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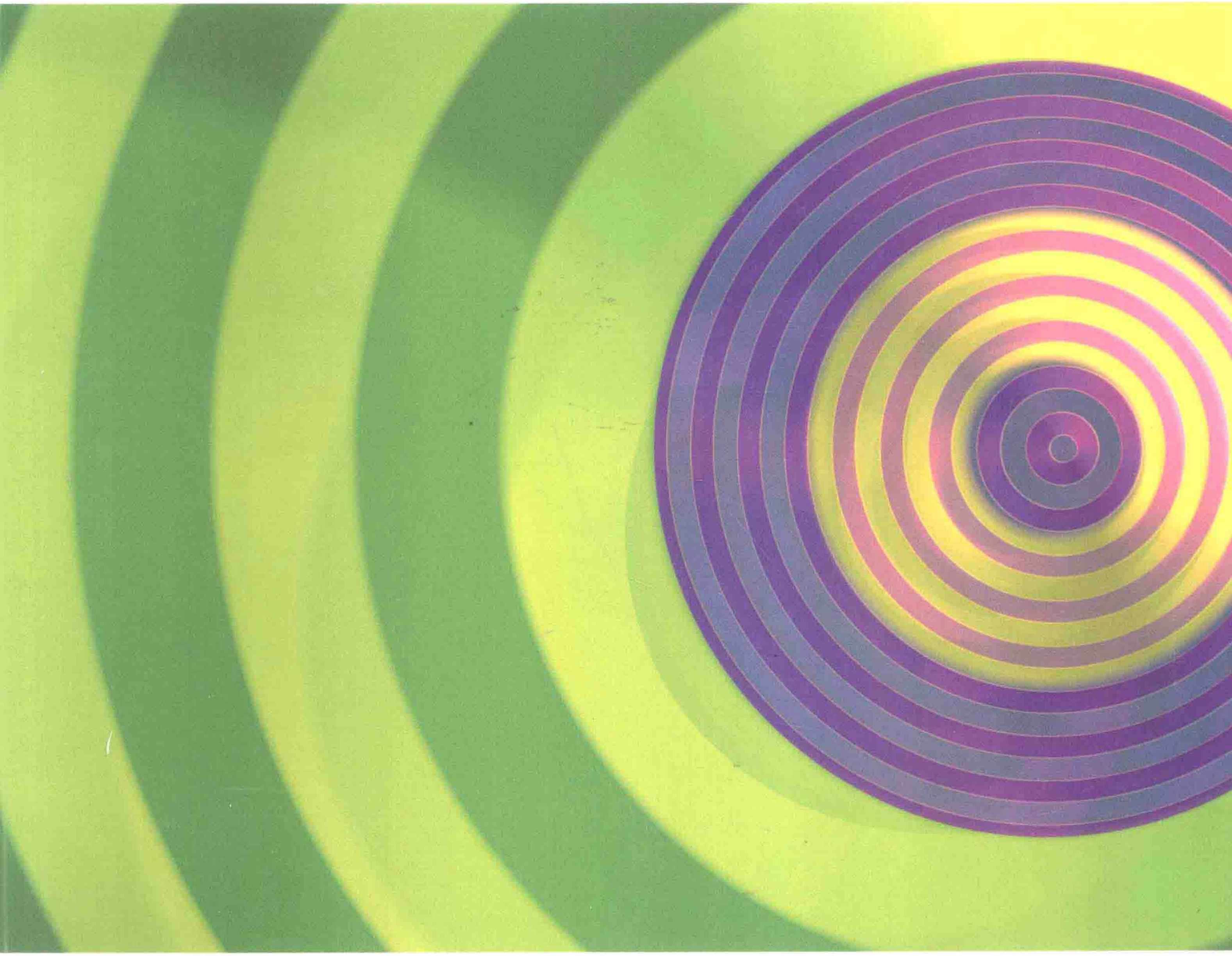

Essentials of Soil Mechanics and Foundations: Basic Geotechnics

David F. McCarthy

Seventh Edition

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The Soil and Rock of Planet Earth

Geologic Overview

It has long been known that the earth is a dynamic constantly changing planet, but facts uncovered by scientists throughout the last half-century indicate that these ongoing changes involve factors of nature that are more profound than ever imagined previously. The major constituents of the earth's outer zone—the soil, rock, and water—are continually subjected to forces that incite change. The changes in rock and soil deposits are often slow and subtle, and may not be recognized over short geologic periods, such as the human lifetime. However, rapid (sometimes instantaneous) changes also occur because of natural phenomena or human activities (mass movements during earthquakes, landslides, and tidal waves, or effects of war and large construction projects). Related to the struggle to survive and the drive to improve, humans have learned about many of the factors responsible for changes that occur in the earth's rock and soil deposits and the factors that affect the (geologically) short-term behavior.

