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17 THE GEOSPHERE AND GEOCHEMISTRY

17.1 INTRODUCTION

The **geosphere**, or solid earth, is that part of the earth upon which humans live and from which they extract most of their food, minerals, and fuels. Once thought to have an almost unlimited buffering capacity against the perturbations of humankind, the geosphere is now known to be rather fragile and subject to harm by human activities. For example, some billions of tons of earth material are mined or otherwise disturbed each year in the extraction of minerals and coal. Two atmospheric pollutant phenomena—excess carbon dioxide and acid rain (see Chapter 15)—have the potential to cause major changes in the geosphere. Too much carbon dioxide in the atmosphere may cause global heating ("greenhouse effect"), which could significantly alter rainfall patterns and turn currently productive areas of the earth into desert regions. The low pH characteristic of acid rain can bring about drastic changes in the solubilities and oxidation-reduction rates of minerals. Erosion caused by intensive cultivation of land is washing away vast quantities of topsoil from fertile farmlands each year. In some areas of industrialized countries, the geosphere has been the dumping ground for toxic chemicals. Ultimately, the geosphere must provide disposal sites for the nuclear wastes of the more than 400 nuclear reactors that have operated worldwide. It may be readily seen that the preservation of the geosphere in a form suitable for human habitation is one of the greatest challenges facing humankind.

The interface between the geosphere and the atmosphere at Earth's surface is very important to the environment. Human activities on the earth's surface may affect climate, most directly through the change of surface albedo, defined as the percentage of incident solar radiation reflected by a land or water surface. For example, if the sun radiates 100 units of energy per minute to the outer limits of the atmosphere, and the earth's surface receives 60 units per minute of the total, then reflects 30 units upward, the albedo is 50 percent. Some typical albedo values for different areas on the earth's surface are: evergreen forests, 7–15%; dry, plowed

fields, 10–15%; deserts, 25–35%; fresh snow, 85–90%; asphalt, 8%. In some heavily developed areas, anthropogenic (human-produced) heat release is comparable to the solar input. The anthropogenic energy release over the 60 square kilometers of Manhattan Island averages about 4 times the solar energy falling on the area; over the 3500 km² of Los Angeles, the anthropogenic energy release is about 13% of the solar flux.

One of the greater impacts of humans upon the geosphere is the creation of desert areas through abuse of land that has marginal amounts of rainfall. This process, called **desertification**, is manifested by declining groundwater tables, salinization of topsoil and water, reduction of surface waters, unnaturally high soil erosion, and desolation of native vegetation. The problem is severe in some parts of the world, particularly Africa's Sahel (southern rim of the Sahara), where the Sahara advanced southward at a particularly rapid rate during the period 1968–73, contributing to widespread starvation in Africa during the 1980s. Large arid areas of the western U.S. are experiencing at least some desertification as the result of human activities and a severe drought during the latter 1980s and early 1990s. As the populations of the western states increase, one of the greatest challenges facing the residents is to prevent additional conversion of land to desert.

The most important part of the geosphere for life on earth is soil. It is the medium upon which plants grow, and virtually all terrestrial organisms depend upon it for their existence. The productivity of soil is strongly affected by environmental conditions and pollutants. Because of the importance of soil, all of Chapter 16 is devoted to its environmental chemistry.

With increasing population and industrialization, one of the more important aspects of human use of the geosphere has to do with the protection of water sources. Mining, agricultural, chemical, and radioactive wastes all have the potential for contaminating both surface water and groundwater. Sewage sludge spread on land may contaminate water by release of nitrate and heavy metals. Landfills may likewise be sources of contamination. Leachates from unlined pits and lagoons containing hazardous liquids or sludges may pollute drinking water.

It should be noted, however, that many soils have the ability to assimilate and neutralize pollutants. Various chemical and biochemical phenomena in soils operate to reduce the harmful nature of pollutants. These phenomena include oxidation-reduction processes, hydrolysis, acid-base reactions, precipitation, sorption, and biochemical degradation. Some hazardous organic chemicals may be degraded to harmless products on soil, and heavy metals may be sorbed by it. In general, however, extreme care should be exercised in disposing of chemicals, sludges, and other potentially hazardous materials on soil, particularly where the possibility of water contamination exists.

17.2 THE NATURE OF SOLIDS IN THE GEOSPHERE

The earth is divided into layers, including the solid iron-rich inner core, molten outer core, mantle, and crust. Environmental chemistry is most concerned with the **lithosphere**, which consists of the outer mantle and the **crust**. The latter is the earth's outer skin that is accessible to humans. It is extremely thin compared with the diameter of the earth, ranging from 5 to 40 km thick.

Most of the solid earth crust consists of rocks. Rocks are composed of minerals, where a **mineral** is a naturally occurring inorganic solid with a definite internal crystal structure and chemical composition. A **rock** is a solid, cohesive mass of pure mineral or an aggregate of two or more minerals.

Structure and Properties of Minerals

The combination of two characteristics is unique to a particular mineral. These characteristics are a defined chemical composition, as expressed by the mineral's chemical formula, and a specific crystal structure. The **crystal structure** of a mineral refers to the way in which the atoms are arranged relative to each other. It cannot be determined from the appearance of visible crystals of the mineral, but requires structural methods such as X-ray structure determination. Different minerals may have the same chemical composition, or they may have the same crystal structure, but cannot have both the identical for truly different minerals.

Physical properties of minerals can be used to classify them. The characteristic external appearance of a pure crystalline mineral is its crystal form. Because of space constrictions on the ways that minerals grow, the pure crystal form of a mineral is often not expressed. Color is an obvious characteristic of minerals, but can vary widely due to the presence of impurities. The appearance of a mineral surface in reflected light describes its luster. Minerals may have a metallic luster or appear partially metallic (or submetallic), vitreous (like glass), dull or earthy, resinous, or pearly. The color of a mineral in its powdered form as observed when the mineral is rubbed across an unglazed porcelain plate is known as streak. Hardness is expressed on Mohs scale, which ranges from 1 to 10 and is based upon 10 minerals that vary from talc, hardness 1, to diamond, hardness 10. Cleavage denotes the manner in which minerals break along planes and the angles in which these planes intersect. For example, mica cleaves to form thin sheets. Most minerals fracture irregularly, although some fracture along smooth curved surfaces or into fibers or splinters. Specific gravity, density relative to that of water, is another important physical characteristic of minerals.

Kinds of Minerals

Although over 2000 minerals are known, only about 25 **rock-forming minerals** make up most of the earth's crust. The nature of these minerals can be better understood with a knowledge of the elemental composition of the crust. Oxygen and silicon make up 49.5% and 25.7% by mass of the earth's crust, respectively. Therefore, most minerals are **silicates** such as quartz, SiO_2 , or orthoclase, $KAlSi_3O_8$. In descending order of abundance, the other elements in the earth's crust are aluminum (7.4%), iron (4.7%), calcium (3.6%), sodium (2.8%), potassium (2.6%), magnesium (2.1%), and "other (1.6%)". Table 17.1 summarizes the major kinds of minerals in the earth's crust.

Secondary minerals are formed by alteration of parent mineral matter. **Clays** are silicate minerals, usually containing aluminum, which constitute one of the most significant classes of secondary minerals. Olivine, augite, hornblende, and feldspars all form clays. Clays are discussed in detail in Section 17.7.

Table 17.1 Major Mineral Groups in the Earth's Crust

Mineral group	Examples	Formula
Silicates	Quartz Olivine Potassium feldspar	SiO_2 (Mg,Fe) ₂ SiO ₄ KAlSi ₃ O ₈
Oxides	Corundum Magnetite	Al_2O_3 Fe_3O_4
Carbonates	Calcite Dolomite	CaCO ₃ CaCO ₃ •MgCO ₃
Sulfides	Pyrite Galena	FeS ₂ PbS
Sulfates	Gypsum	CaSO ₄ •2H ₂ O
Halides	Halite Fluorite	NaCl CaF ₂
Native elements	Copper Sulfur	Cu S

Evaporites

Evaporites are soluble salts that precipitate from solution under special arid conditions, commonly as the result of the evaporation of seawater. The most common evaporite is **halite**, NaCl. Other simple evaporite minerals are sylvite (KCl), thenardite (Na₂SO₄), and anhydrite (CaSO₄). Many evaporites are hydrates, including bischofite (MgCl₂•6H₂O), kieserite (MgSO₄•H₂O), gypsum (CaSO₄•2H₂O), and epsomite (MgSO₄•7H₂O). Double salts, such as carnallite (KMgCl₃•6H₂O), polyhalite (K₂MgCa₂(SO₄)₄•2H₂O), kainite (KMgClSO₄•11/₄H₂O), glaserite (K₃Na(SO₄)₂), and loeweite (Na₁₂Mg₇(SO₄)₁₃•15H₂O), are very common in evaporites.

The precipitation of evaporites from marine and brine sources depends upon a number of factors. Prominent among these are the concentrations of the evaporite ions in the water and the solubility products of the evaporite salts. The presence of a common ion decreases solubility; for example, CaSO₄ precipitates more readily from a brine that contains Na₂SO₄ than it does from a solution that contains no other source of sulfate. The presence of other salts that do not have a common ion increases solubility because it decreases activity coefficients. Differences in temperature result in significant differences in solubility.

The nitrate deposits that occur in the hot and extraordinarily dry regions of northern Chile are chemically unique because of the stability of highly oxidized nitrate salts. The dominant salt, which has been mined for its nitrate content for use

in explosives and fertilizers, is Chile saltpeter, $NaNO_3$. Traces of highly oxidized $CaCrO_4$ and $Ca(ClO_4)_2$ are also encountered in these deposits, and some regions contain enough $Ca(IO_3)_2$ to serve as a commercial source of iodine.

Volcanic Sublimates

A number of mineral substances are gaseous at the magmatic temperatures of volcanoes and are mobilized with volcanic gases. These kinds of substances condense near the mouths of volcanic fumaroles and are called **sublimates**. Elemental sulfur is a common sublimate. Some oxides, particularly of iron and silicon, are deposited as sublimates. Most other sublimates consist of chloride and sulfate salts. The cations most commonly involved are monovalent cations of ammonium ion, sodium, and potassium; magnesium; calcium; aluminum; and iron. Fluoride and chloride sublimates are sources of gaseous HF and HCl formed by their reactions at high temperatures with water, such as the following:

$$2H_2O + SiF_4 + 4HF + SiO_2$$
 (17.2.1)

Igneous, Sedimentary, and Metamorphic Rock

At elevated temperatures deep beneath earth's surface, rocks and mineral matter melt to produce a molten substance called magma. Cooling and solidification of magma produces **igneous rock**. Common igneous rocks include granite, basalt, quartz (SiO₂), pyroxene ((Mg,Fe)SiO₃), feldspar ((Ca,Na,K)AlSi₃O₈), olivine ((Mg,Fe)₂SiO₄), and magnetite (Fe₃O₄). Igneous rocks are formed under waterdeficient, chemically reducing conditions of high temperature and high pressure. Exposed igneous rocks are under wet, oxidizing, low-temperature, and low-pressure conditions. Since such conditions are opposite those conditions under which igneous rocks were formed, they are not in chemical equilibrium with their surroundings when they become exposed. As a result, such rocks disintegrate by a process called weathering. Weathering tends to be slow because igneous rocks are often hard, nonporous, and of low reactivity. Erosion from wind, water, or glaciers picks up materials from weathering rocks and deposits it as sediments or soil. A process called lithification describes the conversion of sediments to sedimentary rocks. In contrast to the parent igneous rocks, sediments and sedimentary rocks are porous, soft, and chemically reactive. Heat and pressure convert sedimentary rock to metamorphic rock.

