a17 The rock cycle < rocks are not everlasting >

> Then the angel flung up his glorious hands to the heaven of heavens, saying:
> "End is there none [you ask] to the universe of God? Lo! also there is no beginning."[1]
> —Joly quotes from the paraphrase of "Richter's Dream" in De Quincy's *System of the Heavens*.[2]

James Hutton (1726-1797), educated in Edinburgh and Paris, M.D. Leyden,1749, farmer 1754-68, elected Fellow of the Royal Society of Edinburgh, 17th November 1783, published *Theory of the Earth*, 1788, realized that rocks do not last forever and that, given time enough, one type may be derived from another. This is the idea of the rock cycle (***Figure a17.1***). In his own words:

> The most solid rocks moulder and decay [weather] upon the surface of the earth, and thus procure a soil, ... From the tops of the mountains to the shores of the sea, all the soils are subject to be moved [eroded] from their places, and to be deposited in a lower situation [as sediments]; ... [3]

This was not the end of his understanding of the process of change: "From the constitution of those materials which comprise the present land, we have reason to conclude that, during the time this land was forming, by the collection of its materials at the bottom of the sea, there had been a former land containing minerals similar to those we find at present in examining the earth ..."

At Earth's surface, solar energy and gravity drives the rock cycle.

Although the source of internal heat and the true nature of metamorphic rocks was not known to Hutton, he reasoned that some source of internal heating—evidenced by volcanic activity and rocks he judged to be igneous that make room for themselves intrusively—drives the rock cycle in Earth's interior and causes the land to be raised from the sea. We can continue for him:

Internal processes change sediments by lithification to *sedimentary rock*. Burial of sedimentary rock results in increase of pressure and temperature. This can cause the appearance of the existing rock to change by recrystallization (without melting) to *metamorphic rock*. Additional heating by primordial and radioactive heat sources can ultimately melt the rock and so form a magma. Positively buoyant magma rises to intrude and may extrude as lava. Volcanism can also be driven by the expansion of gases released from solution as the magma rises and decompresses, and also when it cools and crystallizes in the magma chamber of volcanoes. Intrusive magma or extrusive lava solidifies as *igneous rock*. Volcanism builds volcanic mountains and erupts tephra. Plutonic magmatic processes can cause country rocks to be baked, mineralized, deformed, and raised.