Humans have always realized that soil influences their survival. Soil is the ground on which we stand. We build with soil. We have relied on soil to support structures and the paths of transportation. We depend on soil to grow our food and provide the products we use for living, protection, and comfort. We have trusted the soil to be stable and permanent. In some of these presumptions, we have been incorrect.

This text studies soil as a material that is used to build with or on, but also as a material of the environment that may act in combination with other forces of nature or of civilization to affect landforms, our structures, and the state of our environment. This study is the field of *geotechnics*. This chapter presents a concise overview of important geologic-based information, to provide an understanding of the factors responsible for the formation and behavior of today's rock and soil deposits and the factors that will cause changes in the future. In this introductory study of geotechnics, the agricultural aspects of soil are not considered, with the exception of

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discussions relating to the vegetation used as a means of erosion control and as a factor influencing the creation of present-day soil types.

The earth's crust is composed of soil and rock. *Rock* can be defined as a natural aggregate of minerals that are connected by strong bonding or attractive forces; for this reason, rock is often considered a consolidated material. *Soil* may be defined as the unconsolidated sediments and deposits of solid particles that have resulted from the disintegration of rock. To the construction industry and the engineering profession, however, soil is also assumed to include the residue of vegetable and animal life, including civilization's buried trash, garbage, and industrial wastes.

Soil is a *particulate* material, which means that a soil mass consists of an accumulation of individual particles that are bonded together by mechanical or attractive means, though not as strongly as with rock. In soil (and in most rock), voids exist between particles, and the voids may be filled with a liquid (usually water) or a gas (usually air). As a result, soil deposits are often referred to as a three-phase material or system (solids plus liquid plus gas).

1 Rock: The Source of Soils

Most of the nonorganic materials that are identified as soil originated from rock as the parent material. Rock types are grouped into three major classes—igneous, sedimentary, and metamorphic—determined by their origin or method of formation. The type of soil that subsequently develops relates to the rock type, its mineral components, and the climatic regime of the area.

Igneous rock resulted from the cooling and hardening of molten rock called *magma*, which originated deep within the earth. Molten magma that escaped to and near the surface of the earth through volcanoes and fissures in the earth's crust (termed *lava*) cooled quickly. As a result of rapid cooling, the mineral components solidified into small crystals and possessed a fine, interlocking texture. In some situations, the cooling was so rapid that a crystal-free, glassy texture resulted. The molten materials (lava) that cooled rapidly at or near the earth's surface are called extrusive or volcanic rock types and include the *basalts, rhyolites*, and *andesites*.

Molten rock trapped deep below the surface of the earth (magma) cooled slowly. The mineral components formed in large interlocking crystals, and coarse-textured rocks resulted. These rocks are classified as intrusive or plutonic types and include the *granites* (the most common) as well as the *syenites, diorites,* and *gabbros.*

Many of the mineral combinations in igneous rocks are unstable in the environment existing at the earth's surface. Upon exposure to air, water, chemicals in solution in water, freezing temperatures, varying temperatures, and erosive factors, the rock minerals break down to the soil types existing today. Rock whose chief mineral is quartz or orthoclase (potassium feldspar), minerals with high silica content, decomposes to predominantly sandy or gravelly soil with little clay.[1] Granites, syenites, and rhyolites are in this category. Because of the high silica content, these rocks are classified as acidic.

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[1]According to the engineering definition, coarser soils include sands and gravels and are particles larger than 0.074 mm. Particles that comprise the fine-textured silt and clay category of soils are smaller than 0.074 mm. The 0.074 mm size is close to the smallest particle size observable with the unaided eye under normal conditions. Most clay particles are smaller than 0.002 mm.

Rocks whose minerals contain iron, magnesium, calcium, or sodium, but little silica, such as the gabbros, diabases, and basalts, are classified as basic rocks. These rocks decompose to the fine-textured silt and clay soils.

