GEOCHEMISTRY AND COSMOCHEMISTRY

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Summary

The habitability of the Earth, that is, its ability to sustain life, over 4.5 billion years is a result of the cycling of volatiles such as water and carbon dioxide from the atmosphere to the crust and back. This is but one of many chemical cycles in the coupled crust and atmosphere, most of which are mediated in some way by life. Prior to the origin of life, the Earth evolved in much the same way as the other rocky planets, having been assembled from lunar-to-Mars-sized objects that grew from smaller solids in short periods of time (less than 10 million years). Dates for the origin of the Earth and major geological and cosmochemical events are obtained from the measurement of abundances of radioactive isotopes and their decay products. An exceptional event in the origin of the Earth, relative to the other terrestrial planets, is the formation of the Moon by giant impact, for which ample geochemical evidence exists. Impacts like the Moon-forming collision may have brought water to the Earth despite the dehydrating effects of such an impact. Future studies in geochemistry and cosmochemistry will rely on increasingly sensitive trace element and isotopic analysis of rock samples, sediments and ice cores for climate studies, and samples of meteorites and spacecraft-collected extraterrestrial material.

1. Introduction to Geochemistry and Cosmochemistry

Geochemistry is the study of the composition of the various distinct chemical phases of the Earth, including solid, liquid and gaseous portions. It also encompasses the physical and chemical processes that have shaped the distribution of elements, of isotopes, of mineral compounds, and of volatiles on and within the Earth. Often the term biogeochemical is used to emphasize that in the atmosphere, ocean and uppermost portion of the crust, biological processes have played a role in the Earth chemical evolution through at least the last half of our planet's history. Cosmochemistry deals, formally, with the chemical composition and evolution of the cosmos, but is nearly always restricted to physical-chemical processes associated with the formation of the solar system and its planets.

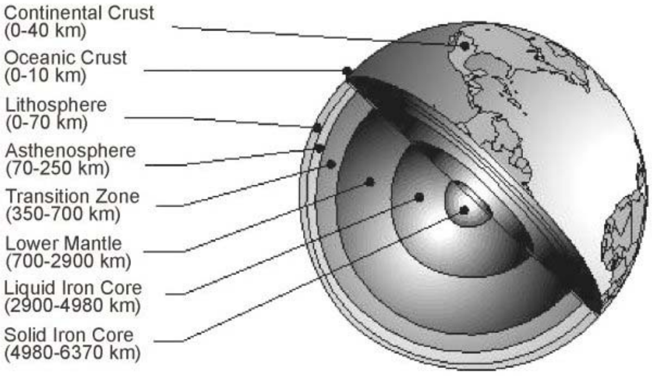

Figure 1. Cutaway of the Earth with chemical and physical layers labeled.

The overall structure of the Earth must be understood in order to gain a context for results in both fields. This structure is derived from detailed analysis of the timing of propagation of earthquake waves around the globe, and the evolution of wave phases and amplitudes during their travels (see *Seismology and Volcanology*). From a chemical point of view, the Earth may be divided into a crust, mantle, and core (Figure 1). The core is a mixture of iron and one or more of sulfur, oxygen, hydrogen, or other materials, and its high electrical conductivity along with rotational and convective motion leads to a magnetic field. The mantle may be divided into two chemically distinct layers, or be well mixed, and is–minus the iron in the core—the portion of the Earth that most closely resembles the chondritic meteorites, which are thought to be part of the original rocky material from which the planets formed. The crust of the Earth is a product of the repeated melting and separation of elements into an outer rind upon which biogeochemistry is played out. It contains a disproportionate abundance of the long-lived radiogenic elements that provide approximately half the heat flow driving surface geology, the other half being deep-seated heat left over from the original assembly of the Earth. From a physical point of view, the Earth is divisible into a liquid outer and solid inner core (see *Mantle and Core of the Earth*), the phase transition being a result of eutectic or peritectic thermodynamic behavior in the impure iron composition. Much of the mantle, except for the very uppermost portion, forms the asthenosphere, a solid layer that moves plastically over long timescales. The crust and upper mantle, by contrast, are rigid and form the lithosphere. Two distinct lithospheric structures are continental crust (see *Continental Crust*) and oceanic crust (see *Oceanic Crust*). Although these strictly are differentiated chemically, they have very different dynamical behaviors because of their opposite density contrasts relative to the asthenosphere. The continental crust is less dense and rides atop the asthenosphere, while the oceanic crust is nearly neutrally buoyant and hence sinks when it cools sufficiently to become denser than the asthenosphere. This is the genesis of plate tectonics discussed below.

