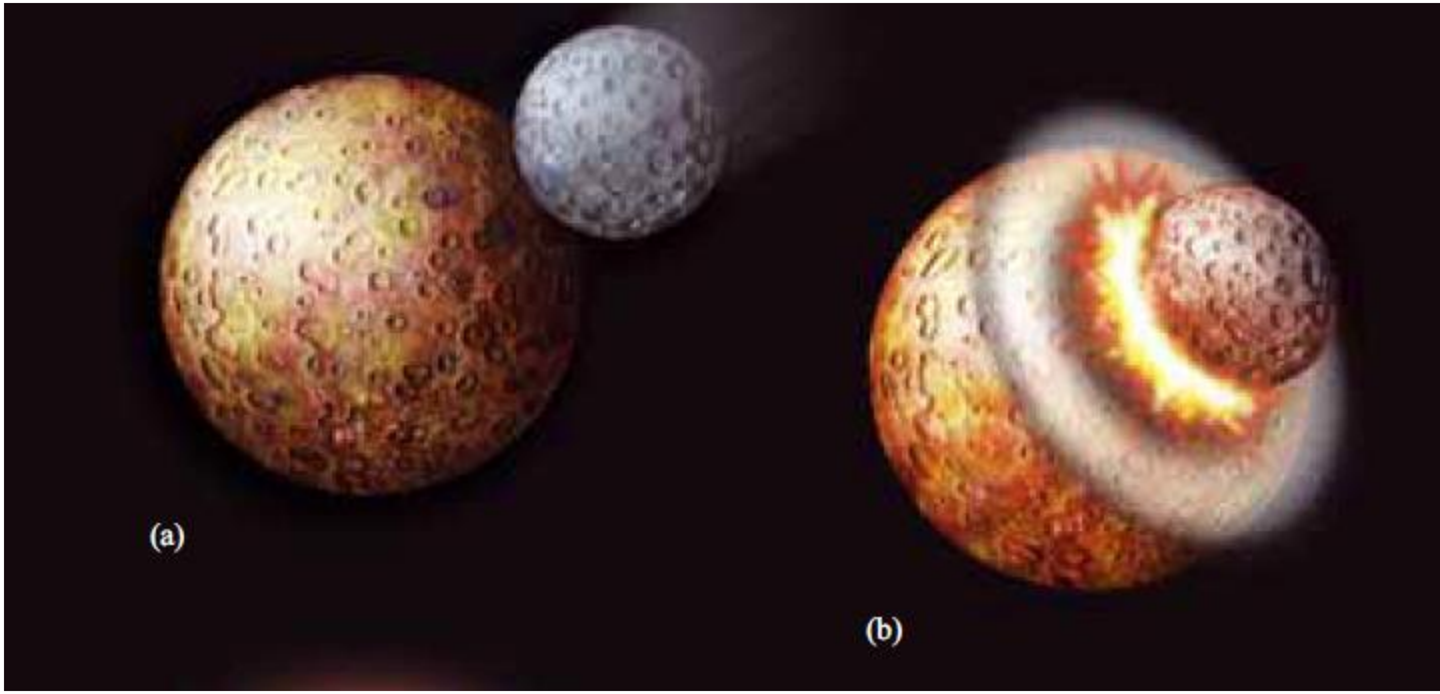
In addition, the low abundances of siderophile elements can be attributed to prior core separation in both the Earth and Theia.