Generally, the acidic rocks are light-colored, while the basic rocks are very dark. Intermediate colors reflect an intermediate chemical composition. Rock types that are intermediate between acidic and basic include the *trachytes, diorites,* and *andesites.* Because of their mineral components, diorite and andesite easily break down into the fine-textured soils.

The clay portion of fine-textured soil is the result of primary rock minerals decomposing to form secondary minerals. The clays are *not* small fragments of the original minerals that existed in the parent rock. Because of this change, the properties and behavior of clay soils are different from those of the gravel, sand, and silt soils, which *are* still composed of the primary rock minerals. Rocks that are acidic (not basic), such as the granites, are considered to be good construction materials.

Sedimentary rocks are formed from accumulated deposits of soil particles or remains of certain organisms that have become hardened by pressure or cemented by minerals. Pressure sufficient to harden or solidify a soil deposit results from the weight of great thicknesses of overlying material. Under this pressure, the deposit is compacted and consolidated, and strong attractive bonds are established. Cementing minerals such as silica, calcium carbonate, and the iron oxides are abundant in soil as a result of rock weathering, and when dissolved in the water circulating through a soil deposit, they precipitate out onto the soil particles. Other cementing may be obtained from within the mass by solution or chemical change of materials. Sedimentary-type rocks include the limestones and dolostone (dolomites),[2] shale (claystone, siltstone, mudstone), sandstone, conglomerate, and breccia.

Geologic conditions in past historic times have had a very significant effect on the location and type of sedimentary rocks that exist across North America today. In early prehistoric times, most of what is now the United States was under water (Figure 1). Gradually, much of the land rose. Accumulated sediments in these shallow seas eventually became the limestones, shales, and sandstones of today. As a consequence of the layered manner of soil deposition, many sedimentary rocks are easily recognized today because of their stratified appearance (Figure 2).

Shales are predominantly formed from deposited clay and silt particles. The degree of hardness varies, depending on the type of minerals, the bonding that developed, and the presence of foreign materials. The hardness is generally due to external pressures and the particle bonds that resulted, not to cementing minerals. Many shales are relatively stable when exposed to the environment, but some expand or delaminate (the layers separate) after contact with water or air. Weathering breaks down shale to fragments of varying sizes. These fragments, in turn, may be quickly reduced back to clay particle sizes. The properties of shale are quite important to the construction industry, for it is estimated that shale represents approximately 50 percent of the rock that is exposed at the earth's surface or closest to the surface under the soil cover. Sound shale can provide a good foundation material. Its use as a construction material is questionable, however, because of its tendency to break down under handling, abuse, and weathering.

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[2]Historically, the term *dolomite* has referred to both the rock-forming mineral $CaMg(CO_3)_2$ and sedimentary rock. *Dolostone* is a recent proposal for designating the rock material, to avoid confusion.

