THE COMPOSITION OF EARTH: ROCKS AND MINERALS

Ruth Siddall
University College London, UK

Keywords: petrology, petrography, mineralogy, rock classification, crust

Contents

1. Introduction
2. Minerals
2.1. Mineral Chemistry and Classification
2.1.1. Native Elements as Minerals
2.1.2. Silicates
2.1.3. Oxides
2.1.4. Sulfides and Sulfates
2.1.5. Phosphates
2.1.6. Carbonates
2.1.7. Halides
2.2. Crystallographic, Optical, and Physical Properties of Minerals
3. Rocks
3.1. Rocks in Earth's Crust
3.1.1. Continental Crust
3.1.2. Oceanic Crust
3.1.3. Igneous Rocks
3.1.4. Sedimentary Rocks
3.1.5. Metamorphic Rocks
3.2. Rocks in Earth's Mantle
3.3. Rocks in Earth's Core and the Evidence from Iron Meteorites
Glossary
Bibliography
Biographical Sketch

Summary

Earth's crust is compositionally the most varied part of the planet. It is dominated by silicate minerals, among which eight elements are pre-eminent (oxygen, silicon, aluminum, magnesium, iron, calcium, sodium, and potassium). With the advent of life, atmospheric carbon has also become locked into the crust as carbonate fossil remains. Produced by the crystallization of molten rock rising from Earth's interior, igneous rocks are the primary crustal material. After formation, these may be transformed by heating and pressure into metamorphic rocks. Once exposed at the surface, both igneous and metamorphic materials may be degraded by wind, ice, and water, yielding fragments (from boulders to particles), which accumulate to form sedimentary rocks. Through the action of plate tectonics, all the rock types can be dragged back beneath the crust, where they melt to feed new igneous rocks, and the cycle is repeated. In total, rock-forming processes have created at least 4000 mineral species, from common quartz to rare gems. By understanding how each species is produced and is related to other

minerals, it is possible not only to investigate the evolution of Earth, but also to improve methods of detecting and utilizing deposits of economic importance.

1. Introduction

Earth is not homogeneous in composition, but is concentrically layered, or differentiated, into compositionally distinct regions (Figure 1; see *The Earth as a Planet*). The crust we live on has the most varied composition, and is the region that will largely be under discussion in this chapter. However, it constitutes the smallest component; the crust represents around 0.5 percent of the total volume of the Earth. Below the crust lies the mantle (c. 83 percent of Earth's volume), which is essentially solid, containing only a few percent of melt in its upper regions. At the Earth's center lies the core, subdivided into a liquid outer core (16 percent of Earth's volume) and a solid inner core (0.5 percent). From the velocity and pathways of seismic waves, plus considerations of densities and elemental abundances, it is apparent that the core is composed of iron plus some nickel. The liquid outer core is also dominated by iron with perhaps sulfur and oxygen present. The mantle is composed of iron-magnesium silicates. Each of these individual solid components is a mineral and they may be combined to form rocks.