2. Geological Processes on the Earth

The Earth's interior is much hotter than its surface because of thermal energy from the original assembly of the Earth, which involved conversion of gravitational potential energy of solid material dispersed through space to disordered kinetic energy (thermal energy, or somewhat inaccurately, heat) in the gravitationally bound sphere of our planet, and because of decay of long-lived radioactive isotopes. Geochemical processes are powered by this heat through the horizontal and vertical movements of portions of the crust, consequent melting and solidification, and phase transitions in rocky material and volatiles like water and carbon dioxide. In addition, many biological processes associated with chemical transformations of nitrogen and carbon phases are powered by sunlight that is captured by pigments in plants and some unicellular organisms, a process called photosynthesis.

Generation of molten silicates can occur in the mantle or in the crust of the Earth, and as this material rises, it is subject to various phase separations that lead to composition changes. Successive meltings and solidifications in the presence of varying amounts of water, and in contact with different crustal rocks and mantle material, lead to dramatic variations in elemental abundances among rocks, as indicated in the schematic compositions of Table 1. Chondrites, to be discussed later, are one type of primitive material well represented in the meteorite collection; as can be seen from the table their principal difference from the mantle is that the latter is dramatically depleted in iron. The differences between crustal and mantle rock are more complex to characterize, and result from repeated cycling of rock through various phases. Crustal rocks range from the low-density granitic rock of the continents to ocean floor basalts, with andesites being an important intermediate composition exuded from volcanoes along the margins of continents. The crustal numbers are average and do not capture the dramatic differences in crustal rock composition from, especially, one continental location to another.

Element	Chondrites	Earth's mantle	Basalt (crustal rock)	Granite (crustal rock)
O	32.	43.	44.	47.
Fe	29.	7.	10.	3.
Si	16.	21.	24.	32.
Mg	12.	23.	3.	0.7
Al	1.	2.	8.	8.
Ca	1.	2.	7.	2.
Na	1.	0.5	2.	3.
K	0.1	0.02	0.1	2.
Other	8.	1.	2.	2.

Table 1.Typical elemental composition (in percent of total) of meteorites and Earth rocks.

Magma generation in the mantle or lower crust, a manifestation of the removal of internal heat, may lead to the intrusion into existing continental rock of new, igneous material, which then solidifies and may remain beneath the surface or be exposed eventually by erosion (removal) of overlying layers. Or, the magma may be exuded to the surface through volcanism. At under the ocean floor, the volcanism is primarily through mid-ocean ridges extended for many thousands of kilometers, where the magma is basaltic in composition, while at continental margins it includes partly recycled continental material and is andesitic in composition. Hot spot volcanism, which can build mid-ocean island chains such as Hawaii, brings up very deep mantle material. Gases that, relative to the Earth's atmosphere, are chemically reduced, accompany especially mid-ocean ridge volcanism, and the compositional contrast between the hot reduced vent water and the surrounding aerobic ocean water provides a source of chemical free energy for life. This may have been one of the early sources of life before photosynthesis (see *Geochemical Origins of the Earth* or *Cosmochemistry*), and a diagram of the materials and dynamics of such regions (Figure 2) illustrates well the complex nature of geochemistry in local environments.