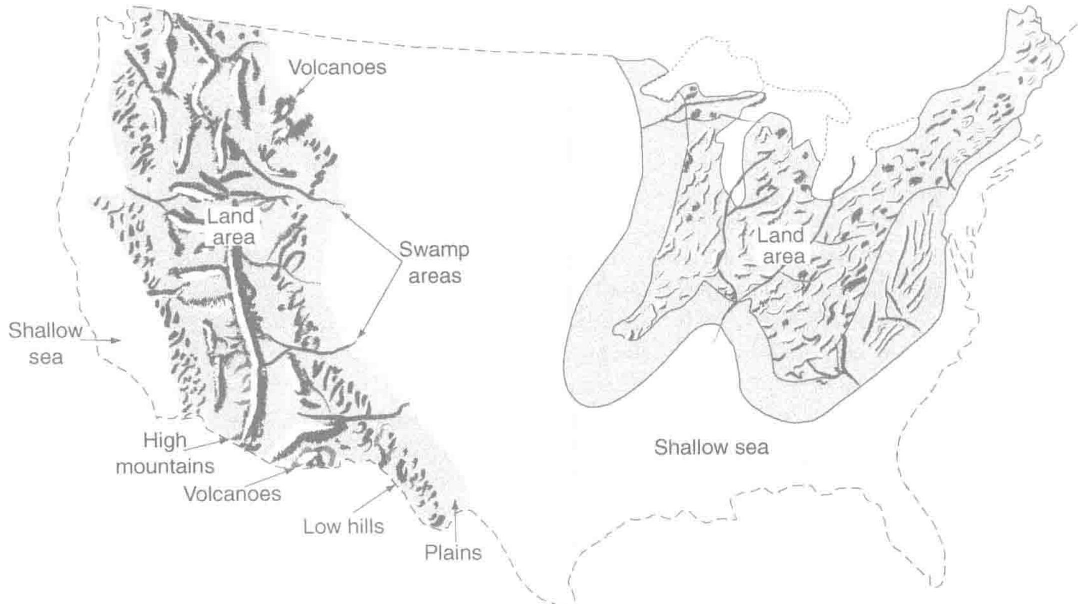


Figure 1 Generalized geographic map of the United States for period approximately 100 million years ago. Sediments deposited in shallow seas became sedimentary rock that exists in such areas today. (*Source:* U.S. Department of the Interior, Geological Survey)

Figure 2 Sedimentary rock in central New York State showing stratified formation.

Sandstone is predominantly quartz cemented together with mostly silica, but also calcium carbonate, or iron compounds. Sandstones are generally considered good construction materials. *Conglomerate* (cemented sand and gravel) and *breccia* (cemented angular rock fragments) are similar to sandstone.

Limestone is predominantly crystalline calcium carbonate (calcite) formed under water. This rock material forms as a result of chemicals precipitating from solution, and from the remains of marine organisms and action of plant life. Because of the sedimentary nature, limestone formations can be heterogeneous and include alien materials such as clays and organic materials (including trapped gases). (Limestone, and limestone-dolomite, formations may be referenced as Karst or Karstic terrain.) The degree of hardness and durability of limestones will vary. Some rock formations are very sound, but some are relatively soluble to ingredients carried by nature's groundwaters, with the result being the development of cavities. If the rock cap for a cavity located near the surface of the limestone formation deteriorates, a typical result is that the overlying earth material collapses into the void (referred to as a sinkhole) (see Figure 3).

Dolostone is a variety of limestone, but harder and more durable. *Marl* and *chalk* are softer forms of limestone.

Weathering of limestones can produce a soil that includes a large range of particle sizes, but the fine-grained soils predominate. Limestone is a good foundation material, provided that the formation is sound and free of cavities. Sound limestone is considered a good construction material.

Frequently, because of the manner of deposition of the original rock-forming sediments, sandstone and shale, or limestone and shale, and sometimes sandstone, limestone, and shale are interbedded.

Metamorphic rock results when any type of existing rock is subject to metamorphism, the changes brought about by combinations of heat, pressure, and plastic flow so that the original rock structure and mineral composition are changed. *Plastic flow* for rock refers to slow viscous movement and rearrangement within the rock mass as it changes and adjusts to the pressures created by external forces. Under these conditions, limestone is changed to *marble* and sandstone to *quartzite*. When subject to metamorphism, shale is transformed to *slate* or *phyllite*. Higher levels of these factors change the shale, or slate, to *schist*. Because

Figure 3 Sinkhole occurrence in area underlain by carbonaceous (limestone family) rock. (*Source:* USGS photo)

of the processes affecting their formation, slates and schists become foliated rocks (that is, layered as in a folio). *Gneiss* is a foliated rock with distinctive banding that results from the metamorphosis of sedimentary rock or basalt or granite. Despite their possibly different origin, a distinction between gneisses and schists is not always clear. These two rock types on occasion appear to be gradational.

Metamorphic rocks formed from sound igneous or sedimentary rocks can be good materials for construction. However, schist, gneiss, and slate are questionable construction materials, because the foliated or banded structure can act to originate planes of weakness that affect strength and durability.

Upon weathering, some metamorphic rocks break down to soil types comparable to that which would be derived from the original igneous or sedimentary-type rock. Others reflect the changes brought about by metamorphism. Gneiss and schist decompose to silt–sand mixtures with mica. Soils from slates and phyllites are more clayey. Soils derived from marble are similar to those resulting from limestone. Decomposition of quartzite generally produces sands and gravels.

The processes of rock changing to soil, soil changing to rock, and alteration of rock are continuous and occur simultaneously. The process of change or alteration takes place over long periods of time, and there is no set sequence in which changes occur.