Sedimentary rocks may be **detrital rocks** consisting of solid particles eroded from igneous rocks as a consequence of weathering; quartz is the most likely to survive weathering and transport from its original location chemically intact. A second kind of sedimentary rocks consists of **chemical sedimentary rocks** produced by the precipitation or coagulation of dissolved or colloidal weathering products. **Organic sedimentary rocks** contain residues of plant and animal remains. Carbonate minerals of calcium and magnesium—**limestone** or **dolomite**—are especially abundant in sedimentary rocks. Important examples of sedimentary rocks are the following:

- Sandstone produced from sand-sized particles of minerals such as quartz
- Conglomerates made up of relatively larger particles of variable size
- · Shale formed from very fine particles of silt or clay
- Limestone, CaCO₃, produced by the chemical or biochemical precipitation of calcium carbonate:

$$Ca^{2+} + CO_3^{2-}$$
 $CaCO_3(s)$

$$Ca^{2+} + 2HCO_3^{-} + h \text{ (algal photosynthesis)} \qquad \{CH_2O\}\text{(biomass)} + CaCO_3(s) + O_2(g)$$

• Chert consisting of microcrystalline SiO₂

Rock Cycle

The interchanges and conversions among igneous, sedimentary, and metamorphic rocks, as well as the processes involved therein, are described by the **rock cycle**. A rock of any of these three types can be changed to a rock of any other type. Or a rock of any of these three kinds can be changed to a different rock of the same general type in the rock cycle. The rock cycle is illustrated in Figure 17.1.

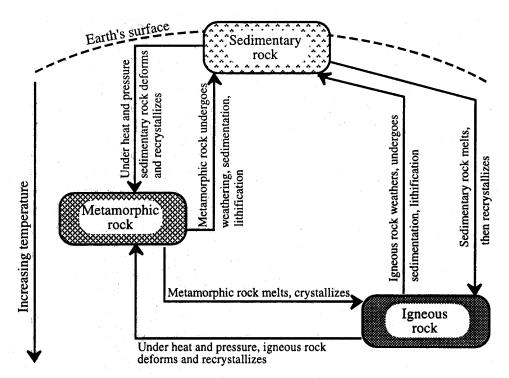


Figure 17.1 The rock cycle

Stages of Weathering

Weathering can be classified into **early**, **intermediate**, and **advanced stages**. The stage of weathering to which a mineral is exposed depends upon time; chemical conditions, including exposure to air, carbon dioxide, and water; and physical conditions such as temperature and mixing with water and air.

Reactive and soluble minerals such as carbonates, gypsum, olivine, feldspars, and iron(II)-rich substances can survive only early weathering. This stage is characterized by dry conditions, low leaching, absence of organic matter, reducing conditions, and limited time of exposure. Quartz, vermiculite, and smectites can survive the intermediate stage of weathering manifested by retention of silica, sodium, potassium, magnesium, calcium, and iron(II) not present in iron(II) oxides. These substances are mobilized in advanced-stage weathering, other characteristics of which are intense leaching by fresh water, low pH, oxidizing conditions (iron(II) iron(III)), presence of hydroxy polymers of aluminum, and dispersion of silica.

17.3 PHYSICAL FORM OF THE GEOSPHERE

The most fundamental aspect of the physical form of the geosphere has to do with Earth's shape and dimensions. The earth is shaped as a **geoid** defined by a surface corresponding to the average sea level of the oceans and continuing as hypothetical sea levels under the continents. This shape is not a perfect sphere because of variations in the attraction of gravity at various places on Earth's surface. This slight irregularity in shape is important in surveying to precisely determine the locations of points on Earth's surface according to longitude, latitude, and elevation above sea level. Of more direct concern to humans is the nature of landforms and the processes that occur on them. This area of study is classified as **geomorphology**.

Plate Tectonics and Continental Drift

The geosphere has a highly varied, constantly changing physical form. Most of the earth's land mass is contained in several massive continents separated by vast oceans. Towering mountain ranges spread across the continents, and in some places the ocean bottom is at extreme depths. Earthquakes, which often cause great destruction and loss of life, and volcanic eruptions, which sometimes throw enough material into the atmosphere to cause temporary changes in climate, serve as reminders that the earth is a dynamic, living body that continues to change. There is convincing evidence, such as the close fit between the western coast of Africa and the eastern coast of South America, that widely separated continents were once joined and have moved relative to each other. This ongoing phenomenon is known as **continental drift**. It is now believed that 200 million years ago much of Earth's land mass was all part of a supercontinent, now called Gowandaland. This continent split apart to form the present-day continents of Antarctica, Australia, Africa, and South America, as well as Madagascar, the Seychelle Islands, and India.

The observations described above are explained by the theory of **plate tectonics**. This theory views Earth's solid surface as consisting of several rigid plates that move relative to each other. These plates drift at an average rate of several centimeters per year atop a relatively weak, partially molten layer that is part of

Earth's upper mantle, called the **asthenosphere**. The science of plate tectonics explains the large-scale phenomena that affect the geosphere, including the creation and enlargement of oceans as the ocean floors open up and spread, the collision and breaking apart of continents, the formation of mountain chains, volcanic activities, the creation of islands of volcanic origin, and earthquakes.

The boundaries between these plates are where most geological activity such as earthquakes and volcanic activity occur. These boundaries are of the three following types:

- **Divergent boundaries** where the plates are moving away from each other. Occurring on ocean floors, these are regions in which hot magma flows upward and cools to produce new solid lithosphere. This new solid material creates **ocean ridges**.
- **Convergent boundaries** where plates move toward each other. One plate may be pushed beneath the other in a **subduction zone** in which matter is buried in the asthenosphere and eventually remelted to form new magma. When this does not occur, the lithosphere is pushed up to form mountain ranges along a collision boundary.
- **Transform fault boundaries** in which two plates slide past each other. These boundaries create faults that result in earthquakes.

The phenomena described above are parts of the **tectonic cycle**, a geological cycle that describes how tectonic plates move relative to each other, magma rises to form new solid rocks, and solid lithospheric rocks sink to become melted, thus forming new magma. The tectonic cycle is illustrated in Figure 17.2.

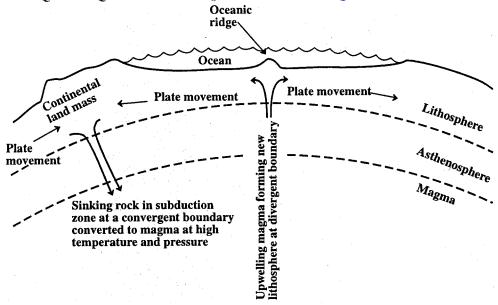


Figure 17.2 Illustration of the techtonic cycle in which upwelling magma along a boundary where two plates diverge creates new lithosphere on the ocean floor, and sinking rock in a subduction zone is melted to form magma.

Structural Geology

Earth's surface is constantly being reshaped by geological processes. The movement of rock masses during processes such as the formation of mountains results in substantial deformation of rock. At the opposite extreme of the size scale are defects in crystals at a microscopic level. **Structural geology** addresses the geometric forms of geologic structures over a wide range of size, the nature of structures formed by geological processes, and the formation of folds, faults, and other geological structures.

Primary structures are those that have resulted from the formation of a rock mass from its parent materials. Primary structures are modified and deformed to produce **secondary structures**. A basic premise of structural geology is that most layered rock formations were deposited in a horizontal configuration. Cracking of such a formation without displacement of the separate parts of the formation relative to each other produces a **joint**, whereas displacement produces a **fault** (see Figure 17.3).

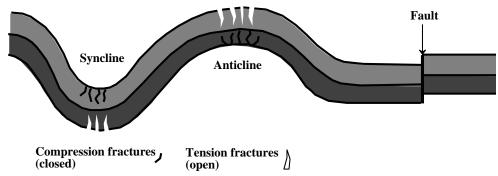


Figure 17.3 Folds (syncline and anticline) are formed by the bending of rock formations. Faults are produced by rock formations moving vertically or laterally in respect to each other.

An important relationship in structural geology is that between the force or **stress** placed upon a geological formation or object and the deformation resulting therefrom, called the **strain**. An important aspect of structural geology, therefore, is **rheology**, which deals with the deformation and flow of solids and semisolids. Whereas rocks tend to be strong, rigid, and brittle under the conditions at Earth's surface, their rheology changes such that they may become weak and pliable under the extreme conditions of temperature and pressure at significant depths below Earth's surface.

Internal and Surface Processes

Related to the physical configuration of the geosphere are several major kinds of processes that occur that change this configuration and that have the potential to cause damage and even catastrophic effects. These can be divided into the two main categories of **internal processes** that arise from phenomena located significantly below the earth's surface, and **surface processes** that occur on the surface.

The two major kinds of internal processes are earthquakes and volcanoes. Earthquakes occur when huge masses of rock formerly locked together abruptly slip relative to each other along a fault. As a result of the movement, the ground may

shake violently and tremendous damage and loss of life can result. The harmful effects of earthquakes are discussed in some detail in Section 17.9.

Volcanoes are the result of emissions of molten rock (lava), gases, steam, ash, and particles due to the presence of magma near the earth's surface. Like earth-quakes, volcanoes are capable of great environmental damage. Environmental aspects of volcanic activity are discussed in Section 17.10.

Geological surface processes occur when rock, soil, mud, ice, or snow move on Earth's surface. Landslides and mudslides, which are discussed in greater detail in Section 17.11, are capable of causing enormous damage and loss of human life. Snow avalanches take a number of lives each winter.

17.4 SEDIMENTS

Vast areas of land, as well as lake and stream sediments, are formed from sedimentary rocks. The properties of these masses of material depend strongly upon their origins and transport. Water is the main vehicle of sediment transport, although wind can also be significant. Hundreds of millions of tons of sediment are carried by major rivers each year.

The action of flowing water in streams cuts away stream banks and carries sedimentary materials for great distances. Sedimentary materials may be carried by flowing water in streams as the following:

- Dissolved load from sediment-forming minerals in solution
- Suspended load from solid sedimentary materials carried along in suspension
- **Bed load** dragged along the bottom of the stream channel.

The transport of calcium carbonate as dissolved calcium bicarbonate provides a straightforward example of dissolved load and is the most prevalent type of such load. Water with a high dissolved carbon dioxide content (usually present as the result of bacterial action) in contact with calcium carbonate formations contains Ca²⁺ and HCO₃ ions. Flowing water containing calcium as such *temporary hardness* may become more basic by loss of CO₂ to the atmosphere, consumption of CO₂ by algal growth, or contact with dissolved base, resulting in the deposition of insoluble CaCO₃:

$$Ca^{2+} + 2HCO_3$$
 $CaCO_3(s) + CO_2(g) + H_2O$ (17.4.1)

Most flowing water that contains dissolved load originates underground, where the water has had the opportunity to dissolve minerals from the rock strata that it has passed through.

Most sediments are transported by streams as suspended load, obvious in the observation of "mud" in the flowing water of rivers draining agricultural areas or finely divided rock in Alpine streams fed by melting glaciers. Under normal conditions, finely divided silt, clay, or sand make up most of the suspended load, although larger particles are transported in rapidly flowing water. The degree and

rate of movement of suspended sedimentary material in streams are functions of the velocity of water flow and the settling velocity of the particles in suspension.

Bed load is moved along the bottom of a stream by the action of water "pushing" particles along. Particles carried as bed load do not move continuously. The grinding action of such particles is an important factor in stream erosion.

Typically, about $^{2}/_{3}$ of the sediment carried by a stream is transported in suspension, about $^{1}/_{4}$ in solution, and the remaining small fraction as bed load. The ability of a stream to carry sediment increases with both the overall rate of flow of the water (mass per unit time) and the velocity of the water. Both are higher under flood conditions, so floods are particularly important in the transport of sediments.

Streams mobilize sedimentary materials through **erosion**, **transport** materials along with stream flow, and release them in a solid form during **deposition**. Deposits of stream-borne sediments are called **alluvium**. As conditions such as lowered stream velocity begin to favor deposition, larger, more settleable particles are released first. This results in **sorting** such that particles of a similar size and type tend to occur together in alluvial deposits. Much sediment is deposited in flood plains where streams overflow their banks.