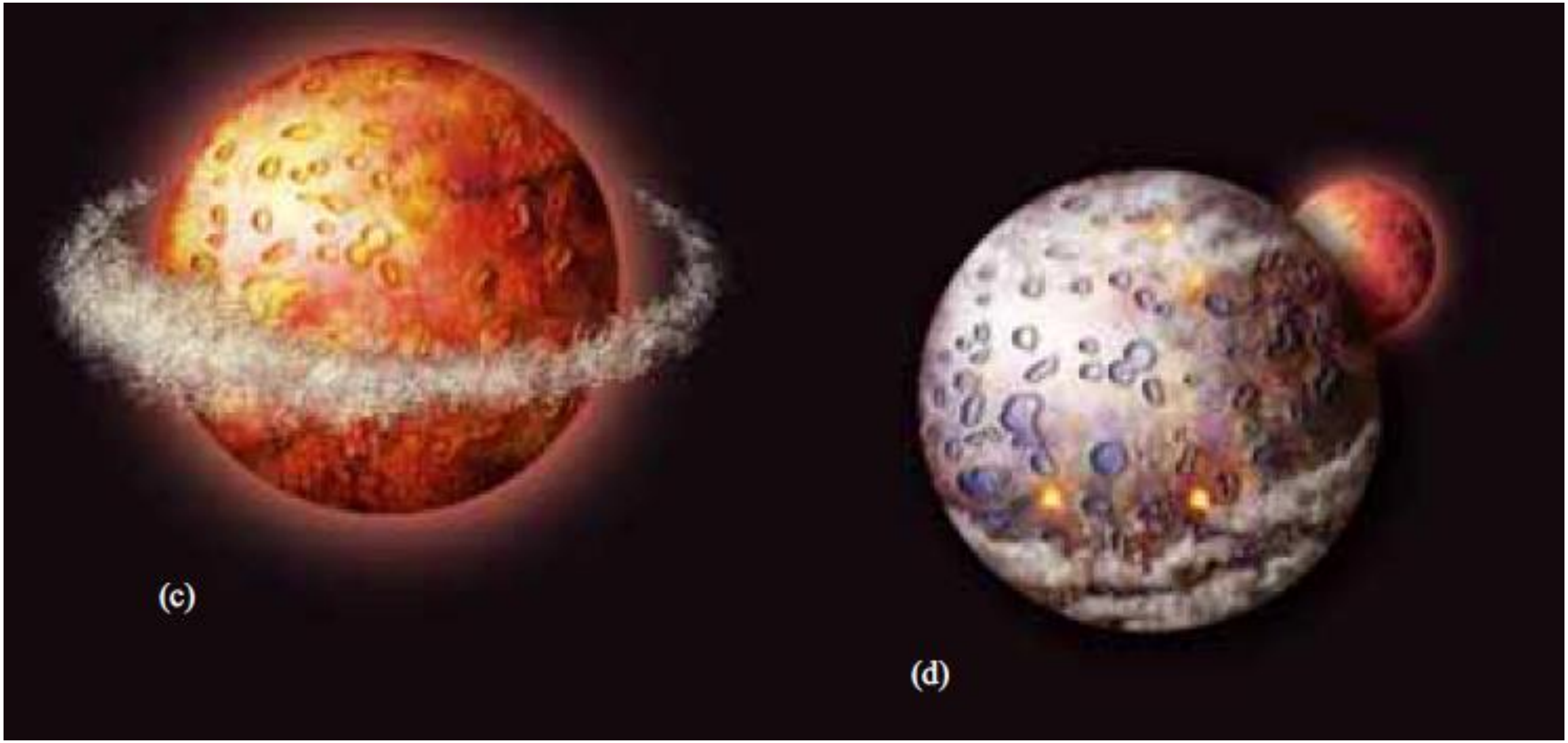
The Moon formed from mantle material derived from the colliding, partially differentiated planetary embryos. This mantle material was already depleted in Ni, Fe, and S due to the development of cores within the embryos.

Therefore, there would have been relatively little Ni, Fe and S left to differentiate inwards once the Moon had formed.

the collision and aftermath between the proto-Earth and Theia. Both bodies were large enough to have differentiated into core, mantle and primary crust as a result of accretionary heating

Following collision (a and b), the cores of the two bodies are thought to have combined and the mantles became mixed while Some material was fragmented and vaporised and scattered into orbit around the Earth.