There are many rock types. To establish a proper perspective, the construction industry's concern is generally not with rocks' names but with their properties. In-place properties, such as hardness, and possible presence of fractures or fissures affect drilling, blasting, and excavation operations. The suitability for use as a foundation for structures is related to strength, durability, and possible presence of cavities or of fractures and fissures. The commercial value of excavated and crushed rock for fill and as an ingredient of concrete is influenced by soundness and durability. In a general way, desirable and undesirable properties have been associated with the different rock types.

2 Soil Categories: Transported, Residual

Soil deposits can be grouped into one of two broad categories—residual or transported—based on the process responsible for the formation. *Residual Soil* formations are created from the weathering of rock or the accumulation of organic materials where the material remains at the location of origin. *Transported soils* are those materials that have been moved from the place of origin; transportation may have resulted from the effects of gravity, wind, water, glaciers, or human activity—either singularly or in combination. The presence of a soil formation that blankets an area is a result of global position, geologic history, climate, and topography; but as a simplified generalization, residual formations are more apt to be found in humid and tropic regions of the planet (reflecting the strong influence of that type of climate), whereas transported soils are more prevalent for the temperate and cold climatic regions. Though the engineering properties of all soil deposits (the properties important for designing and constructing structural foundations, earthworks projects, construction site work, etc.) are affected by the method responsible for the development and accumulation, some important properties of the two categories differ because of the different formation processes. The general distribution of residual soil formations and transported soil deposits across the United States is indicated by Figure 4.

Figure 4 Distribution of transported soil and residual soil formations for the United States. (Compiled from several sources)

Transported Soils

Transported soils are those materials that have been moved from their place of origin. Soil particles are often segregated according to size by, or during, the transportation process. The process of transplantation and deposition has a significant effect on the properties of the resulting soil mass; various details are discussed in subsequent sections of this chapter. Much of the knowledge about the engineering-related properties and behavior of soil formations is based on the vast experience gained from construction projects in areas of the world where transported soil deposits exist (which relate to the geography of the many established population and industrial areas of the world, such as locations near bodies of water, in temperate climates, etc.).

Gravity- and Wind-Transported Soils. Gravity is generally capable of transporting aggregate particles only limited distances, such as down a hill or mountain slope, with the result that little change in the soil material is brought about by the transportation procedure.

Wind can move small particles by rolling or carrying them. Soils carried by wind and subsequently deposited are designated *aeolian* deposits. Particles of small sand sizes can be rolled and carried short distances. Accumulations of such wind-deposited sands often form dunes. Dunes are typically characterized by low hill and ridge formations.They generally occur in sandy desert areas and on the down-wind side of bodies of water having sandy beaches. Dune material is a good source of sand for some construction purposes, but if the particles are of uniform size and very weathered and rounded, the sand may not be highly suitable for all construction purposes.

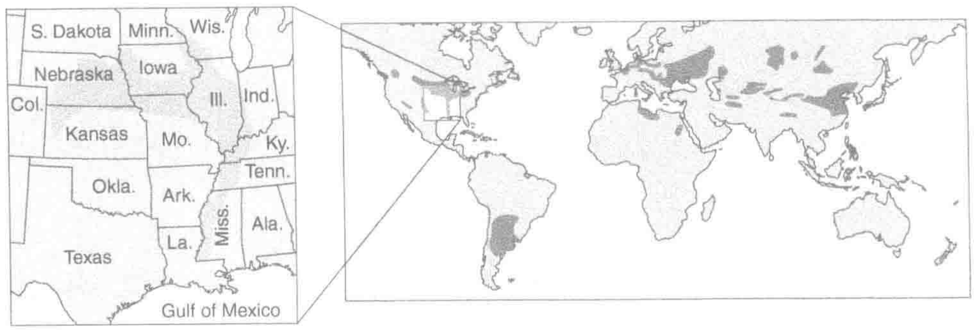
Fine-textured soils, the silts and clays, can be carried great distances by wind. Silt soils in arid regions have no moisture to bond the particles together and are very susceptible to the effects of wind. Clay, however, has sufficient bonding or cohesion to withstand the eroding effects of wind. Deposits of wind-blown silts laid down in a loose condition that has been retained because of particle-bonding or cementing minerals is classified as *loess*. Significant loess deposits are found in North America, Europe, and Asia (Figure 5(a)).