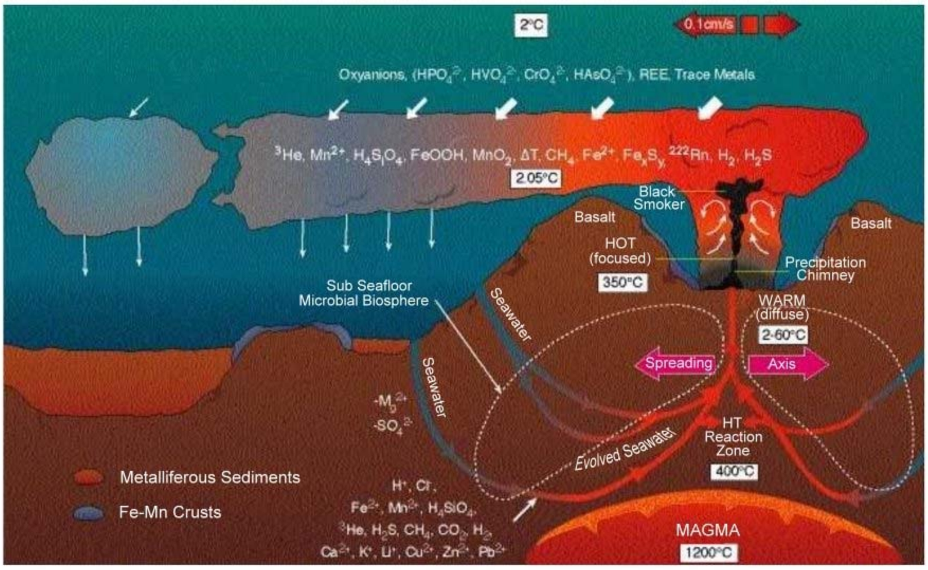

Figure 2. A cartoon of the chemical ions, atoms, and molecules circulating within mid-ocean ridge vents, as well as schematic indications of temperature and circulation patterns. Velocity is that of the horizontal motion of the hot plume. Courtesy of Georgy Cody, CIW.

On continents, igneous intrusions may be raised with other rock types into mountain ranges, by compressive forces, or volcanism on continents may also build mountains. These are eroded through the action of water and to a lesser extent wind. The erosion products travel downward, along the gravity gradient, through streams, rivers, glaciers, groundwater, and ultimately reach close basin lakes or the ocean (see *Tectonics and Surface Process Interactions*). Sediments may be deposited along the way in any number of different environments ranging from lake bottoms, to hanging glacial valleys, to beaches (see *Sedimentary Geochemistry*). Over time, compression and lithification converts these into layers of sedimentary rocks. Much sedimentary material is deposited in the oceans, to be recycled through volcanism by plate tectonics. Sedimentary layers on continents or their margins may be buried, heated and subjected to modest pressures, leading to so-called metamorphic rock. This again may be uplifted and then exposed in new mountain ranges or plateaus, along with igneous rocks and sedimentary layers, to be eventually eroded by water to sediments once more. Divergence of continents along new plate margins (see below) may instead drop large amounts of sediments into deep basins. Within all of this activity, chemistry on small to large scales is ongoing, much of it with the mediation of life; as well the melting of rock within continents may produce and separate ores of valuable metals eventually accessible for extraction. The details of many of these processes are provided in the accompanying articles, but one should not forget as well the inspiring beauty created as well by geologic processes (Figure 3).

Figure 3. Among the grandest of vistas created by Earth’s geology: the Grand Canyon of the Colorado River, in Arizona, USA.

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Biographical Sketch

Jonathan I. Lunine, is Professor of Planetary Sciences and of Physics, and chairs the Theoretical Astrophysics Program at the University of Arizona. He is a Distinguished Visiting Scientist at JPL. His research interests include the formation and evolution of planets, and organic chemistry leading to the origin of life. He is an interdisciplinary scientist on the Cassini mission to Saturn, and on the Next Generation Space Telescope. Dr. Lunine is the author of the book *Earth: Evolution of a Habitable World* (Cambridge University Press, 1999). He is a fellow of the American Geophysical Union, which awarded him the James B. Macelwane medal, and winner of the Harold C. Urey Prize (American Astronomical Society) and Ya. B. Zeldovich Award of COSPAR's Commission B. Dr. Lunine earned a B.S. in Physics and Astronomy from the University of Rochester in 1980, followed by M.S. (1983) and Ph.D. (1985) degrees in Planetary Science from the California Institute of Technology.