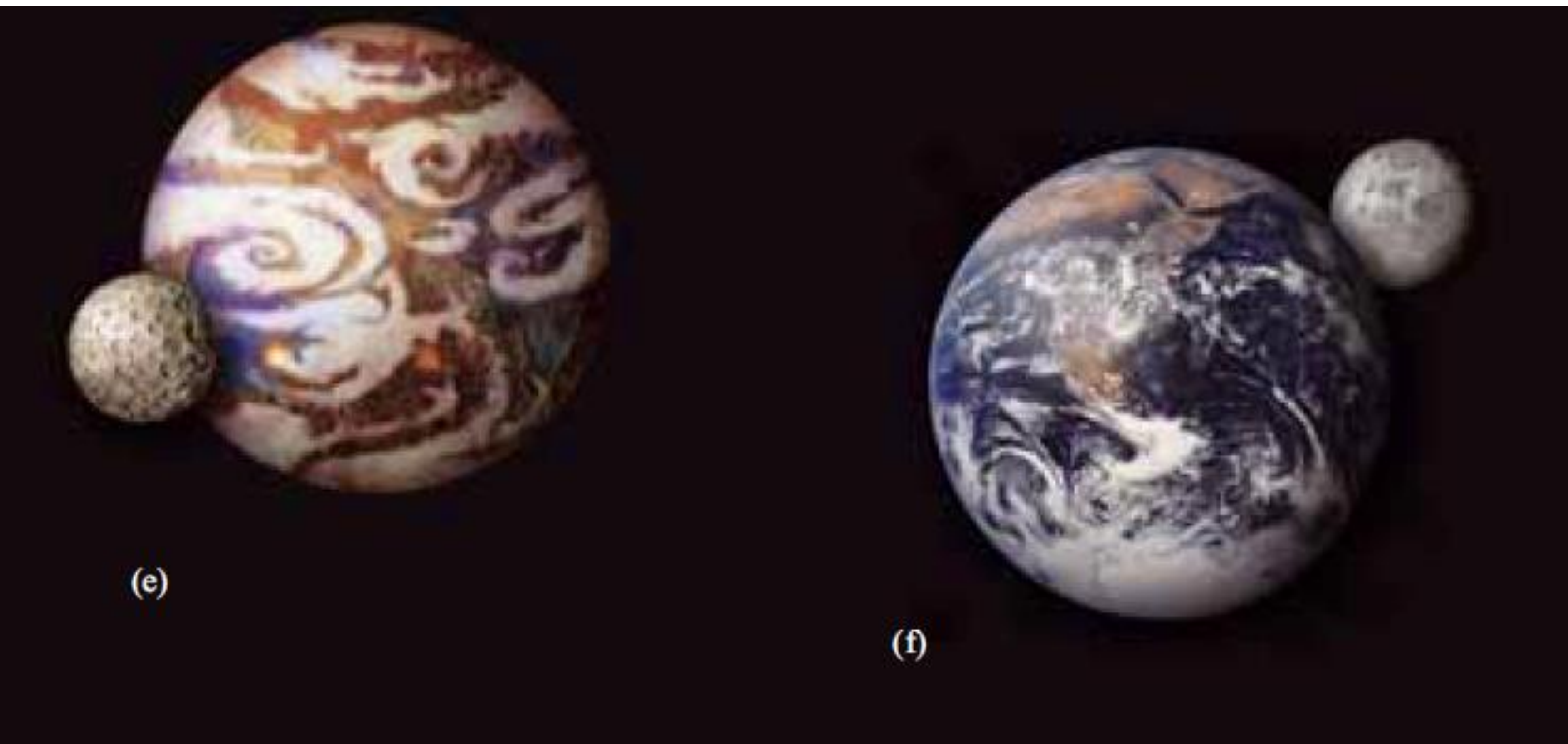




Some of the debris fell back to Earth while the remainder accreted under its own gravity to form the Moon.

The heat of accretion would again have resulted in wholesale lunar melting. The Moon then cooled and differentiated into mantle, primary crust and possibly a small core, depending on how much of the core of Theia was dispersed around the Earth and how much merged with the Earth’s core.

The Moon and, presumably, the Earth were subject to further meteorite bombardment and the formation of large craters. Some of these impacts were intense enough to initiate melting of the lunar mantle, flooding the larger impact structures with basalt and forming the lunar maria.



Over time the Moon’s orbit has slowly decayed, its rate of rotation becoming synchronised with its orbit as the distance between the two bodies progressively increases.

For the Moon's crust and mantle, this depletion was probably further augmented by further differentiation immediately after its formation. Moreover, the Moon's depletion in volatile elements, relative to the Earth, can be explained if the Moon accreted from the partially vaporised debris coalescing after the impact.

In these circumstances, the more volatile elements would have had the opportunity to escape into space prior to accretion.