In the United States, great thicknesses of loess exist in the vicinity of the Mississippi and Missouri rivers. With these materials, accumulations have built up slowly, and grasses growing at the surface could keep pace with the rate of deposit. The resulting rootholes and grass channels that remain have created a soil that has a high porosity and cleavage in the vertical direction. Natural and human-made cuts in this material will stand with nearly vertical slopes, as illustrated in Figure 5(b). However, if the soil is exposed to excessive water (becomes saturated or inundated), or is subject to severe ground vibrations, the soil's stable structure can be broken down. Subsidence or settlement results. Consequently, loess formations should be considered as poor foundation soils unless they can be protected from the effects of water and vibrations.

Volcanic eruptions have also produced "wind-transported" soils. The volcanic ash carried into the air with the escaping gases consists of small fragments of igneous rock. The soil type expected to result will be related to the mineral characteristics of the igneous rock, as discussed earlier. Generally, remains of volcanic ash deposits are limited. Because of surface deposition, they are quickly affected by weathering agents.

Glacial Deposits. Much of Canada and the northern United States, as well as northern Europe and Asia, have been subjected to the past effects of massive moving sheets of ice, the continental glaciers (see Figure 6). The most recent geological period of glaciation is referred to as the Great Ice Age, and scientists generally estimate that it covered the span of time extending from about 2 million years ago to about 10,000 years ago. Recent theories supported by evidence consider that extended glaciation occurred periodically even earlier throughout prehistoric times, in cycles apparently related to the significant variation that occurs in the earth's orbit (which gradually varies from nearly circular to elliptical, with the related change in distance between the sun and the earth being approximately 11 million miles), to variations in the tilt of the earth's axis with respect to the plane of the orbit (from about 21.5° to about 24.5°), and to a wobble about the axis of rotation. Conditions conducive to glaciation apparently develop on approximately 100,000-year cycles.

The past periods of glaciation resulted in some present-day areas having been covered once (Figure 6), some areas several times. Glaciers expanded and advanced over the land



(a)

(b)

Figure 5 (a) Major loess deposits of the world (shaded areas); enlargement shows area of loess deposits in central United States. (b) Highway cut through loess deposit in Iowa shows natural vertical cleavage.

when climatic conditions permitted or contributed to the formation of ice. Glacial advance ceased when melting at its limits equaled the rate of expansion. When, because of climatic or other changes, the rate of melting exceeded the rate of growth, the glaciers receded or shrank. Generally, glacier expansion or shrinkage and movement were slow. At present, only the polar regions of the planet remain covered by glacial ice, and for the present the condition is considered stable.

Considerable quantities of soil have been moved and deposited by or because of glacial action. Such deposits are referred to as *glacial drift*. However, although glaciers moved vast quantities of soil and created a surface topography, the major topographical features such as mountain ranges or plains areas are not the direct result of glaciers. Indirectly, however, major topographical features have very likely been affected by the continental glaciers. The glaciers were several thousand feet thick in many areas, and this had two very significant effects: The tremendous amount of water taken to form the glaciers lowered the level of the

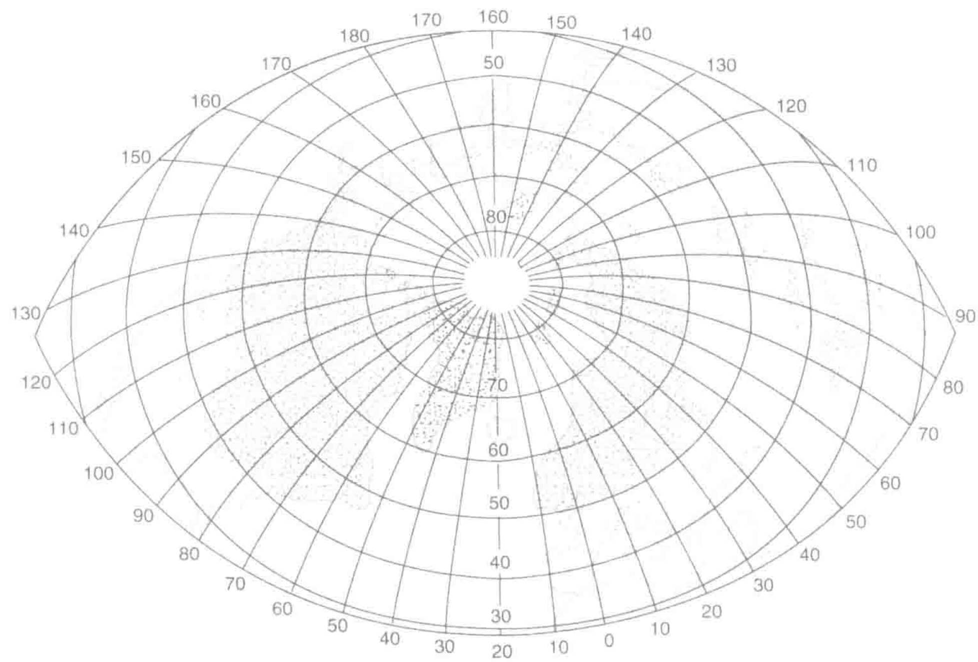
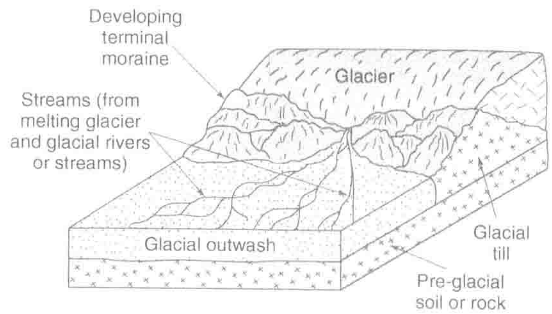


