Earth Materials

Introduction to Mineralogy and Petrology

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Solutions for review questions

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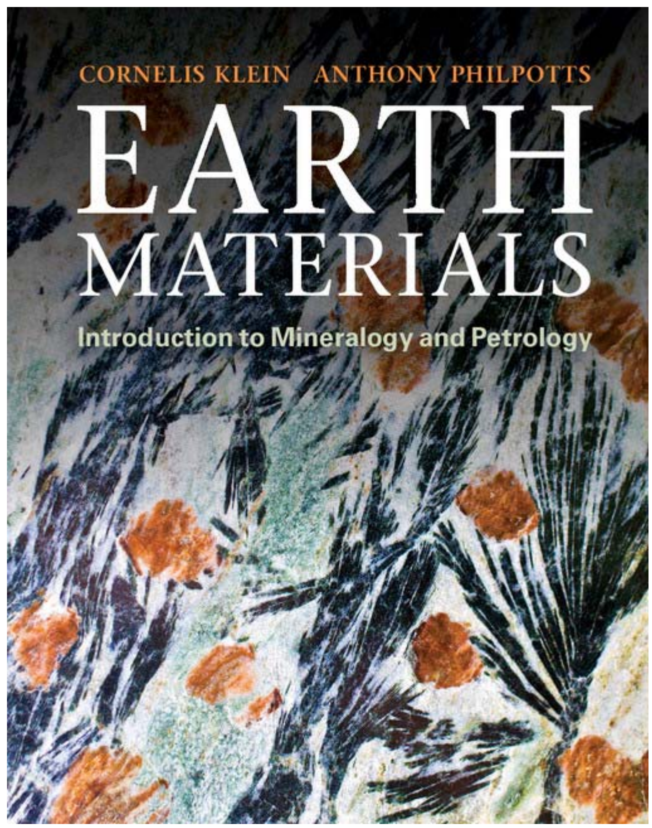

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Solutions to Chapter 1 Problems

1. Where were most of Earth's chemical elements formed?

Most of the Earth's chemical elements were formed from interstellar dust that was thrown out from exploding stars known as supernovae. During these explosions, elements heavier than iron are formed by nuclear reactions.

2. Why are the terrestrial inner planets small compared with the outer gas giant planets?

The planets formed from solid materials that condensed from the solar nebula. Because the terrestrial planets formed near the Sun, where temperatures were relatively high, only refractory minerals could condense from the solar nebula. These minerals involve the less abundant heavy elements in the solar nebula, so the terrestrial planets are small. The outer gas giant planets formed farther from the Sun where temperatures were low enough for ices of water, carbon dioxide, ammonia, and methane to condense. Because these ices involve the more abundant elements in the solar nebula (H, O, C), these outer planets are much larger than the terrestrial planets.

3. What is a chondrule, and why do we use the composition of chondritic meteorites to determine the composition of the Earth?

Chondrules are millimeter-size spheres of extremely fine-grained silicates (olivine and pyroxene) that characterize chondritic meteorites, which are the most common type of meteorite. These small spheres were formed by sudden heating and cooling of dust particles in the solar nebula, and they consequently form one of the oldest known structures in the solar system. Chondritic meteorites all have absolute ages of 4.6 billion years. The Earth is believed to have formed by the accretion of the same material that formed chondritic meteorites. Their composition is therefore considered to be similar to the bulk-Earth composition.

4. What caused the Earth to be so hot early in its history that its outer part would have been molten?

Several sources of heat caused the Earth to have a hot beginning. To begin with, the kinetic energy of the accretionary process would have generated considerable heat. In addition, heat was generated by radioactive decay and the formation of the iron-nickel core (conversion of potential energy to heat). The amount of heat produced by these processes would have been sufficient to make the outer part of the Earth Molten.

5. What are the major divisions of the Earth?

The major divisions of the Earth are the following:

Core -- divided into inner solid and outer liquid parts.

Mantle -- divided into a lower and upper part, which may or may not interact through convection.

Crust – The thin outer part of the Earth, which under continents is of generally granitic composition and under oceans is of basaltic composition.