17.5 CLAYS

Clays are extremely common and important in mineralogy. Furthermore, in general (see Chapter 18), clays predominate in the inorganic components of most soils and are very important in holding water and in plant nutrient cation exchange. All clays contain silicate and most contain aluminum and water. Physically, clays consist of very fine grains having sheet-like structures. For purposes of discussion here, **clay** is defined as a group of microcrystalline secondary minerals consisting of hydrous aluminum silicates that have sheet-like structures. Clay minerals are distinguished from each other by general chemical formula, structure, and chemical and physical properties. The three major groups of clay minerals are the following:

- Montmorillonite, Al₂(OH)₂Si₄O₁₀
- Illite, K₀₋₂Al₄(Si₈₋₆Al₀₋₂)O₂₀(OH)₄
- Kaolinite, Al₂Si₂O₅(OH)₄

Many clays contain large amounts of sodium, potassium, magnesium, calcium, and iron, as well as trace quantities of other metals. Clays bind cations such as Ca^{2+} , Mg^{2+} , K^+ , Na^+ , and NH_4^+ , which protects the cations from leaching by water but keeps them available in soil as plant nutrients. Since many clays are readily suspended in water as colloidal particles, they may be leached from soil or carried to lower soil layers.

Olivine, augite, hornblende, and feldspars are all parent minerals that form clays. An example is the formation of kaolinite $(Al_2Si_2O_5(OH)_4)$ from potassium feldspar rock (KAlSi₃O₈):

$$2KAlSi_3O_8(s) + 2H^+ + 9H_2O$$
 $Al_2Si_2O_5(OH)_4(s) + 2K^+(aq) + 4H_4SiO_4(aq)$ (17.5.1)

The layered structures of clays (Figure 17.4) consist of sheets of silicon oxide alternating with sheets of aluminum oxide. The silicon oxide sheets are made up of tetrahedra in which each silicon atom is surrounded by four oxygen atoms. Of the four oxygen atoms in each tetrahedron, three are shared with other silicon atoms that are components of other tetrahedra. This sheet is called the **tetrahedral sheet**. The aluminum oxide is contained in an **octahedral sheet**, so named because each aluminum atom is surrounded by 6 oxygen atoms in an octahedral configuration. The structure is such that some of the oxygen atoms are shared between aluminum atoms and some are shared with the tetrahedral sheet.

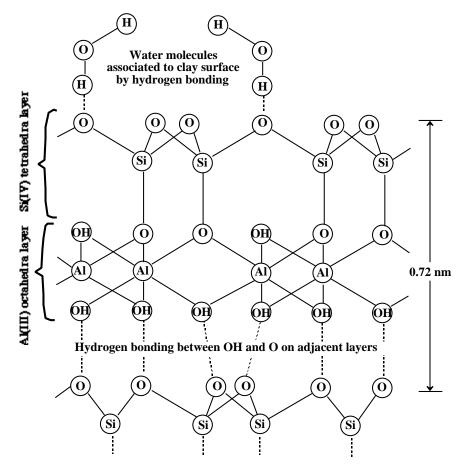


Figure 17.4 Representation of the structure of kaolinite, a two-layer clay.

Structurally, clays can be classified as either **two-layer clays** in which oxygen atoms are shared between a tetrahedral sheet and an adjacent octahedral sheet, and **three-layer clays** in which an octahedral sheet shares oxygen atoms with tetrahedral sheets on either side. These layers composed of either two or three sheets are called **unit layers**. A unit layer of a two-layer clay typically is around 0.7 nanometers (nm) thick, whereas that of a three-layer clay exceeds 0.9 nm in thickness. The structure of the two-layer clay kaolinite is represented in Figure 17.4. Some clays, particularly

the montmorillonites, may absorb large quantities of water between unit layers, a process accompanied by swelling of the clay.

Clay minerals may attain a net negative charge by **ion replacement**, in which Si(IV) and Al(III) ions are replaced by metal ions of similar size but lesser charge. Compensation must be made for this negative charge by association of cations with the clay layer surfaces. Since these cations need not fit specific sites in the crystalline lattice of the clay, they may be relatively large ions, such as K⁺, Na⁺, or NH₄⁺. These cations are called **exchangeable cations** and are exchangeable for other cations in water. The amount of exchangeable cations, expressed as milliequivalents (of monovalent cations) per 100 g of dry clay, is called the **cation-exchange capacity**, **CEC**, of the clay and is a very important characteristic of colloids and sediments that have cation-exchange capabilities.

17.6 GEOCHEMISTRY

Geochemistry deals with chemical species, reactions, and processes in the lithosphere and their interactions with the atmosphere and hydrosphere. Environmental geochemistry is the branch of geochemistry that explores the complex interactions among the rock/water/air/life systems that determine the chemical characteristics of the surface environment. Obviously, geochemistry and its environmental subdiscipline are very important areas of environmental chemistry with many applications related to the environment.

Physical Aspects of Weathering

Defined in Section 17.2, *weathering* is discussed here as a geochemical phenomenon. Rocks tend to weather more rapidly when there are pronounced differences in physical conditions—alternate freezing and thawing and wet periods alternating with severe drying. Other mechanical aspects are swelling and shrinking of minerals with hydration and dehydration, as well as growth of roots through cracks in rocks. Temperature is involved in that the rates of chemical weathering (below) increase with increasing temperature.

Chemical Weathering

As a chemical phenomenon, weathering can be viewed as the result of the tendency of the rock/water/mineral system to attain equilibrium. This occurs through the usual chemical mechanisms of dissolution/precipitation, acid-base reactions, complexation, hydrolysis, and oxidation-reduction.

Weathering occurs extremely slowly in dry air but is many orders of magnitude faster in the presence of water. Water, itself, is a chemically active weathering substance and it holds weathering agents in solution such that they are transported to chemically active sites on rock minerals and contact the mineral surfaces at the molecular and ionic level. Prominent among such weathering agents are CO_2 , O_2 , organic acids (including humic and fulvic acids, see Section 11.9), sulfur acids $(SO_2(aq), H_2SO_4)$, and nitrogen acids (HNO_3, HNO_2) . Water provides the source of H^+ ion needed for acid-forming gases to act as acids as shown by the following:

$$CO_2 + H_2O H^+ + HCO_3^-$$
 (17.6.1)

$$SO_2 + H_2O H^+ + HSO_3^-$$
 (17.6.2)

Rainwater is essentially free of mineral solutes. It is usually slightly acidic due to the presence of dissolved carbon dioxide or more highly acidic because of acid-rainforming constitutents. As a result of its slight acidity and lack of alkalinity and dissolved calcium salts, rainwater is *chemically aggressive* (see Section 13.7) toward some kinds of mineral matter, which it breaks down by chemical weathering processes. Because of this process, river water has a higher concentration of dissolved inorganic solids than does rainwater.

The processes involved in chemical weathering may be divided into the following major categories:

• **Hydration/dehydration**, for example:

$$CaSO_4(s) + 2H_2O$$
 $CaSO_4 \cdot 2H_2O(s)$
 $2Fe(OH)_3 \cdot xH_2O(s)$ $Fe_2O_3(s) + (3 + 2x)H_2O(s)$

• **Dissolution**, for example:

$$CaSO_4 \cdot 2H_2O(s)$$
 (water) $Ca^{2+}(aq) + SO_4^{2-}(aq) + 2H_2O$

• Oxidation, such as occurs in the dissolution of pyrite:

$$4\text{FeS}_{2}(s) + 15\text{O}_{2}(g) + (8 + 2x)\text{H}_{2}\text{O}$$
$$2\text{Fe}_{2}\text{O}_{3} \cdot x\text{H}_{2}\text{O} + 8\text{SO}_{4}^{2} \cdot (aq) + 16\text{H}^{+}(aq)$$

or in the following example in which dissolution of an iron(II) mineral is followed by oxidation of iron(II) to iron(III):

$$Fe_2SiO_4(s) + 4CO_2(aq) + 4H_2O 2Fe^{2+} + 4HCO_3^- + H_4SiO_4$$

 $4Fe^{2+} + 8HCO_3^- + O_2(g) 2Fe_2O_3(s) + 8CO_2 + 4H_2O$

The second of these two reactions may occur at some distance from the first, resulting in net transport of iron from its original location. Iron, manganese, and sulfur are the major elements that undergo oxidation as part of the weathering process.

• **Dissolution with hydrolysis** occurs with the hydrolysis of carbonate ion when mineral carbonates dissolve:

$$CaCO_{3}(s) + H_{2}O Ca^{2+}(aq) + HCO_{3}(aq) + OH(aq)$$

Hydrolysis is the major means by which silicates undergo weathering as shown by the following reaction of forsterite:

$$Mg_2SiO_4(s) + 4CO_2 + 4H_2O \qquad 2Mg^{2+} + 4HCO_3^- + H_4SiO_4$$

The weathering of silicates yields soluble silicon as species such as H₄SiO₄, and residual silicon-containing minerals (clay minerals).

• Acid hydrolysis, which accounts for the dissolution of significant amounts of CaCO₃ and CaCO₃•MgCO₃ in the presence CO₂-rich water:

$$CaCO_3(s) + H_2O + CO_2(aq)$$
 $Ca^{2+}(aq) + 2HCO_3(aq)$

• **Complexation**, as exemplified by the reaction of oxalate ion, C₂O₄²⁻ with aluminum in muscovite, K₂(Si₆Al₂)Al₄O₂₀(OH)₄:

$$K_2(Si_6Al_2)Al_4O_{20}(OH)_4(s) + 6C_2O_4^{2-}(aq) + 20 H^+$$

 $6AlC_2O_4^{+}(aq) + 6Si(OH)_4 + 2K^+$

Reactions such as these largely determine the kinds and concentrations of solutes in surface water and groundwater. Acid hydrolysis, especially, is the predominant process that releases elements such as Na⁺, K⁺, and Ca²⁺ from silicate minerals.

17.7 GROUNDWATER IN THE GEOSPHERE

Groundwater (Figure 17.5) is a vital resource in its own right that plays a crucial role in geochemical processes, such as the formation of secondary minerals. The nature, quality, and mobility of groundwater are all strongly dependent upon the rock formations in which the water is held. Physically, an important characteristic of such formations is their **porosity**, which determines the percentage of rock volume available to contain water. A second important physical characteristic is **permeability**, which describes the ease of flow of the water through the rock. High permeability is usually associated with high porosity. However, clays tend to have low permeability even when a large percentage of the volume is filled with water.

Most groundwater originates as **meteoric** water from precipitation in the form of rain or snow. If water from this source is not lost by evaporation, transpiration, or to stream runoff, it may infiltrate into the ground. Initial amounts of water from precipitation onto dry soil are held very tightly as a film on the surfaces and in the micropores of soil particles in a **belt of soil moisture**. At intermediate levels, the soil particles are covered with films of water, but air is still present in larger voids in the soil. The region in which such water is held is called the **unsaturated zone** or **zone of aeration** and the water present in it is **vadose water**. At lower depths in the presence of adequate amounts of water, all voids are filled to produce a **zone of saturation**, the upper level of which is the **water table**. Water present in a zone of saturation is called **groundwater**. Because of its surface tension, water is drawn somewhat above the water table by capillary-sized passages in soil in a region called the capillary fringe.

The water table (Figure 17.6) is crucial in explaining and predicting the flow of wells and springs and the levels of streams and lakes. It is also an important factor in determining the extent to which pollutant and hazardous chemicals underground are

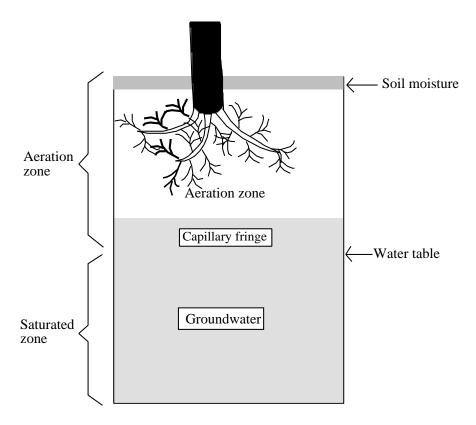


Figure 17.5 Some major features of the distribution of water underground.