Figure 6 Areas of the Northern Hemisphere that have been covered by glacial ice (shaded areas). (*Source:* After Ernst Antevs, "Maps of the Pleistocene Glaciations," Geological Society of America, Bulletin 40, 1929)

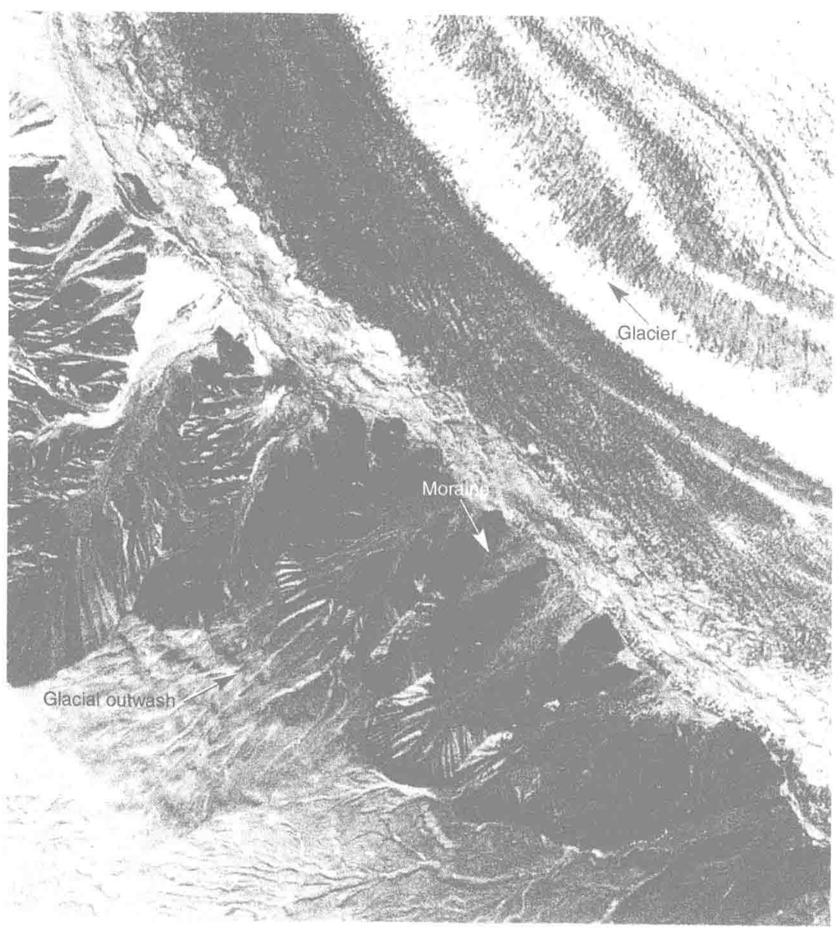
sea by some 125–150 m (400–500 ft), and the tremendous weight of the glaciers caused the land beneath them to depress. As a result of the lowering of the sea level, the continental limits of North America extended beyond their current limits. It is probable that much glacially eroded soil was dropped or washed to areas that are now under the sea. As a result of the land's being depressed, areas of low elevation were subsequently flooded. After the glaciers retreated and the areas were relieved of their weight, the land rose in elevation. Rock and soil deposits that had been carried to the low flooded areas rose to create new land surfaces. Many lake areas became diminished in size or disappeared entirely. The Great Salt Lake in Utah, for instance, is the shrunken remains of a 50,000-km^2 (20,000-square-mile) glacial lake that once had a depth in excess of 300 m (1,000 ft).