6. What two important layers in the Earth are responsible for plate tectonics?

Another important division in the outer part of the Earth is the distinction between the lithosphere and the asthenosphere. The relatively rigid 100 km-thick lithosphere is broken into eight major plates whose movement on the underlying less viscous asthenosphere creates plate tectonics, the process by which the Earth is able to convectively cool and, in so doing, create rocks.

7. What are the main types of plate boundaries, and what types of rock might be formed there?

There are three main types of boundaries between tectonic plates – divergent, convergent, and transform boundaries. At divergent plate boundaries, especially in oceanic areas, basalt is the main igneous rock formed. At convergent plate boundaries igneous rocks of andesitic composition are formed. Other important rocks are formed near convergent boundaries, including thick sequences of sedimentary rocks formed by sediment eroded from the mountains that characterize these boundaries. Heat and elevated pressures generated at convergent boundaries produce a variety of metamorphic rocks. Along transform boundaries, sedimentary rocks can form in pull-apart basins. Rocks along these boundaries become highly sheared.

Solutions to Chapter 2 Problems

1. What is a mineral, and why is it important to specify naturally occurring?

A mineral is a naturally occurring solid, with an ordered atomic arrangement, and a definite (but commonly not fixed) chemical composition. Almost all minerals are of inorganic origin.

"Naturally occurring" distinguishes minerals from those that are synthetic, meaning those that are made by laboratory techniques in research laboratories or by commercial processes.

2. Why does table salt (NaCl) break into cubelike cleavage fragments?

The internal structure of halite is based on Na+ and Cl- ions in a cubic pattern. The bonds between the ions are relatively weak, leading to well-developed cleavage in three directions at 90° to each other (in the shape of a cube).

3. What is the composition, shape, and electrical charge on the basic building unit of all silicate minerals?

The basic building unit in all silicates is that of a tetrahedron, in which a central Si4+ ion is surrounded by four O2- ions, located at the four corners of the tetrahedron.

4. What are some common uses for the mineral quartz (SiO2)?

Quartz, SiO2, in the form of quartz sand, is a major component of cement used in the construction industry. It is also a major source in the making of silica glass. Synthetic quartz is used in electronic applications, an example of which is the use thereof in quartz watches.

5. How does the arrangement of silica tetrahedra in the crystal structures of quartz and talc differ?

The atomic structure of quartz consists of an infinite framework of $(SiO_4)^{4-}$ tetrahedra without any other cations present. The structure of talc, on the other hand, is made of two infinitely extending tetrahedral sheets (linking tetrahedra in only two dimensions, not three, as in quartz) between which is an infinitely extending, well-bonded sheet of Mg^{2+} ions.

6. Although the cation to anion ratio in garnet is fixed, what allows it to have a wide compositional range, and why are such widely different compositions still classified as the same mineral?

A generalized formula for all garnets is $A_3B_2(SiO_4)_3$, where A and B represent atomic positions in which several different cations may be housed. The subscripts in this formula are 3: 2: 3 and these are the same for all garnet compositions. The A atomic site can house Mg^{2+}, Fe^{2+}, Mn^{2+}, or Ca^{2+} and the B site may house Al^{3+}, Fe^{3+}, or Cr^{3+}. Such variability in atomic site occupancy leads to a wide range of compositions all of which are based on the same atomic structure.

7. Can minerals be synthesized in the laboratory?

Yes, many minerals are routinely synthesized. Diamonds, rubies, sapphires, and emeralds are commonly produced for the gem trade. Synthetic quartz is used in electronic applications.

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8. On what basis are minerals classified into different chemical groups, and of these, which forms the largest group?

Minerals are grouped chemically into native elements and the more complex compounds by the compositions of their anion or anionic group. For example, sulfides have S2- as the anion; oxides have O2- as the anion. The mineral group that contains (SiO4)4- anionic tetrahedra, the silicates, is the largest mineral group.

9. What is a crystal, and does the crystalline state require that crystal faces be present?

A specific, well-formed crystal exhibits a combination of crystal faces that reflects the internal, ordered atomic arrangement of that crystal. A rounded grain of that same mineral lacks all evidence of external crystal form but the internal atomic arrangement inside that rounded grain is identical to that of the well-formed crystal. In other words, both a quartz crystal and a quartz sand grain possess the same internal crystallinity.