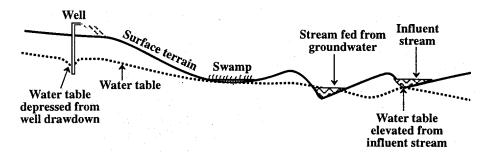


Figure 17.6 The water table and influences of surface features on it.

likely to be transported by water. The water table can be mapped by observing the equilibrium level of water in wells, which is essentially the same as the top of the saturated zone. The water table is usually not level, but tends to follow the general contours of the surface topography. It also varies with differences in permeability and water infiltration. The water table is at surface level in the vicinity of swamps and frequently above the surface where lakes and streams are encountered. The water level in such bodies may be maintained by the water table. **Influent** streams or reservoirs are located above the water table; they lose water to the underlying aquifer and cause an upward bulge in the water table beneath the surface water.

Groundwater **flow** is an important consideration in determining the accessibility of the water for use and transport of pollutants from underground waste sites. Various parts of a body of groundwater are in hydraulic contact so that a change in pressure at one point will tend to affect the pressure and level at another point. For example, infiltration from a heavy localized rainfall may affect the water table at a point remote from the infiltration. Groundwater flow occurs as the result of the natural tendency of the water table to assume even levels by the action of gravity.

Groundwater flow is strongly influenced by rock permeability. Porous or extensively fractured rock is relatively highly **pervious**, meaning that water can migrate through the holes, fissures, and pores in such rock. Because water can be extracted from such a formation, it is called an **aquifer**. By contrast, an **aquiclude** is a rock formation that is too impermeable or unfractured to yield groundwater. Impervious rock in the unsaturated zone may retain water infiltrating from the surface to produce a **perched water table** that is above the main water table and from which water may be extracted. However, the amounts of water that can be extracted from such a formation are limited and the water is vulnerable to contamination.

Water Wells

Most groundwater is tapped for use by water wells drilled into the saturated zone. The use and misuse of water from this source has a number of environmental implications. In the U.S., about 2/3 of the groundwater pumped is consumed for irrigation; lesser amounts of groundwater are used for industrial and municipal applications.

As water is withdrawn, the water table in the vicinity of the well is lowered. This **drawdown** of water creates a **zone of depression**. In extreme cases the groundwater is severely depleted and surface land levels can even subside (which is one reason that Venice, Italy is now very vulnerable to flooding). Heavy drawdown can result in infiltration of pollutants from sources such as septic tanks, municipal refuse sites, and hazardous-waste dumps. When soluble iron(II) or manganese(II) are present in groundwater, exposure to air at the well wall can result in the formation of deposits of insoluble iron(III) and manganese(IV) oxides produced by bacterially catalyzed processes:

$$4\text{Fe}^{2+}(aq) + \text{O}_2(aq) + 10\text{H}_2\text{O} \qquad 4\text{Fe}(\text{OH})_3(s) + 8\text{H}^+$$
 (17.7.1)

$$2\text{Mn}^{2+}(aq) + \text{O}_2(aq) + (2x+2)\text{H}_2\text{O} \qquad 2\text{MnO}_2 \cdot x\text{H}_2\text{O}(s) + 4\text{H}^+$$
 (17.7.2)

Deposits of iron(III) and manganese(IV) that result from the processes outlined above line the surfaces from which water flows into the well with a coating that is relatively impermeable to water. The deposits fill the spaces that water must traverse to enter the well. As a result, they can seriously impede the flow of water into the well from the water-bearing aquifer. This creates major water source problems for municipalities using groundwater for water supply. As a result of this problem, chemical or mechanical cleaning, drilling of new wells, or even acquisition of new water sources may be required.

17.8 ENVIRONMENTAL ASPECTS OF THE GEOSPHERE

Most of the remainder of this chapter deals specifically with the environmental aspects of geology and human interactions with the geosphere. The following sections discuss how natural geological phenomena affect the environment through occurrences such as volcanic eruptions that might blast so much particulate matter and acid gas into the atmosphere that it could have a temporary effect on global climate, or massive earthquakes that disrupt surface topography and disturb the flow and distribution of groundwater and surface water. Also discussed are human influences on the geosphere and the strong connection between the geosphere and the anthrosphere.

Going back several billion years to its formation as a ball of dust particles collected from the universe and held together by gravitational forces, earth has witnessed constant environmental change and disruption. During its earlier eons, earth was a most inhospitable place for humans and, indeed, for any form of life. Heat generated by gravitational compression of primitive earth and by radioactive elements in its interior caused much of the mass of the planet to liquify. Relatively high-density iron sank into the core, and lighter minerals, primarily silicates, solidified and floated to the surface.

Although Earth changes almost imperceptibly during a human lifetime, the planet is in fact in a state of constant change and turmoil. It is known that continents have formed, broken apart, and moved around. Rock formations produced in ancient oceans have been thrust up onto continental land and huge masses of volcanic rock exist where volcanic activity is now unknown and has been absent for millions of years. Earth still unleashes enormous forces that push molten rock to the surface and move continents continuously as evidenced from volcanic activity, and from earth-quakes resulting from the movement of great land masses relative to each other. Earth's surface is constantly changing as new mountain ranges are heaved up and old ones are worn down.

Humans have learned to work with, against, and around natural earth processes and phenomena to exploit earth's resources and to make these processes and phenomena work for the benefit of humankind. Human efforts have been moderately successful in mitigating some of the major hazards posed by natural geospheric phenomena, although such endeavors often have had unforeseen detrimental consequences that sometimes are not manifested until many years after they were first applied. The survival of modern civilization and, indeed, of humankind will depend upon how intelligently humans work with the earth, rather than against it. That is why it is so important for humans to have a fundamental understanding of the geospheric environment.

An important consideration in human interaction with the geosphere is the application of engineering to geology. Engineering geology takes account of the geological characteristics of soil and rock in designing buildings, dams, highways, and other structures in a manner compatible with the geological strata on which they rest. Engineering geology must consider a large number of geological factors including type, strength, and fracture characteristics of rock, tendency for landslides to occur, susceptibility to settling, and likelihood of erosion. Engineering geology is an important consideration in land-use planning.

Natural Hazards

Earth presents a variety of natural hazards to the creatures that dwell on it. Some of these are the result of internal processes that arise from the movement of land masses relative to each other and from heat and intrusions of molten rock from below the surface. The most common such hazards are earthquakes and volcanoes. Whereas internal processes tend to force matter upward, often with detrimental effects, surface processes are those that generally result from the tendency of matter to seek lower levels. Such processes include erosion, landslides, avalanches, mudflows, and subsidence.

A number of natural hazards result from the interaction and conflict between solid Earth and liquid and solid water. Perhaps the most obvious such hazard consists of floods when too much water falls as precipitation and seeks lower levels through streamflow. Wind can team with water to increase destructive effects, such as beach erosion and destruction of beachfront property resulting from wind-driven seawater. Ice, too, can have some major effects on solid earth. Evidence of such effects from Ice Age times include massive glacial moraines left over from deposition of till from melting glaciers, and landscape features carved by advancing ice sheets.

Anthropogenic Hazards

All too often, attempts to control and reshape the geosphere to human demands have been detrimental to the geosphere and dangerous to human life and well-being. Such attempts may exacerbate damaging natural phenomena. A prime example of this interaction occurs when efforts are made to control the flow of rivers by straightening them and building levees. The initial results can be deceptively favorable in that a modified stream may exist for decades, flowing smoothly and staying within the confines imposed by humans. But eventually, the forces of nature are likely to overwhelm the efforts of humans to control them, such as when a record flood breaks levees and destroys structures constructed in flood-prone areas. Landslides of mounds of earthen material piled up from mining can be very destructive. Destruction of wetlands in an effort to provide additional farmland can have some detrimental effects upon wildlife and upon the overall health of ecosystems.

17.9 EARTHQUAKES

Earthquakes usually arise from plate tectonic processes and originate along plate boundaries occurring as motion of ground resulting from the release of energy that accompanies an abrupt slippage of rock formations subjected to stress along a fault. Basically, two huge masses of rock tend to move relative to each other, but are locked together along a fault line. This causes deformation of the rock formations, which increases with increasing stress. Eventually, the friction between the two moving bodies is insufficient to keep them locked in place, and movement occurs along an existing fault, or a new fault is formed. Freed from constraints on their movement, the rocks undergo elastic rebound, causing the earth to shake, often with catastrophic effects.

The location of the initial movement along a fault that causes an earthquake to occur is called the **focus** of the earthquake. The surface location directly above the focus is the **epicenter**. Energy is transmitted from the focus by **seismic waves**. Seismic waves that travel through the interior of the earth are called **body waves** and those that traverse the surface are **surface waves**. Body waves are further categorized as **P-waves**, compressional vibrations that result from the alternate compression and expansion of geospheric material, and **S-waves**, consisting of shear waves manifested by sideways oscillations of material. The motions of these waves are detected by a **seismograph**, often at great distances from the epicenter. The two types of waves move at different rates, with P-waves moving faster. From the arrival times of the two kinds of waves at different seismographic locations, it is possible to locate the epicenter of an earthquake.

Adding to the terror of earthquakes is their lack of predictability. An earthquake can strike at any time—during the calm of late night hours or in the middle of busy rush hour traffic. Although the exact prediction of earthquakes has so far eluded investigators, the locations where earthquakes are most likely to occur are much better known. These are located in lines corresponding to boundaries along which tectonic plates collide and move relative to each other, building up stresses that are suddenly released when earthquakes occur. Such interplate boundaries are locations of preexisting faults and breaks. Occasionally, however, an earthquake will occur within a plate, made more massive and destructive because when it occurs the thick lithosphere is ruptured.

The scale of earthquakes can be estimated by the degree of motion that they cause and by their destructiveness. The former is termed the **magnitude** of an earthquake and is commonly expressed by the **Richter scale**. The Richter scale is open-ended, and each unit increase in the scale reflects a 10-fold increase in magnitude. Several hundred thousand earthquakes with magnitudes from 2 to 3 occur each year; they are detected by seismographs, but are not felt by humans. Minor earthquakes range from 4 to 5 on the Richter scale, and earthquakes cause damage at a magnitude greater than about 5. Great earthquakes, which occur about once or twice a year, register over 8 on the Richter scale.

The **intensity** of an earthquake is a subjective estimate of its potential destructive effect. On the Mercalli intensity scale, an intensity III earthquake feels like the passage of heavy vehicles; one with an intensity of VII causes difficulty in standing, damage to plaster, and dislodging of loose brick, whereas a quake with an intensity of XII causes virtually total destruction, throws objects upward, and shifts huge masses of earthen material. Intensity does not correlate exactly with magnitude.

Distance from the epicenter, the nature of underlying strata, and the types of structures affected may all result in variations in intensity from the same earthquake. In general, structures built on bedrock will survive with much less damage than those constructed on poorly consolidated material. Displacement of ground along a fault can be substantial, for example, up to 6 or 7 meters along the San Andreas fault during the 1906 San Francisco earthquake. Such shifts can break pipelines and destroy roadways. Highly destructive surface waves can shake vulnerable structures apart.

The shaking and movement of ground are the most obvious means by which earthquakes cause damage. In addition to shaking the ground, earthquakes can cause

it to rupture, subside, or rise. **Liquefaction** is an important phenomenon that occurs during earthquakes with ground that is poorly consolidated and in which the water table may be high. Liquefaction results from separation of soil particles accompanied by water infiltration such that the ground behaves like a fluid.

Another devastating phenomenon consists of **tsunamis**, large ocean waves resulting from earthquake-induced movement of the ocean floor. Tsunamis sweeping onshore at speeds up to 1000 km/hr have destroyed many homes and taken many lives, often large distances from the epicenter of the earthquake itself. This effect occurs when a tsunami approaches land and forms huge breakers, some as high as 10–15 meters, or even higher. On April 1, 1946, an earthquake off the coast of Alaska generated a Tsunami estimated to be more than 30 meters high that killed 5 people in a nearby lighthouse. About 5 hours later, a Tsunami generated by the same earthquake reached Hilo, Hawaii, and killed 159 people with a wave exceeding 15 meters high. The March 27, 1964, Alaska earthquake generated a tsunami over 10 meters high that hit a freighter docked at Valdez, tossing it around like matchwood. Miraculously, nobody on the freighter was killed, but 28 people on the dock died.