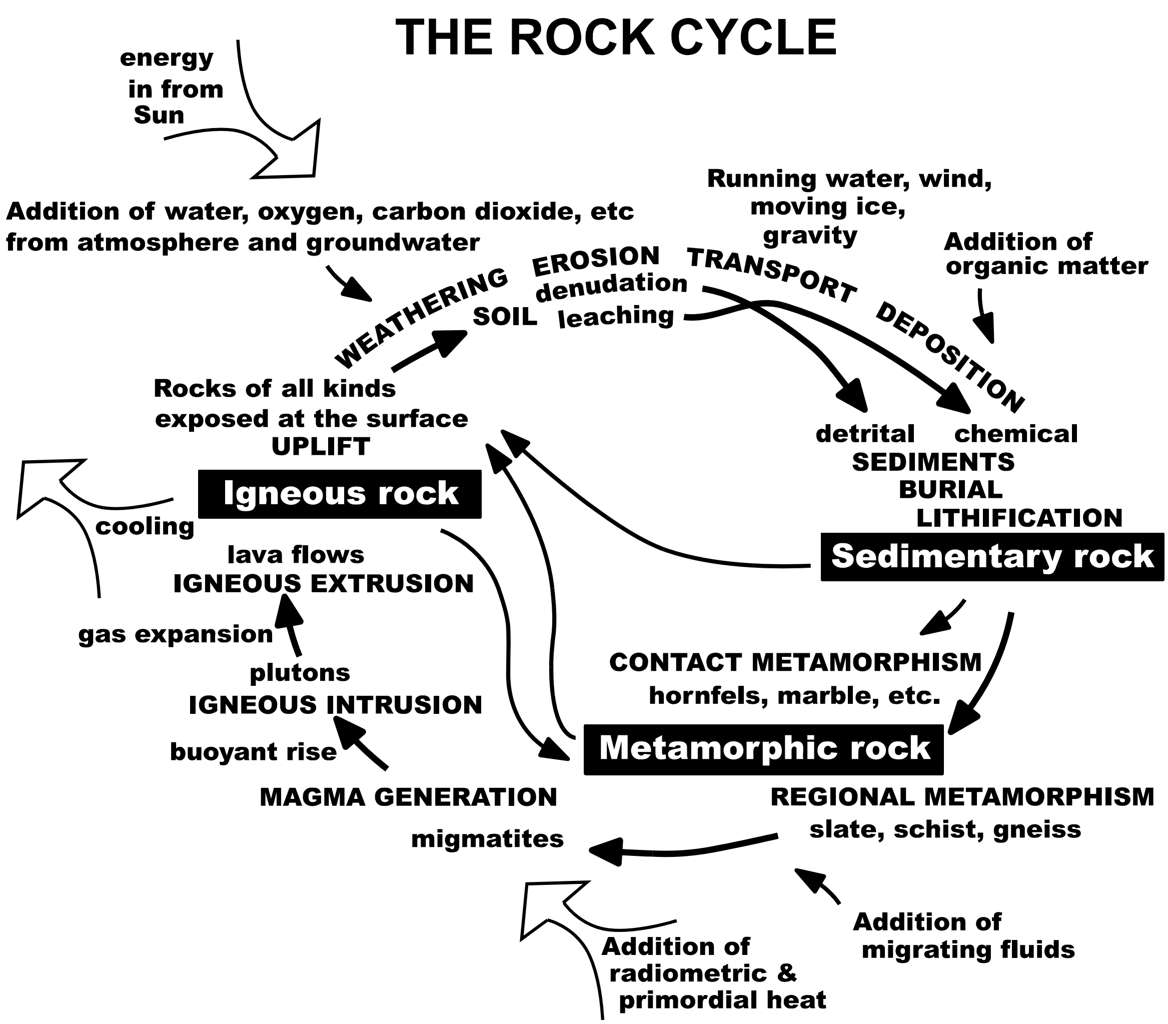
Hutton (whose doctoral thesis in 1749 was *Inaugural physico-medical dissertation on the blood and the circulation of the microcosm*) in 1788 wrote of the macrocosm: "We are thus led to see a circulation in the matter of the globe, and a system of beautiful economy in the works of nature. This earth, like the body of an animal, is wasted at the same time that it is repaired. It has a state of growth and augmentation; it has another state which is that of diminution and decay. This world is thus destroyed in one part, but it is renewed in another." Nature thereby provides "perpetually ... for the growth and prosperity of plants, and for the life and comfort of the various animals." In this, he is able, to his satisfaction, "to trace the efficient, as well as to perceive the final cause" (1792).[5] ❑

Figure a17.1 **The rock cycle** [6] At Earth's surface, solar energy drives the rock cycle. In Earth's interior, primordial and radiometric heat drives the rock cycle.

The word *rock* refers to solid Earth materials. The word *stone* refers to a granular, massive, or glassy, breakable rock. Three *rock types* with distinctly different origins are: *igneous* (examples: basalt and gabbro, rhyolite and granite), *sedimentary* (examples: sand and sandstone, clay and shale, lime mud and limestone), and *metamorphic* (examples: slate, schist, and gneiss; quartzite, marble). Hybrids of these types occur: tephra, welded tuff, metasediments, and migmatite. Other Earth materials (not rocks) are: sediment in suspension as dust in air or mud in water, sediment undergoing transport as in dune sand or stream-bed gravels, colluvium (unconsolidated particulate material on a slope), soil, water, salt in solution, and air.

The origin of rocks is inferred from their texture, composition, and field associations. The rock cycle is a concept that helps to organize our understanding of rocks in ways that suggest how Earth materials can cycle though each rock type *if* Earth is exceedingly older than historical or human time. This enquiry, ongoing since 1788 when James Hutton conceived of the rock cycle, has established that its every part requires—for the circulations of Earth materials though each—the passage of geological lengths of time.

Corroboration, for Earth's great age, is the discovery (beginning 1905, Boltwood)[7] of radioactive elements that act as clocks and give absolute geological ages of Earth materials. Earth's apparent age, so calculated, is 4.5 billion years old. This is plausible as astronomers (beginning 1924, Hubble)[8] have since found that Earth is in a universe that is at least three times older.



A cycle is itself without beginning or ending, so a description of the changes that recur in it can begin with any of them, and we can choose to begin a description of the rock cycle with rock exposed at Earth's surface.

At Earth's surface, rock weathers to soil (*not* to sediments) when exposed to the gases of the atmosphere and surface waters. It weathers mechanically by physical breakup and chemically by chemical reactions, such as hydrolysis, to soil (the physical components of which are fragments of the original rock and its minerals, and new products, which are clay and salts).