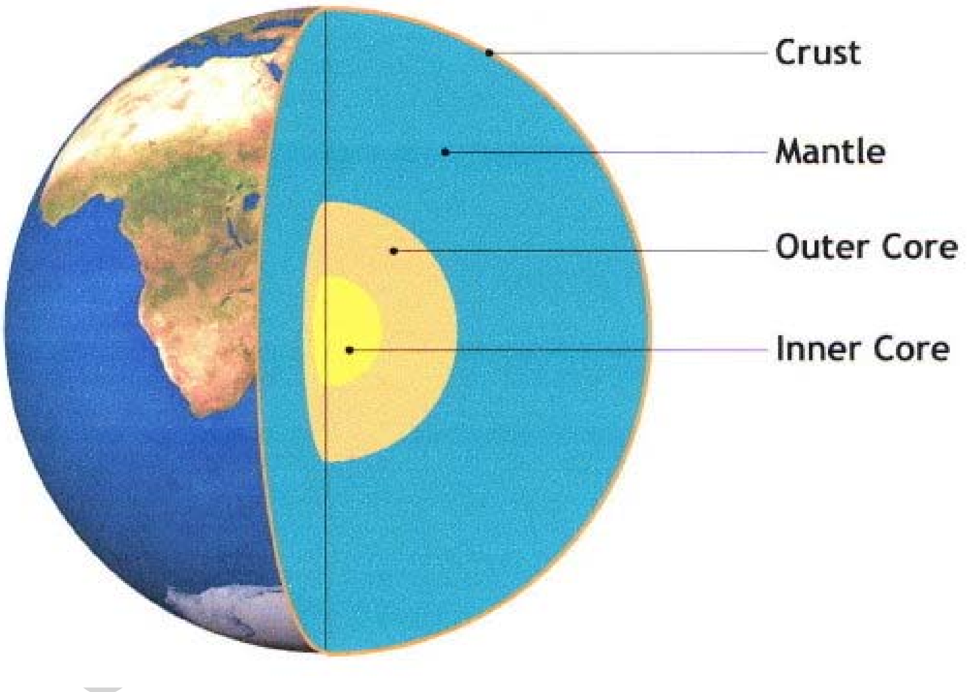

Figure 1. The concentric layers of the Earth

The study of minerals and their behavior is called "mineralogy." "Petrology" is the study of rocks in terms of their mineralogy, composition, textures, formation, and associations, whereas "petrography" is the science of describing rocks. There are some 4000 species of minerals, and new ones are continually being discovered. However, the majority of rocks are composed dominantly of only a few (say, three or four) main minerals and a similar number of accessory minerals (those present in amounts less than 5 percent). Many species of minerals can be assigned to a family, whereby certain characteristics, such as a dominant chemical component or the symmetry of the crystal structure are shared. Because of twists of nature other minerals occur in only certain restricted types of petrogenetic setting; these are consequently very rare and infrequently encountered. This is true for many gem minerals. Some minerals are known to occur only in a single or very few geographical locations; these too are obviously of great rarity.

Conveniently for the petrographer, there are a limited number of major rock-forming minerals that occur in the majority of igneous, sedimentary, and metamorphic rocks. Of these the most ubiquitous by far are the feldspars, which occur in most varieties of rock. Also common are quartz, pyroxene, olivine, mica, amphibole, calcite, dolomite, and clay. Less common, but nevertheless important, are a group of minerals known as the feldspathoids and the minerals that commonly occur in accessory amounts: apatite, zircon, sphene (titanite), and rutile. Other relatively abundant and particularly distinctive minerals belong to the families of garnet, spinel, and tourmaline. Minerals generally restricted to metamorphic rocks (and the sediments derived from them) include epidote, staurolite, talc, chloritoid, stilpnomelane, and the aluminum silicate varieties, kyanite, andalusite, and sillimanite.

Many minerals are subject to alteration, especially due to weathering or percolating fluids. Commonly these break down to fine-grained clay minerals. Rocks rich in olivine and pyroxene are susceptible to alteration to the serpentine group of clay minerals. Chlorite is also common as a secondary mineral. Should petrographers be able to identify to a reasonable level the minerals listed above, then they are well on their way to describing the bulk of the rocks encountered on Earth.

The most complex mineralogical settings are those associated with zones of liberalization as the result of the flow of fluids of a wide variety of chemical composition, concentrating elements that are otherwise not common in many rocks. These include metallic and ore minerals (which are also common accessories in many rocks) plus many of the weird and wonderful "one-offs."

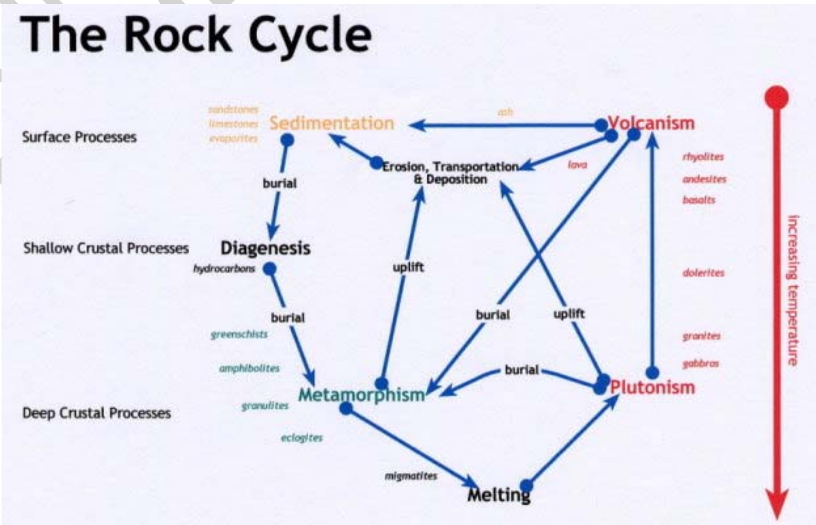

Figure 2. The rock cycle (rocks named are discussed in the text)