Literally millions of lives have been lost in past earthquakes, and damage from an earthquake in a developed urban area can easily run into billions of dollars. As examples, a massive earthquake in Egypt and Syria in 1201 A.D. took over 1 million lives, one in Tangshan, China, in 1976 killed about 650,000, and the 1989 Loma Prieta earthquake in California cost about 7 billion dollars. Numerous lives were lost in earthquakes that took place in Turkey, Greece, and Taiwan in 1999.

Significant progress has been made in designing structures that are earthquake-resistant. As evidence of that, during a 1964 earthquake in Niigata, Japan, some buildings tipped over on their sides due to liquefaction of the underlying soil, but remained structurally intact! Other areas of endeavor that can lessen the impact of earthquakes is the identification of areas susceptible to earthquakes, discouraging development in such areas, and educating the public about earthquake hazards. Accurate prediction would be a tremendous help in lessening the effects of earthquakes, but so far has been generally unsuccessful. Most challenging of all is the possibility of preventing major earthquakes. One unlikely possibility would be to detonate nuclear explosives deep underground along a fault line to release stress before it builds up to an excessive level. Fluid injection to facilitate slippage along a fault has also been considered.

17.10 VOLCANOES

Volcanoes

In addition to earthquakes, the other major subsurface process that has the potential to massively affect the environment consists of emissions of molten rock (lava), gases, steam, ash, and particles due to the presence of magma near the earth's surface. This phenomenon is called a **volcano** (Figure 17.7). Volcanoes can be very destructive and damaging to the environment.

Volcanoes take on a variety of forms that are beyond the scope of this chapter to cover in detail. Basically, they are formed when magma rises to the surface. This frequently occurs in subduction zones created where one plate is pushed beneath

another (see Figure 17.2). The downward movement of solid lithospheric material subjects it to high temperatures and pressures that cause the rock in it to melt and rise to the surface as magma. Molten magma issuing from a volcano at temperatures usually in excess of 500°C, and often as high as 1,400°C, is called **lava**, and is one of the more common manifestations of volcanic activity.

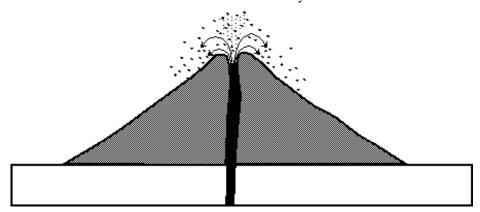


Figure 17.7 Volcanoes come in many shapes and forms. A classically shaped volcano may be a cinder cone formed by ejection of rock and lava, called pyroclastics, from the volcano to produce a relatively uniform cone.

On May 18, 1980, Mount St. Helens, a volcano in Washington State, erupted, blowing out about 1 cubic kilometer of material. This massive blast spread ash over half the United States, causing about \$1 billion in damages and killing an estimated 62 people, many of whom were never found. Many volcanic disasters have been recorded throughout history. Perhaps the best known of these is the 79 A.D. eruption of Mount Vesuvius, which buried the Roman city of Pompei with volcanic ash.

Temperatures of **lava**, molten rock flowing from a volcano, typically exceed 500°C and may get as high as 1400°C or more. Lava flows destroy everything in their paths, causing buildings and forests to burn and burying them under rock that cools and becomes solid. Often more dangerous than a lava flow are the **pyroclastics** produced by volcanoes and consisting of fragments of rock and lava. Some of these particles are large and potentially very damaging, but they tend to fall quite close to the vent. Ash and dust may be carried for large distances and, in extreme cases, as was the case in ancient Pompei, may bury large areas to some depth with devastating effects. The explosion of Tambora volcano in Indonesia in 1815 blew out about 30 cubic kilometers of solid material. The ejection of so much solid into the atmosphere had such a devastating effect on global climate that the following year was known as "the year without a summer," causing widespread hardship and hunger because of global crop failures.

A special kind of particularly dangerous pyroclastic consists of **nuée ardente**. This term, French for "glowing cloud," refers to a dense mixture of hot toxic gases and fine ash particles reaching temperatures of 1000°C that can flow down the slopes of a volcano at speeds of up to 100 km/hr. In 1902 a nuée ardente was produced by the eruption of Mont Pelée on Martinique in the Caribbean. Of as many as 40,000 people in the town of St. Pierre, the only survivor was a terrified prisoner shielded from the intense heat by the dungeon in which he was imprisoned.

One of the more spectacular and potentially damaging volcanic phenomena is a **phreatic eruption** which occurs when infiltrating water is superheated by hot magma and causes a volcano to literally explode. This happened in 1883 when uninhabited Krakatoa in Indonesia blew up with an energy release of the order of 100 megatons of TNT. Dust was blown 80 kilometers into the stratosphere, and a perceptible climatic cooling was noted for the next 10 years. As is the case with earthquakes, volcanic eruptions may cause devastating tsunamis. Krakatoa produced a tsunami 40 meters high that killed 30 to 40 thousand people on surrounding islands.

Some of the most damaging health and environmental effects of volcanic eruptions are caused by gases released to the atmosphere. Huge quantities of water vapor are often evolved. Dense carbon dioxide gas can suffocate people near the point of release. Highly toxic H₂S and CO gases may be released by volcanoes. Volcanoes tend to give off acid gases such as hydrogen chloride produced by the subduction and heating of sodium chloride entrained in ocean sediment. Sulfur oxides released by volcanoes may affect the atmosphere. In 1982 El Chichón erupted in Mexico, producing comparatively little dust but huge quantities of sulfur oxides. These gases were converted to sulfuric acid droplets in the atmosphere, which reflected enough sunlight to cause a perceptible cooling in climate. Eventually the sulfuric acid released fell as acidic precipitation, "acid rain."

Volcanic activity could change the global environment dramatically. Massive volcanic eruptions many millions of years ago were probably responsible for widespread extinctions of organisms on earth's surface. These effects occur primarily by the ejection of particles and sulfuric acid precursors into the atmosphere causing global cooling and potential harm to the protective stratospheric ozone layer. Although such an extinction event is unlikely in modern times, a volcanic eruption such as that of the Tambora volcano described above could certainly happen. With humankind "living on the edge" as far as grain supplies are concerned, widespread starvation resulting from a year or two of crop failures would almost certainly occur.

17.11 SURFACE EARTH MOVEMENT

Surface geological features are formed by upward movement of materials from earth's crust. With exposure to water, oxygen, freeze-thaw cycles, organisms, and other influences on the surface, surface features are subject to two processes that largely determine the landscape—weathering and erosion. As noted earlier in this chapter, weathering consists of the physical and chemical breakdown of rock, and erosion is the removal and movement of weathered products by the action of wind, liquid water, and ice. Weathering and erosion work together in that one augments the other in breaking down rock and moving the products. Weathered products removed by erosion are eventually deposited as sediments and may undergo diagenesis and lithification to form sedimentary rocks.

One of the most common surface processes that can adversely affect humans consists of **landslides** that occur when soil or other unconsolidated materials slide down a slope. Related phenomena include rockfalls, mudflows, and snow avalanches. As shown in Figure 17.8, a landslide typically consists of an upper slump that is prevented from sliding farther by a mass of material accumulated in a lower

flow. Figure 17.8 illustrates what commonly happens in a landslide when a mass of earth moves along a slip plane under the influence of gravity. The stability of earthen material on a slope depends upon a balance between the mass of slope material and the resisting force of the shear strength of the slope material. There is a tendency for the earth to move along slip planes. In addition to the earthen material itself, water, vegetation, and structures constructed by humans may increase the driving force leading to a landslide. The shear strength is, of course, a function of the geological material along the slip plane and may be affected by other factors as well, such as the presence of various levels of water and the degree and kinds of vegetation growing on the surface.

The tendency of landslides to form is influenced by a number of outside factors. Climate is important because it influences the accumulation of water that often precedes a landslide as well as the presence of plants that can also influence soil stability. Although it would seem that plant roots should stabilize soil, the ability of some plants to add significant mass to the slope by accumulating water and to destabilize soil by aiding water infiltration may have an opposite effect, making soil on a slope much more susceptible to landslides. Disturbance of earth by road building or other construction may cause landslides to occur. Earth may be shaken loose by earthquakes, causing landslides to occur.

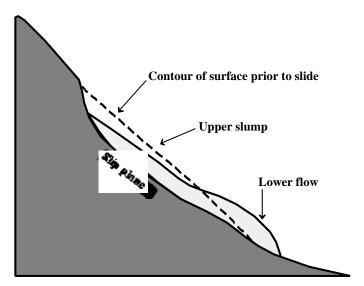


Figure 17.8 A landslide occurs when earth moves along a slip plane. Typically, a landslide consists of an upper slump and lower flow. The latter serves to stabilize the slide, and when it is disturbed, such as by cutting through it to construct a road, the earth may slide farther.

Loss of life and property from landslides can be substantial. In 1970, a devastating avalanche of soil, mud, and rocks initiated by an earthquake slid down Mt. Huascaran in Peru killing an estimated 20,000 people. Sometimes the effects are indirect. In 1963 as many as 2600 people were killed near the Vaiont Dam in Italy. A sudden landslide filled the reservoir behind the dam with earthen material and, although the dam held, the displaced water spilled over its abutments as a wave 90 meters high, wiping out structures and lives in its path.

Although often ignored by developers, the tendency toward landslides is predictable. Knowledge of the tendency for landslides to occur can be used to determine areas in which homes and other structures should not be built. Slope stability maps based upon the degree of slope, the nature of underlying geological strata, climatic conditions, and other factors can be used to assess the risk of landslides. Evidence of a tendency for land to slide can be observed from effects on existing structures, such as walls that have lost their alignment, cracks in foundations, and poles that tilt. The likelihood of landslides can be minimized by moving material from the upper to the lower part of a slope, avoiding the loading of slopes, and avoiding measures that might change the degree and pathways of water infiltration into slope materials. In cases where the risk is not too severe, retaining walls can be constructed to reduce the effects of landslides.

Several measures can be used to warn of landslides. Simple visual observations of changes in the surface can be indicative of an impending landslide. More sophisticated measures include tilt meters and devices that sense vibrations accompanying the movement of earthen materials.

In addition to landslides, there are several other kinds of mass movements that have the potential to be damaging. **Rockfalls** occur when rocks fall down slopes so steep that at least part of the time the falling material is not in contact with the ground. The fallen material accumulates at the bottom of the fall as a pile of **talus**. A much less spectacular event is **creep**, in which movement is slow and gradual. The action of frost—frost heaving—is a common form of creep. Though usually not life-threatening, over a period of time creep may ruin foundations and cause misalignment of roads and railroads with significant, often very costly, property damage frequently the result.

Special problems are presented by permanently frozen ground in arctic climates such as Alaska or Siberia. In such areas the ground may remain permanently frozen, thawing to only a shallow depth during the summer. This condition is called **permafrost**. Permafrost poses particular problems for construction, particularly where the presence of a structure may result in thawing such that the structure rests in a pool of water-saturated muck resting on a slick surface of frozen water and soil. The construction and maintenance of highways, railroads, and pipelines, such as the Trans-Alaska pipeline in Alaska, can become quite difficult in the presence of permafrost.

Some types of soils, particularly so-called expansive clays, expand and shrink markedly as they become saturated with water and dry out. Although essentially never life-threatening, the movement of structures and the damage caused to them by expansive clays can be very high. Aside from years when catastrophic floods and earthquakes occur, the monetary damage done by the action of expansive soil exceeds that of earthquakes, landslides, floods, and coastal erosion combined.

Sinkholes are a kind of earth movement resulting when surface earth falls into an underground cavity. They rarely injure people but occasionally causes spectacular property damage. Cavities that produce sinkholes may form by the action of water containing dissolved carbon dioxide on limestone (See Chapter 11, Reaction 11.7.6); loss of underground water during drought or from heavy pumping, thus removing support that previously kept soil and rock from collapsing; heavy underground water flow; and other factors that remove solid material from underground strata.