Soil denudation (wearing away of bed rock by mass wasting, running water, wind, and glacial ice) and leaching (by soaked in rain water that joins the water table and leaves via springs) are collectively called *erosion*. Products of erosion are sorted and separated during transportation and the transported clasts and salts are deposited in different places as detrital and chemical sediments respectively.

An accumulation off sediments can, in time, lithify (means “become stone”) to sedimentary rock (The word harden is not used as it can apply to igneous rocks that are glasses).

Lithification processes, collectively referred to as “diagenesis,” include: compaction (example: clay to shale), cementation (example: sand to sandstone), and partial recrystallization (example: lime mud to limestone).[9]

Note: Pressure by itself does not lithify sand to sandstone: its diagenesis is mostly by cementation and also, sometimes, by partial recrystallization and crystal overgrowths.

Burial of sedimentary rock subjects it to an increase of pressure by the overburden and to increase of temperature by the blanketing effect of the overburden that allows sediments to heat by conduction towards equilibrium at their depth with the temperature gradient of the whole Earth.

The minerals of a rock are stable only within certain ranges of temperature and depth-related confining and, imposed from without, directed pressure, and chemical environment (their contact with other minerals and mineralizing fluids in the rock). Change of any of these beyond the limit of stability for a rock’s minerals causes recrystallization. Recrystallization *without melting* of a preexisting rock is metamorphism, specifically: *contact metamorphism* caused by a change of temperature (examples: shale to hornfels, sandstone to quartzite, limestone to marble), *dynamic metamorphism* caused by shear (deforming) pressure (example: rock to mylonite), and *regional metamorphism* caused by a change of temperature and directed pressure (example: shale to slate, schist, gneiss, and granulite).

A rock can heat to the point of melting. The heat can be from radioactive sources in the rock, by advection into the rock from igneous sources, or by conduction into the rock when it has been carried down by subduction to depths of as much as 60 km.

Note: Increase of pressure cannot cause a rock to melt. Quite the reverse! Increase of pressure can cause a melt to solidify (An example of a solid due to pressure is methane hydrate at water depths greater than 300 meters in continental-rise sediments). *Decrease* of pressure can reduce the melting temperature of a rock so that at a given temperature in Earth’s interior, a decrease of pressure can cause melting. (Decompression melting explains the origin of basaltic magmas that result from partial melting of asthenosphere peridotite in its rise beneath oceanic ridges.)

Recrystallization of *crustal* rock requires the presence of a fluid (such as H_2O, or CO_2) in the rock to allow for the reorganization of its crystalline materials. When components of this mediating fluid, or salts brought in by it, or both become part of the crystals of the recrystallizing rock, the process is called *metasomatism*. To indicate that a bulk composition is different from that of the original, the resulting metamorphic rock is referred to as a metasomatic rock.

Partial melting of a foliated metamorphic rock produces a magma that, if still this mixture, solidifies as an igneous rock called a *migmatite*.

Magma where it forms is usually less dense that the country rock and, when it more than merely wets the material it is between, gravity causes it to rise buoyantly. Rising magma intrudes and makes room for itself at a level where it achieves neutral buoyancy (a condition sought by scuba divers in water). At this higher level in Earth’s interior, it will cool and begin to crystallize. Exsolved volatiles of “first boilings” due to lowering pressure on magma as it rises and later vents, and “second boilings” due to crystallization (of first formed anhydrous crystals), exert gas pressure that can result in volcanic activity.

Extrusions of lava cool (basaltic ones from white hot 1200°C, through yellow 1100°C, orange 900°C, bright red 700°C, dull red 500°C, to black)[10] and degas to solidify as volcanic rock. Volcanic gas explosions produce tephra (pyroclastics of all sorts) that are thrown or are carried by the wind to where they accumulate as pyroclastic fall deposits, or travel as nuée ardente (each a gassy cloud or mass of glowing ash and pumice)[11] to where they accumulate as pyroclastic flow or surge deposits.

Note: Intrusions of magma and extrusions of lava solidify (crystallize or, if glassy, harden) to igneous rock (they do not only cool to, as they may degas to, nor do they necessarily crystallize to). Avoid using the phrase “crystallizes to igneous rock” as this is not so for vast volumes of natural glasses such as obsidian, pumice, scoria, and tuff (these amorphous solids *are not* crystalline).