A rock is a solid aggregate of mineral grains. There are three main classes of rock: igneous, sedimentary, and metamorphic. Igneous rocks form from the crystallization of a melt or magma. Lavas are magmas erupted through volcanoes and thus accumulate on the surface. Magmas that do not reach the surface are intrusive, and solidify to form plutons or sheet-like sills and dykes. Sedimentary rocks are produced by the weathering, erosion, transportation, and deposition of pre-existing rocks, and metamorphism is the transformation of pre-existing rocks by heat, pressure, or deformation. Igneous rocks may be eroded to form sediments and these sediments may be transformed by heat and pressure to produce metamorphic rocks. In turn, igneous rocks may become metamorphosed and metamorphic rocks may become eroded. These interrelationships are known as "the rock cycle" (Figure 2). The various fabrics or textures exhibited by individual rocks are often characteristic of their modes of formation and therefore they can be categorized into these three main subdivisions. In nature, however, the boundaries between these rocks may well be gradational, and there are a few rock types that do not fit perfectly into a single category.

2. Minerals

A mineral may be defined as an inorganic solid with a predictable and ordered atomic structure and a definite chemical composition (which should not imply that the composition is fixed). Many minerals have compositions that vary within certain bounds. For example olivine may vary in composition from the species fayalite, which is iron silicate (Fe_2SiO_4), to forsterite (magnesium silicate, Mg_2SiO_4), and have any proportion of Fe and Mg in between. The pure forms are known as "end-members."

Additionally, there are always minor substitutions of trace elements for major elements within the crystal structure. For example manganese and calcium may replace a small proportion of the iron or magnesium ions in olivines. While these do not affect the overall characteristics of the mineral, they may be responsible for variations in some properties, particularly color. For example, the Hope diamond is blue because of trace substitutions of boron for carbon ions.

All minerals fit into one of seven crystal systems, based on the internal symmetry of crystals and the relative lengths and orientation of their axes. This is reflected by the faces of crystals that have undergone unrestricted growth. This is a physical, rather than chemical, property. The commonly occurring rock-forming minerals are listed in Table 1, giving their formulae, structural group, and common lithological occurrences. Figure 3 illustrates some examples of minerals in both hand specimen and under the microscope.

2.1. Mineral Chemistry and Classification

There are numerous schemes for classifying minerals based on their chemistry, but most focus on either the major element or on the type of compound it forms. The latter method of classification is used in this summary covering common and familiar mineral species. This list is far from exhaustive. Mineral groups not covered here include unusual salts, such as nitrates and the ammonia minerals, which occur only infrequently in nature.

-
-
-

Bibliography

Cox K.G., Bell J.D., and Pankhurst, R.J. (1979). *The Interpretation of Igneous Rocks*, 464 pp. London: Allen and Unwin.

Deer W.A., Howie, R.A., and Zussman, J. (1992). *An Introduction to the Rock Forming Minerals*, 696 pp. London: Longman.

Dott R.L. (1964). Wacke, greywacke, and matrix: what approach to immature sandstone classification? *Journal of Sedimentary Petrology* **34**, 625–632.

Dunham R. J. (1962). Classification of carbonate rocks according to depositional texture. in: *Classification of Carbonate Rocks. American Association of Petroleum Geologists Memoir 1,* (ed. W.E. Ham), pp. 108–121.

Folk R.L. (1974) *Petrology of Sedimentary Rocks*, 182 pp. Hemphills, Austin, Texas.

Le Bas M.J. and Streckeisen A.L. (1991). The IUGS systematics of igneous rocks. *Journal of the Geological Society of London* **148**, 825–833.

Le Maitre R.W. *et al.* (eds.) (1989). *A Classification of Igneous Rocks and Glossary of Terms: Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks*, 208 pp. Oxford: Blackwell Scientific.

Pettijohn F.J., Potter P.E., and Siever R. (1972). *Sand and Sandstone*, 617 pp. London: Springer.

Powers M.C. (1953). A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology* **23**, 117–119.

Yardley, B.W.D. (1989). *An Introduction to Metamorphic Petrology*, 248 pp. London: Longman.

Biographical Sketch

Ruth Siddall is a lecturer in geology at University College London. Her research interests embrace petrology, petrography, and geoarchaeology, particularly in the Mediterranean.