17.12 STREAM AND RIVER PHENOMENA

A **stream** consists of water flowing through a channel. The area of land from which water that flows into a stream is drawn is the stream's **drainage basin**. The sizes of streams are described by **discharge** defined as the volume of water flowing past a given point on the stream per unit time. Discharge and **gradient**, the steepness of the downward slope of a stream determine the stream **velocity**.

Internal processes raise masses of land and whole mountain ranges, which in turn are shaped by the action of streams. Streams cut down mountain ranges, create valleys, form plains, and produce great deposits of sediment, thus playing a key role in shaping the geospheric environment. Streams spontaneously develop bends and curves by cutting away the outer parts of stream banks and depositing materials on the inner parts. These curved features of streams are known as **meanders**. Left undisturbed, a stream forms meanders across a valley in a constantly changing pattern. The cutting away of material by the stream and the deposition of sediment eventually forms a generally flat area. During times of high stream flow, the stream leaves its banks, inundating parts or all of the valley. The accompanying erosion and deposition of matter creates a **floodplain**.

A **flood** occurs when a stream develops a high flow such that it leaves its banks and spills out onto the floodplain. Floods are arguably the most common and damaging of surface phenomena in the geosphere. Though natural and in many respects beneficial occurrences, floods cause damage to structures located in their paths, and the severity of their effects is greatly increased by human activities.

A number of factors determine the occurrence and severity of floods. One of these is the tendency of particular geographic areas to receive large amounts of rain within short periods of time. One such area is located in the middle of the continental United States, where warm, moisture-laden air from the Gulf of Mexico is carried northward during the spring months to collide with cold air from the north; the resultant cooling of the moist air can cause torrential rains to occur, resulting in severe flooding. In addition to season and geography, geological conditions have a strong effect on flooding potential. Rain falling on a steep surface tends to run off rapidly, creating flooding. A watershed can contain relatively massive quantities of rain if it consists of porous, permeable materials that allow a substantial rate of infiltration, assuming that it is not already saturated. Plants in a watershed tend to slow runoff and loosen soil, enabling additional infiltration. Through transpiration (see Chapter 18, Section 18.2), plants release moisture to the atmosphere quickly, enabling soil to absorb more moisture.

Several terms are used to describe flooding. When the **stage** of a stream, that is, the elevation of the water surface, exceeds the stream bank level, the stream is said to be at **flood stage**. The highest stage attained defines the flood **crest**. **Upstream** floods occur close to the inflow from the drainage basin, usually the result of intense rainfall. Whereas upstream floods usually affect smaller streams and watersheds, **downstream floods** occur on larger rivers that drain large areas. Widespread spring snowmelt and heavy, prolonged spring rains, often occurring together, cause downstream floods.

Floods are made more intense by higher fractions and higher rates of runoff,

both of which may be aggravated by human activities. This can be understood by comparing a vegetated drainage basin to one that has been largely denuded of vegetation and paved over. In the former case, rainfall is retained by vegetation, such as grass cover. Thus, the potential flood water is delayed, the time span over which it enters a stream is extended, and a higher proportion of the water infiltrates into the ground. In the latter case, less rainfall infiltrates, and the runoff tends to reach the stream quickly and to be discharged over a shorter time period, thus leading to more-severe flooding. These factors are illustrated in Figure 17.9.

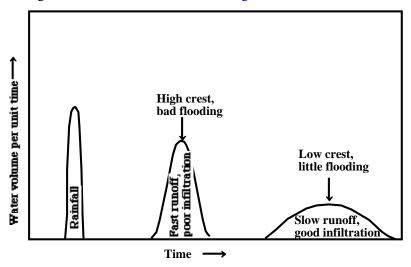


Figure 17.9 Influence of runoff on flooding.

The conventional response to the threat of flooding is to control a river, particularly by the construction of raised banks called levees. In addition to raising the banks to contain a stream, the stream channel may be straightened and deepened to increase the volume and velocity of water flow, a process called channelization. Although effective for common floods, these measures may exacerbate extreme floods by confining and increasing the flow of water upstream such that the capacity to handle water downstream is overwhelmed. Another solution is to construct dams to create reservoirs for flood control upstream. Usually, such reservoirs are multipurpose facilities designed for water supply, recreation, and to control river flow for navigation in addition to flood control. The many reservoirs constructed for flood control in recent decades have been reasonably successful. There are, however, conflicts in the goals for their uses. Ideally, a reservoir for flood control should remain largely empty until needed to contain a large volume of floodwater, an approach that is obviously inconsistent with other uses. Another concern is that of exceeding the capacity of the reservoir, or dam failure, the latter of which can lead to catastrophic flooding.

17.13 PHENOMENA AT THE LAND-OCEAN INTERFACE

The coastal interface between land masses and the ocean is an important area of environmental activity. The land along this boundary is under constant attack from the waves and currents from the ocean, so that most coastal areas are always changing. The most common structure of the coast is shown in cross section in Figure 17.10. The beach, consisting of sediment, such as sand formed by wave action on coastal rock, is a sloping area that is periodically inundated by ocean waves. Extending from approximately the high tide mark to the dunes lining the landward edge of the beach is a relatively level area called the **berm**, which is usually not washed over by ocean water. The level of water to which the beach is subjected varies with the tides. Through wind action, the surface of the water is in constant motion as undulations called **ocean waves**. As these waves reach the shallow water along the beach, they "touch bottom" and are transformed to **breakers**, characterized by crested tops. These breakers crashing onto a beach give it much of its charm, but can also be extremely destructive.

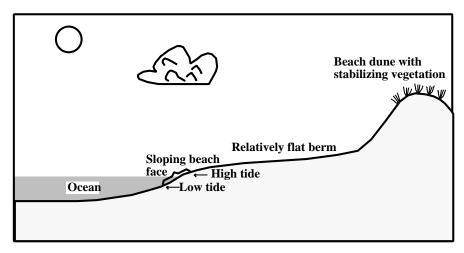


Figure 17.10 Cross section of the ocean/land interface along a beach.

Coastlines exhibit a variety of features. Steep valleys carved by glacial activity, then filled with rising seawater, constitute the picturesque fjords characteristic of much of the coast of Norway. Valleys, formerly on land, now filled with seawater, constitute **drowned valleys**. **Estuaries** occur where tidal salt water mixes with inflowing fresh water.

Erosion is a constant feature of a beachfront. Unconsolidated beach sand can be shifted readily, sometimes spectacularly through great distances over short periods of time, by wave action. Sand, pebbles, and rock in the form of rounded cobbles constantly wear against the coast by wave action, exerting a constant abrasive action called **milling**. This action is augmented by the chemical weathering effects of seawater, in which the salt content may play a role.

Some of the more striking alterations to coastlines occur during storms such as hurricanes and typhoons. The low pressure that accompanies severe storms tends to suck ocean water upward. This effect, usually combined with strong winds blowing onshore and coinciding with high tide, can cause ocean water to wash over the berm on a beach to attack dunes or cliffs inland. Such a **storm surge** can remove large quantities of beach, damage dune areas, and wash away structures unwisely constructed too close to the shore. A storm surge associated with a hurricane washed

away most of the structures in Galveston, Texas, in 1900, claiming 6000 lives.

An especially vulnerable part of the coast consists of barrier islands, long, low strips of land roughly paralleling the coast some distance offshore. High storm surges may wash completely over barrier islands, partially destroying them and shifting them around. Many dwellings unwisely constructed on barrier islands, such as the outer banks of North Carolina, have been destroyed by storm surges during hurricanes.

The Threat of Rising Sea Levels

Any significant temporary or permanent rise in sea level poses significant risks to lives and property of large numbers of people who live at, or in some cases even below, sea level. Such an event occurred on February 1, 1953, in the Netherlands. This event occurred when high tides and strong winds combined to breach the system of dikes protecting much of the Netherlands from seawater. About 1/6 of the country was flooded as far inland as 64 kilometers from the coast. A total of approximately 2000 people were killed by the severe flooding and approximately 100,000 people were left without homes.

Although isolated instances of flooding by seawater caused by combinations of tidal and weather phenomena will continue to occur, a much more long-lasting threat, and one not nearly so amenable to remediation measures, such as dike construction, is posed by long-term increases in sea level. These could result from global warming due to the greenhouse gas emissions discussed in Chapter 15. Several phenomena associated with global warming have the potential to raise ocean levels to destructive highs. Simple expansion of warmed oceanic water could raise sea levels by about 1/3 meter over the next century. The melting of glaciers, such as those in the Alps, has probably raised ocean levels about 5 cm during the last century, and the process is continuing. The greatest concern, however, is that global warming could cause the great West Antarctic ice sheet to melt, which would raise sea levels by as much as 6 meters.

Much uncertainty exists regarding the possibility of the West Antarctic ice sheet's melting and causing increases in sea level. There should be some compensating effect in that hotter air produced by greenhouse warming could carry much more atmospheric moisture to the Antarctic regions where the moisture would be deposited as snow. The net result could well be an increase in solid snow and ice in the Antarctic, and an accompanying decrease in sea levels. Some of the uncertainty regarding the status of the West Antarctic ice sheet may be alleviated in the future by highly accurate space satellite measurements. The measurement of sea levels has proven to be a difficult task because the levels of the surface of land keep changing. Land most recently covered with Ice Age glaciers in areas such as Scandinavia is still "springing back" from the immense mass of the glaciers, so that sea levels measured by gauges fixed on land actually appear to be dropping by several millimeters per year in such locations. An opposite situation exists on the east coast of North America, where land was pushed outward and raised around the edge of the enormous sheet of ice that covered Canada and the northern U.S. about 20,000 years ago and is now settling back. Factors such as these illustrate the advantages of remarkably accurate satellite technology now used in the determination of sea levels.

17.14 PHENOMENA AT THE LAND-ATMOSPHERE INTERFACE

The interface between the atmosphere and land is a boundary of intense environmental activity. The combined effects of air and water tend to cause significant changes to the land materials at this interface. The top layer of exposed land is especially susceptible to physical and chemical weathering. Here, air laden with oxidant oxygen contacts rock, originally formed under reducing conditions, causing oxidation reactions to occur. Acid naturally present in rainwater as dissolved CO₂ or as pollutant sulfuric, sulfurous, nitric, or hydrochloric acid, can dissolve portions of some kinds of rocks. Organisms such as lichens, which consist of fungi and algae growing symbiotically on rock surfaces, drawing carbon dioxide, oxygen, or nitrogen from air, can grow on rock surfaces at the boundary of the atmosphere and geosphere, causing additional weathering to take place.

One of the most significant agents affecting exposed geospheric solids at the atmosphere/geosphere boundary is wind. Wind both erodes solids and acts as an agent to deposit solids on geospheric surfaces. The influence of wind is especially pronounced in dry areas. A major factor in wind erosion is wind **abrasions** in which solid particles of sand and rock carried by wind tend to wear away exposed rock and soil. Loose, unconsolidated sand and soil may be removed in large volumes by wind, a process called **deflation**.

The potential for wind to move matter is illustrated by the formation of large deposits of **loess**, consisting of finely divided soil carried by wind. Loess particles are typically several tens of micrometers in size, small enough to be carried great distances by wind. Especially common are loess deposits that originated with matter composed of rock ground to a fine flour by Ice Age glaciers. This material was first deposited in river valleys by flood waters issuing from melting glaciers, then blown some distance from the rivers by strong winds after drying out.

One of the more common geospheric features created by wind is a **dune**, consisting of a mound of debris, usually sand, dropped when wind slows down. As a dune builds, it forms an obstruction that slows wind even more, so that more sediment is dropped and, in the presence of sediment-laden wind, dunes several meters or more high may form rapidly. In forming a dune, heavier, coarser particles settle first so that the matter in dunes is sorted according to size, just like sediments deposited by flowing streams. In areas in which winds are prevalently from one direction, as is usually the case, dunes show a typical shape, as illustrated in Figure 17.11. It is seen that the steeply sloping side, called the **slip face**, is downwind.