10. What is a rock, and how does it differ from a mineral?

A rock is made up of a mixture of minerals that are bound together to form a solid material. Sand might contain a mixture of minerals but it would not be considered a rock until it were cemented together, in which case it would become a sandstone.

11. What is the difference between a rock's texture and structure?

A rock's texture refers to the way in which its constituent grains relate to one another. It describes features that are visible at the scale of the individual grains. Structure, on the other hand, refers to larger-scale features, which commonly are produced by variations in the abundance of minerals at the hand-specimen our outcrop scale, such as layering in sedimentary rocks.

12. From a geological map of the area where you live, determine how many rock-forming periods your home area has experienced and approximately what fraction of geologic time these periods represent.

For most areas, only a few rock-forming periods will have occurred, and their total duration will be only a very small fraction of all geologic time.

13. What single process has been operating continuously since the beginning of the Earth and has been responsible for the formation of most rocks and drives plate tectonics.

Ever since the Earth was formed it has been cooling. Cooling drives the convection that moves tectonic plates. The formation of magma removes the latent heat of melting from the source region and releases it when the magma crystallizes to form an igneous rock. Heat is required to drive the reactions that produce metamorphic rocks.

14. Give brief definitions of igneous, sedimentary, and metamorphic rocks, and describe how you might distinguish between them.

Igneous rocks are formed from the solidification of molten rock—magma. If magma solidifies slowly beneath the surface, it typically crystallizes to a relatively coarse-grained rock in which early crystallizing minerals are commonly surrounded by later-crystallizing minerals. The rock owes its strength to the interlocking way in which its crystals form. If magma crystallizes rapidly on the surface as a volcanic rock, its grain size is fine, but commonly larger crystals (phenocrysts) that were growing prior to eruption are present in the fine-grained groundmass. If cooling is very rapid the igneous rock may be glassy.

Sedimentary rocks are formed by the cementing together of sedimentary particles. The particles may come from the disintegration of silicate rocks, in which case the main constituent is usually quartz, with lesser amounts of feldspar and other minerals. Near shores where marine life is abundant the sedimentary particles may consist of broken shells and corals, in which case the sediment is composed largely of calcium carbonate. Some sediment can form by direct precipitation of carbonates, sulphates, and chlorides from water as a result of evaporation. Most sedimentary rocks exhibit prominent sub-horizontal layering (bedding).

Metamorphic rocks are formed by the recrystallization of other rocks as a result of changes in the temperature, pressure, or composition of fluids in the environment. These changes can take place on a regional scale as a result of plate tectonic motions, especially near convergent plate boundaries. Recrystallization of rock in such environments develops a prominent foliation. Recrystallization can also take place near igneous intrusions as a result of heat released during cooling. These rocks do not develop a foliation but recrystallize to rock with polygonal-shaped grains.

15. What general distinction can you make between the igneous rocks of the ocean floor and those of the continental crust?

Igneous rocks of the ocean floor are predominantly volcanic rocks of basaltic composition. In contrast, the igneous rocks of continental regions tend to be of granitic composition.

16. What sedimentary rock do we make the greatest use of in the modern world?

Limestone is used in the manufacture of cement, which binds together concrete, the main construction material of the modern world.

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17. What feature characterizes most regionally metamorphosed rocks?

Regional metamorphic rocks are typically formed near convergent plate boundaries. The recrystallization therefore takes place under compressive stresses, and minerals that are platy (e.g., mica) or needle-like (amphibole) tend to grow with their long axes perpendicular to the maximum compressive stress. This causes the rock to develop a strong foliation (e.g., slate or schist).

18. Where does the largest production of new rock take place on Earth?

The largest production of new rock takes place at midocean ridges, where basaltic magma rises in response to the dilation of the lithosphere, with production of dikes and lava flows.