Some of the environmental effects of dunes result from their tendency to migrate with the prevailing winds. Migration occurs as matter is blown by the wind up the gently sloping face of the dune and falls down the slip face. Migrating sand dunes have buried forest trees, and dust dunes in drought-stricken agricultural areas have filled road ditches, causing severely increased maintenance costs.

17.15 EFFECTS OF ICE

The power of ice to alter the geosphere is amply demonstrated by the remains of past glacial activity from the Ice Age. Those large areas of the earth's surface that

were once covered with layers of glacial ice 1 or 2 kilometers in thickness show evidence of how the ice carved the surface, left massive piles of rock and gravel, and rich deposits of fresh water. The enormous weight of glaciers on earth's surface compressed it, and in places it is still springing back 10,000 or so years after the glaciers retreated. Today, the influence of ice on earth's surface is minimal, and there

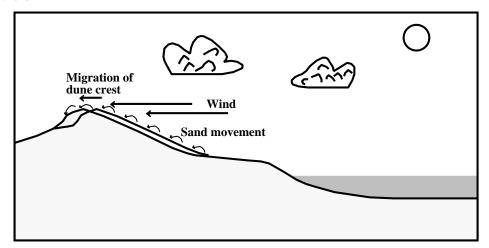


Figure 17.11 Shape and migration of a dune as determined by prevailing wind direction.

is substantial concern that melting of glaciers by greenhouse warming will raise sea levels so high that coastal areas will be inundated.

Glaciers form at sufficiently high latitudes and altitudes such that snow does not melt completely each summer. This occurs when snow becomes compacted over several to several thousand years such that the frozen water turns to crystals of true ice. Huge masses of ice with areas of several thousand square kilometers or more, and often around 1 kilometer thick, occur in polar regions and are called **continental glaciers**. Both Greenland and the Antarctic are covered by continental glaciers. **Alpine glaciers** occupy mountain valleys.

Heavy glaciers flow on a slope. This rate of flow is usually only a few meters per year, but may reach several kilometers per year. If a glacier flows into the sea, it may lose masses of ice as icebergs, a process called **calving**. Ice may also be lost by melting along the edges. The processes by which ice is lost are termed **ablation**.

Glacial ice affects the surface of the geosphere by both erosion and deposition. It is easy to imagine that a flowing mass of glacial ice is very efficient in scraping away the surface over which it flows, a process called **abrasion**. Adding to the erosive effect is the presence of rocks frozen into the glaciers that can act like tools to carve the surface of the underlying rock and soil. Whereas abrasion tends to wear rock surfaces away, producing a fine rock powder, larger bits of rock can be dislodged from the surface over which the glacier flows and be carried along with the glacial ice.

When glacial ice melts, the rock that has been incorporated into it is left behind. This material is called **till**, or if it has been carried for some distance by water running off the melting glacier it is called **outwash**. Piles of rock left by melting

glaciers produce unique structures called moraines.

Although the effects of glaciers described above are the most spectacular manifestations of the action of ice on the geosphere, at a much smaller level, ice can have some very substantial effects. Freezing and expansion of water in pores and small crevices in rock are major contributors to physical weathering processes. Freeze/thaw cycles are also very destructive to some kinds of structures, such as stone buildings.

17.16 EFFECTS OF HUMAN ACTIVITIES

Human activities have profound effects on the geosphere. Such effects may be obvious and direct, such as strip mining, or rearranging vast areas for construction projects, such as roads and dams. Or the effects may be indirect, such as pumping so much water from underground aquifers that the ground subsides, or abusing soil such that it no longer supports plant life well and erodes. As the source of minerals and other resources used by humans, the geosphere is dug up, tunnelled, stripped bare, rearranged, and subjected to many other kinds of indignities. The land is often severely disturbed, air can be polluted with dust particles during mining, and water may be polluted. Many of these effects, such as soil erosion caused by human activities, are addressed elsewhere in this book.

Extraction of Geospheric Resources: Surface Mining

Many human effects on the geosphere result from extraction of resources from Earth's crust. The most damaging method of resource extraction is surface mining, employed in the United States to extract virtually all of the rock and gravel that is mined, well over half of the coal, and numerous other resources. Properly done, with appropriate restoration practices, surface mining does minimal damage and may even be used to improve surface quality, such as by the construction of surface reservoirs where rock or gravel have been extracted. In earlier times, before strict reclamation laws were in effect, surface mining, particularly of coal, left large areas of land scarred, devoid of vegetation, and subject to erosion.

Several approaches are employed in surface mining. Sand and gravel located under water are extracted by **dredging** with draglines or chain buckets attached to large conveyers. In most cases, resources are covered with an **overburden** of earthen material that does not contain any of the resource that is being sought. This material must be removed as **spoil**. **Open-pit mining** is, as the name implies, a procedure in which gravel, building stone, iron ore, and other materials are simply dug from a big hole in the ground. Some of these pits, such as several from which copper ore has been taken in the U. S., are truly enormous in size.

The best known (sometimes infamous) method of surface mining is **strip mining**, in which strips of overburden are removed by draglines and other heavy earth-moving equipment to expose seams of coal, phosphate rock, or other materials. Heavy equipment is used to remove a strip of overburden, and the exposed mineral resource is removed and hauled away. Overburden from a parallel strip is then removed and placed over the previously mined strip, and the procedure is repeated numerous times. Older practices left the replaced overburden as relatively steep erosion-prone banks. On highly sloping terrain, overburden is removed on progres-

sively higher terraces and placed on the terrace immediately below.

Environmental Effects of Mining and Mineral Extraction

Some of the environmental effects of surface mining have been mentioned above. Although surface mining is most often considered for its environmental effects, subsurface mining can also have a number of effects, some of which are not immediately apparent and may be delayed for decades. Underground mines have a tendency to collapse, leading to severe subsidence. Mining disturbs groundwater aquifers. Water seeping through mines and mine tailings may become polluted. One of the more common and damaging effects of mining on water occurs when pyrite, FeS₂, commonly associated with coal, is exposed to air and becomes oxidized to sulfuric acid by bacterial action to produce acid mine water (see Chapter 12, Section 12.8). Some of the more damaging environmental effects of mining are the result of the processing of mined materials. Usually, ore is only part, often a small part, of the material that must be excavated. Various beneficiation processes are employed to separate the useful fraction of ore, leaving a residue of tailings. A number of adverse effects can result from environmental exposure of tailings. For example, residues left from the beneficiation of coal are often enriched in pyrite, FeS₂, which is oxidized microbiologically and chemically to produce damaging acidic drainage (acid mine water). Uranium ore tailings unwisely used as fill material have contaminated buildings with radioactive radon gas.

17.17 AIR POLLUTION AND THE GEOSPHERE

The geosphere can be a significant source of air pollutants, of which volcanic activity is one of the most common. Volcanic eruptions, fumaroles, hot springs, and geysers can emit toxic and acidic gases, including carbon monoxide, hydrogen chloride, and hydrogen sulfide. Greenhouse gas CO₂ and CH₄ can come from volcanic sources. Massive volcanic eruptions may inject huge amounts of particulate matter into the atmosphere. The incredibly enormous 1883 eruption of the East Indies volcano Krakatoa blew about 2.5 cubic kilometers of solid matter into the atmosphere, some of which penetrated well into the stratosphere. This material stayed aloft long enough to circle the earth several times, causing red sunsets and a measurable lowering of temperature worldwide.

The 1982 eruption of the southern Mexico volcano El Chicón showed the importance of the type of particulate matter in determining effects on climate. The matter given off by this eruption was unusually rich in sulfur, so that an aerosol of sulfuric acid formed and persisted in the atmosphere for about 3 years, during which time the mean global temperature was lowered by several tenths of a degree due to the presence of atmospheric sulfuric acid. By way of contrast, the eruption of Mt. St. Helens in Washington State in the U.S. 2 years earlier had little perceptible effect on climate, although the amount of material blasted into the atmosphere was about the same as that from El Chicón. The material from the Mt. St. Helens eruption had comparatively little sulfur in it, so the climatic effects were minimal.

Thermal smelting processes used to convert metal fractions in ore to usable forms have caused a number of severe air pollution problems that have affected the geosphere. Many metals are present in ores as sulfides, and smelting can release large quantities of sulfur dioxide, as well as particles that contain heavy metals such

as arsenic, cadmium, or lead. The resulting acid and heavy metal pollution of surrounding land can cause severe damage to vegetation so that devastating erosion occurs. One such area is around a large nickel smelter in Sudbury, Ontario, Canada, where a large area of land has become denuded of vegetation. Similar dead zones have been produced by copper smelters in Tennessee and in eastern Europe, including the former Soviet Union.

Soil and its cultivation produces significant quantities of atmospheric emissions. Waterlogged soil, particularly that cultivated for rice, generates significant quantities of methane, a greenhouse gas. The microbial reduction of nitrate in soil releases nitrous oxide, N_2O , to the atmosphere. However, soil and rock can also remove atmospheric pollutants. It is believed that microorganisms in soil account for the loss from the atmosphere of some carbon monoxide, which some fungi and bacteria can metabolize. Carbonate rocks, such as calcium carbonate, $CaCO_3$, can neutralize acid from atmospheric sulfuric acid and acid gases.

As discussed in Section Chapter 14, Section 14.6, masses of atmospheric air can become trapped and stagnant under conditions of a temperature inversion in which the vertical circulation of air is limited by the presence of a relatively warm layer of air overlaying a colder layer at ground level. The effects of inversions can be aggravated by topographical conditions that tend to limit circulation of air. Figure 17.12 shows such a condition, in which surrounding mountain ridges limit horizontal air movement. Air pollutants may be forced up a mountain ridge from a polluted area to significantly higher altitudes than they would otherwise reach. Because of this "chimney effect," air pollutants may reach mountain pine forests that are particularly susceptible to damage from air pollutants such as ozone formed along with photochemical smog.

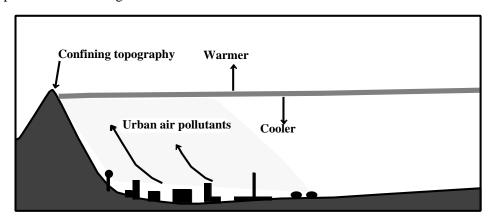


Figure 17.12 Topographical features, such as confining mountain ridges, may work with temperature inversions to increase the effects of air pollution.

17.18 WATER POLLUTION AND THE GEOSPHERE

Water pollution is addressed in detail elsewhere in this book. Much water pollution arises from interactions of groundwater and surface water with the geosphere. These aspects are addressed briefly here.

The relationship between water and the geosphere is twofold. The geosphere

may be severely damaged by water pollution. This occurs, for example, when water pollutants produce contaminated sediments, such as those contaminated by heavy metals or PCBs. In some cases, the geosphere serves as a source of water pollutants. Examples include acid produced by exposed metal sulfides in the geosphere or synthetic chemicals improperly discarded in landfills.

The sources of water pollution are divided into two main categories. The first of these consists of **point sources**, which enter the environment at a single, readily identified entry point. An example of a point source would be a sewage-water outflow. Point sources tend to be those directly identified as to their origins from human activities. **Nonpoint sources** of pollution are those from broader areas. Such a source is water contaminated by fertilizer from fertilized agricultural land, or water contaminated with excess alkali leached from alkaline soils. Nonpoint sources are relatively harder to identify and monitor. Pollutants associated with the geosphere are usually nonpoint sources.

An especially common and damaging geospheric source of water pollutants consists of sediments carried by water from land into the bottoms of bodies of water. Most such sediments originate with agricultural land that has been disturbed such that soil particles are eroded from land into water. The most common manifestation of sedimentary material in water is opacity, which seriously detracts from the esthetics of the water and inhibits the growth of light-requiring algae. Sedimentary material deposited in reservoirs or canals can clog them and eventually make them unsuitable for water supply, flood control, navigation, and recreation. Suspended sediment in water used as a water supply can clog filters and add significantly to the cost of treating the water. Sedimentary material can devastate wildlife habitats by reducing food supplies and ruining nesting sites. Turbidity in water can severely curtail photosynthesis, thus reducing primary productivity necessary to sustain the food chains of aquatic ecosystems.