19. Water plays what important roles when circulating through fractures in newly formed oceanic crust?

Water circulating through newly formed oceanic crust near midocean ridges cools the rock and converts some of the igneous minerals to hydrous alteration minerals. When the ocean floor is subducted at a convergent plate boundary, the increased pressure eventually causes metamorphic reactions to take place that release the water. This water then rises into the overlying mantle wedge where it lowers the melting point of the mantle peridotite, and andesitic magma is formed. This magma rises to form andesitic rocks, or it may pond at lower levels in the crust and cause melting of crustal rock to form bodies of granite.

20. What common volcanic rock forms above subducting tectonic plates and what role does water play in its origin?

Andesite is the common volcanic rock formed above subduction zones. Melting of mantle peridotite under anhydrous conditions generates basaltic magma. As the water content is increased, however, the magma that is formed contains higher concentrations of silica and becomes andesitic. Andesite is consequently the hydrous melting product of mantle peridotite. The water in this magma is made evident when andesite erupts. The water comes out of solution in the magma and makes many andesitic eruptions explosive.

21. Why are granite batholiths common above subducting tectonic plates?

Basaltic or andesitic magma rising into the base of the crust above subduction zones may spread laterally near the base of the crust where the heat and fluids they release can cause melting of the lower crust to form bodies of granitic magma. This magma can rise to form granite batholiths.

22. What is the source of sediment in forearc basins and what is a common characteristic of these sedimentary beds?

The greatest relief on Earth is created at convergent plate boundaries, where oceanic trenches lie next to mountain chains. This relief results in the formation and transport of large quantities of sediment from the mountains toward the ocean trench. Some of the sediment may reach the trench, but most is trapped in forearc basins. Much of the sediment is deposited from turbidity currents, which create beds that are graded from coarse, dense particles at the base to the fine, less dense particles at the top.

23. Why are the sedimentary rocks of rift valleys commonly red-colored and still contain a considerable amount of the relatively soft mineral feldspar?

The sediment that is transported and deposited in rift valleys is normally in contact with air or groundwater that is in contact with air. Most of this sediment therefore accumulates under relatively oxidizing conditions, in which case iron is converted to the red Fe2O3. Transportation distances from the source of the sediment to the site of deposition are short, and there is insufficient time for the harder minerals to abrade and eliminate the softer minerals. Sandstones in rift valleys, therefore, commonly contain considerable amounts of feldspar in addition to quartz.

24. From where do mantle plumes derive their heat?

Mantle plumes are believed to derive their heat from deep in the mantle, possibly as deep as the core-mantle boundary. Mantle plumes appear to have very deep roots because they are unaffected by lithospheric plate motion. In addition, high concentrations of 3He versus the more common 4He over mantle plumes point to the tapping of a primitive source that has not been outgassed since formation of the planet.

25. How are shallow epeiric seas that flood continents related to plate tectonics?

During periods of exceptionally active ocean-floor spreading large quantities of new ocean crust are formed. This hot material has relatively low density and consequently floats high and displaces ocean water onto continents flooding them with shallow seas.

26. What plate-tectonic processes deflect isotherms up or down in the Earth?

Isotherms are deflected down and up at convergent and divergent plate boundaries, respectively. Subduction of cold ocean floor rocks at convergent plate boundaries deflects isotherms downward, taking cold rocks to considerable depth. This produces high-pressure low-temperature metamorphic rocks in these subduction zones. Release of water from the subducted slab causes melting in the overlying mantle wedge. When this magma rises into the crust it deflects isotherms upward. At divergent plate boundaries the mantle rises in response to the divergence, and this brings isotherms closer to the surface. As the mantle decompresses it partially melts and the rise of magma can move isotherms still closer to the surface.

27. Trace the role played by water and carbon dioxide in metamorphic rocks in going from their formation near midocean ridges to the production of granite by partial melting of continental crust above subducting plates.

Newly formed oceanic crust at a midocean ridge is cooled and altered by water circulating through fractures. Many hydrous and carbonate minerals are formed as a result of this hydrothermal activity. When these rocks experience increased pressure on being subducted, the alteration minerals are converted to higher-pressure minerals and eventually water and carbon dioxide are released from the subducting slab. These volatiles rise into the overlying plate where they participate in the formation of andesitic magma and metamorphic minerals. Magma rising from the mantle may pond at the base of the crust, where it can partially melt crustal rocks to form granitic magma.