17.19 WASTE DISPOSAL AND THE GEOSPHERE

The geosphere receives many kinds and large amounts of wastes. Its ability to cope with such wastes with minimal damage is one of its most important characteristics and is dependent upon the kinds of wastes disposed on it. A variety of wastes, ranging from large quantities of relatively innocuous municipal refuse to much smaller quantities of potentially lethal radioactive wastes, are deposited on land or in landfills. These are addressed briefly in this section.

Municipal Refuse

The currently favored method for disposing of municipal solid wastes—household garbage—is in **sanitary landfills** (Figure 17.13) consisting of refuse piled on top of the ground or into a depression such as a valley, compacted, and covered at frequent intervals by soil. Frequent covering of the refuse with soil minimizes loss of blowing trash, water contamination, and other undesirable effects. A completed landfill can be put to beneficial uses, such as a recreational area; because of settling, gas production, and other factors, landfill surfaces are generally not suitable for building construction. Modern sanitary landfills are much preferable to the open

dump sites that were once the most common means of municipal refuse disposal.

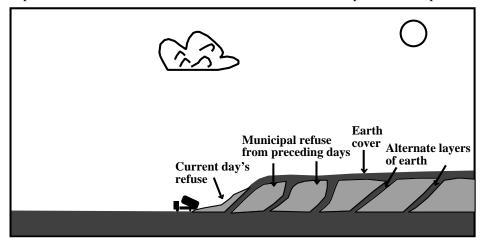


Figure 17.13 Structure of a sanitary landfill.

Although municipal refuse is much less dangerous than hazardous chemical waste, it still poses some hazards. Despite prohibitions against the disposal of cleaners, solvents, lead storage batteries, and other potentially hazardous materials in landfills, materials that pose some environmental hazards do find their way into landfills and can contaminate their surroundings.

Landfills produce both gaseous and aqueous emissions. Biomass in landfills quickly depletes oxygen by aerobic biodegradation of microorganisms in the landfill,

$${CH_2O}(biomass) + O_2 CO_2 + H_2O$$
 (17.19.1)

emitting carbon dioxide. Over a period of many decades the buried biodegradable materials undergo anaerobic biodegradation,

$$2\{CH_2O\}$$
 $CO_2 + CH_4$ (17.19.2)

releasing methane as well as carbon dioxide. Although often impractical and too expensive, it is desirable to reclaim the methane as fuel, and some large sanitary landfills are major sources of methane. Released methane is a greenhouse gas and can pose significant explosion hazards to structures built on landfills. Although produced in much smaller quantities than methane, hydrogen sulfide, H₂S, is also generated by anaerobic biodegradation. This gas is toxic and has a bad odor. In a properly designed sanitary landfill, hydrogen sulfide releases are small and the gas tends to oxidize before it reaches the atmosphere in significant quantities.

Water infiltrating into sanitary landfills dissolves materials from the disposed refuse and runs off as **leachate**. Contaminated leachate is the single greatest potential pollution problem with refuse disposal sites, so it is important to minimize its production by designing landfills in a way that keeps water infiltration as low as possible. The anaerobic degradation of biomass produces organic acids that give the leachate a tendency to dissolve acid-soluble solutes, such as heavy metals. Leachate can infiltrate into groundwater, posing severe contamination problems. This is mini-

mized by siting sanitary landfills over formations of poorly permeable clay or depositing layers of clay in the landfill before refuse is put into it. In addition, impermeable synthetic polymer liners may be placed in the bottom of the landfill. In areas of substantial rainfall, infiltration into the landfill exceeds its capacity to hold water so that leachate flows out. To prevent water pollution downstream, this leachate should be controlled and treated.

Hazardous chemical wastes are disposed of in so-called **secure landfills**, which are designed to prevent leakage and geospheric contamination of toxic chemicals disposed in them. Such a landfill is equipped with a variety of measures to prevent contamination of groundwater and the surrounding geosphere. The base of the landfill is made of compacted clay that is largely impermeable to leachate. An impermeable polymer liner is placed over the clay liner. The surface of the landfill is covered with material designed to reduce water infiltration, and the surface is designed with slopes that also minimize the amount of water running in. Elaborate drainage systems are installed to collect and treat leachate.

The most pressing matter pertaining to geospheric disposal of wastes involves radioactive wastes. Most of these wastes are **low-level** wastes, including discarded radioactive laboratory chemicals and pharmaceuticals, filters used in nuclear reactors, and ion-exchange resins used to remove small quantities of radionuclides from nuclear reactor cooler water. Disposed of in properly designed landfills, such wastes pose minimal hazards.

Of greater concern are the **high-level** radioactive wastes, primarily fission products of nuclear power reactors and byproducts of nuclear weapons manufacture. Many of these wastes are currently stored as solutions in tanks, many of which have outlived their useful lifetimes and pose leakage hazards, at sites such as the federal nuclear facility at Hanford, Washington, where plutonium was generated in large quantities during post-World War II years. Eventually, such wastes must be placed in the geosphere such that they will pose no hazards. Numerous proposals have been advanced for their disposal, including disposal in salt formations, subduction zones in the seafloor, and ice sheets. The most promising sites appear to be those in poorly permeable formations of igneous rock. Among these are basalts, which are strong, glassy igneous types of rock found in the Columbia River plateau. Granite and pyroclastic welded tuffs fused by past high temperature volcanic eruptions are also likely possibilities as sites for disposing of nuclear wastes and keeping them isolated for tens of thousands of years.

CHAPTER SUMMARY

The chapter summary below is presented in a programmed format to review the main points covered in this chapter. It is used most effectively by filling in the blanks, referring back to the chapter as necessary. The correct answers are given at the end of the summary.

That part of the earth upon which humans live and from which they extract most of their food, minerals, and fuels is called the ¹______. A condition manifested by declining groundwater tables, salinization of topsoil and water, reduction of surface waters, unnaturally high soil erosion, and desolation of native

vegetation is ²	. Earth's crust is ³
<u> </u>	. A naturally occurring inorganic
solid with a definite internal crystal	structure and chemical composition in the
	a solid, cohesive mass of pure mineral or an
	Some of the characteristics
used to describe minerals are ⁶	
	There are only about ⁷ rock-
forming minerals, most of which are 8_	
	eral matter, one of the most common classes
of which are ¹⁰ The chemical	formula of halite is 11 and it is an
example of a class of minerals called ¹²	. The condensation of 13 At elevated
vapor-phase mineral constituents forms	. At elevated
	ce, rocks and mineral matter melt to produce
a molten substance called ¹⁴	
	sphere and water this kind of rock undergoes
processes and eve	
rock, which may be converted	
	converted among the three kinds of rock just
mentioned are described by the 12	The mass movements of ges, and other huge features of the geosphere
rocks to form continents, mountain rang	ges, and other nuge features of the geosphere
solids and samisolids in the goognbare i	
linds of processes that shangs the conf	iguration of the geosphere can be divided into
the two main categories of 22	iguration of the geosphere can be divided into
Two major kinds of internal processes a	are those that cause ²³
and those that result in the formation of	
face processes are ²⁵	. The three kinds of
•	may be carried by flowing water in streams
	. Clays may be defined as ²⁷
Clay minerals may attain a net negative	charge by ²⁸ ,
as a consequence of which these minera	
deals with cher	mical species, reactions, and processes in the
	th the atmosphere and hydrosphere. As a
chemical phenomenon, weathering can	be viewed as ³¹
	. The major categories of chemical
weathering are ³²	
	. The percentage of rock volume available to
contain water is called its ³³	and the ease of flow of the water through
the rock is called its ³⁴	Water present in a zone of saturation in
mineral strata is called ³⁵	Two oxidation/reduction reactions that
can clog the walls of water wells and in	npede the flow of water into the well are ³⁶
	T : 27
	Tsunamis are ³⁷
A stream consists of ³⁸	. A region along a

- 20. plate tectonics
- 21. rheology
- 22. internal processes and surface processes
- 23. earthquakes
- 24. volcanoes
- 25. landslides and subsidence
- 26. dissolved, suspended, or bed load
- 27. a group of microcrystalline secondary minerals consisting of hydrous aluminum silicates that have sheet-like structures
- 28. ion replacement
- 29. exchangeable cations
- 30. Geochemistry
- 31. the result of the tendency of the rock/water/mineral system to attain equilibrium
- 32. hydration/dehydration, dissolution/precipitation, acid-base reactions, complexation, hydrolysis, and oxidation-reduction
- 33. porosity
- 34. permeability
- 35. groundwater
- 36. $^{4}\text{Fe}^{2+}(aq) + O_{2}(aq) + 10H_{2}O + ^{4}\text{Fe}(OH)_{3}(s) + ^{8}\text{H}^{+} \\ 2\text{Mn}^{2+}(aq) + O_{2}(aq) + (2x + 2)H_{2}O + ^{2}\text{Mn}O_{2} \cdot xH_{2}O(s) + ^{4}\text{H}^{+}$
- 37. large ocean waves resulting from earthquake-induced movement of ocean floor.
- 38. water flowing through a channel
- 39. the floodplain
- 40. berm
- 41. raised ocean levels
- 42. the deposition of windblown soil
- 43. till
- 44. moraines
- 45. strip mining
- 46. Beneficiation
- 47. tailings
- 48. an aerosol of sulfuric acid
- 49. lower
- 50. temperature inversion
- 51. point and nonpoint sources
- 52. gaseous and aqueous
- 53. oxygen
- 54. methane
- 55. leachate
- 56. secure landfills
- 57. leakage and geospheric contamination of toxic chemicals disposed in them

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QUESTIONS AND PROBLEMS

- 1. Of the following, the one that is **not** a manifestation of desertification is (a) declining groundwater tables, (b) salinization of topsoil and water, (c) production of deposits of MnO₂ and Fe₂O₃•H₂O from anaerobic processes, (d) reduction of surface waters, (e) unnaturally high soil erosion.
- 2. Give an example of how each of the following chemical or biochemical phenomena in soils operates to reduce the harmful nature of pollutants: (a) oxidation-reduction processes, (b) hydrolysis, (c) acid-base reactions, (d) precipitation, (e) sorption, (f) biochemical degradation.
- 3. Why do silicates and oxides predominate among earth's minerals?
- 4. Give the common characteristic of the minerals with the following formulas: NaCl, Na₂SO₄, CaSO₄•2H₂O, MgCl₂•6H₂O, MgSO₄•7H₂O, KMgClSO₄•11/₄H₂O, K₂MgCa₂(SO₄)₄•2H₂O.
- 5. Explain how the following are related: weathering, igneous rock, sedimentary rock, soil.
- 6. Where does most flowing water that contains dissolved load originate? Why does it tend to come from this source?
- 7. What role might be played by water pollutants in the production of dissolved load and in the precipitation of secondary minerals from it?

- 8. As defined in this chapter, are the ions involved in ion replacement the same as exchangeable cations? If not, why not?
- 9. Match the following:
 - A. Metamorphic rock
 - B. Chemical sedimentary rocks
 - C. Detrital rock
 - D. Organic sedimentary rocks
- 1. Produced by the precipitation or coagulation of dissolved or colloidal weathering products
- 2. Contain residues of plant and animal remains
- 3. Formed from action of heat and pressure on sedimentary rock
- 4. Formed from solid particles eroded from igneous rocks as a consequence of weathering
- 10. Speculate regarding how water present in poorly consolidated soil might add to the harm caused by earthquakes.
- 11. In what sense might volcanoes contribute to air pollution? What possible effects could this have on climate?
- 12. Explain how excessive pumping of groundwater might adversely affect streams, particularly in regard to the flow of small streams.
- 13. Which three elements are most likely to undergo oxidation as part of chemical weathering process? Give example reactions of each.
- 14. Match the following:
 - A. Groundwater
 - B. Vadose water
 - C. Meteoric water
 - D. Water in capillary fringe
- 1. Water from precipitation in the form of rain or snow
- 2. Water present in a zone of saturation
- 3. Water held in the unsaturated zone or zone of aeration
- 4. Water drawn somewhat above the water table by surface tension