As a glacier grew or advanced, it gathered and pushed soil ahead of it, or enveloped and gathered the soil into itself. All sizes of particles were picked up and mixed together, with no sorting according to size. Some of the material picked up was subsequently dropped during the advance, either under the glacier or in front of it, and then overrun by the continued movement. When a glacier advance stopped, soil being pushed by the glacier and soil being freed by the melting process accumulated in front of the glacier. When the glacier receded, all soil trapped in the melting ice was dropped. Such direct glacial deposits are a heterogeneous mixture of all soil sizes and are termed *glacial till.*

The land form or topographic surface resulting after a glacier receded is called a *ground moraine* or *till plain.* The hills and ridges of till that formed at the front of the glacier and marked its farthest advance are *terminal moraines* (Figure 7). *Recessional*



(a)



(b)

Figure 7 (a) The development of a terminal moraine and outwash plain in front of a glacier. (b) Aerial photo of glacier showing developing moraine and outwash area.

moraines are hills or ridges that represent deposits along the front of a glacier where it made temporary stops during the recession process. (Long Island, located in the northeastern United States, illustrates such a glacial landform of geographical importance;[3] the western segment provides approximately half the land area for New York City, and the island houses one of the world's highest population densities.) Debris dropped along the side of a glacier as it moved through a valley is termed a *lateral moraine*. Long low hills of till that extend in the direction of the glacial movement are called *drumlins*.

Where the till material was dropped under the glacier and overrun, it became very dense and compact, and can provide excellent foundation support. The suitability of a till material for construction purposes, such as for a compacted earth fill, depends on the quantity and range of sizes of the soil particles; till deposits that have a preponderance of coarse particles are good construction materials, whereas deposits containing large percentages of silt and clay materials are, generally, relatively difficult to handle and compact.

Where an area was subjected to repeated glacial action, early deposits could be overlain by the more recent glacial till, or the original deposits may have been moved and redeposited by the more recent glacier as a new landform. As a result, the original source of a material may be difficult to determine. In some situations, however, the color may provide information about its source. With reference to glacial deposits in the northern United States, material gathered by glaciers from the Hudson Bay area in Canada is gray, whereas soils picked up from glaciers originating in the area northwest of the Great Lakes are red in color as a result of the high iron content in the original soils of that area.

Even while the glaciers covered a land area, there were streams and rivers of water flowing on the surface of the glaciers and in subterranean tunnels eroded within the glaciers. These flowing bodies of water carried material picked up from the land surface or

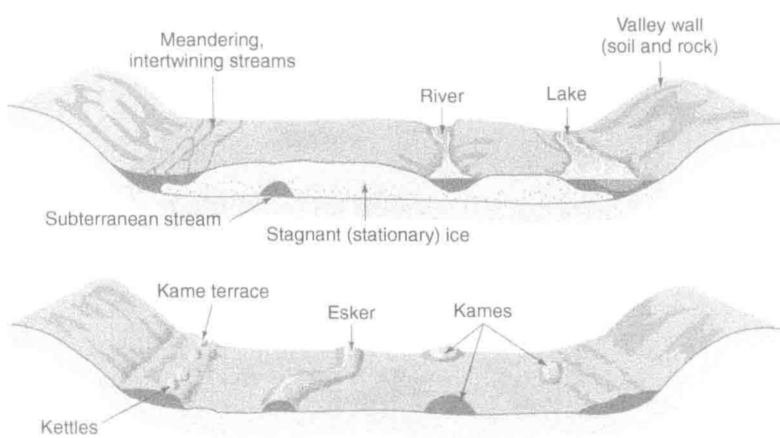


Figure 8 Flowing water on a glacier and resulting effect on landform.

[3]Present-day Long Island is actually the result of two glacial actions, one forming the eastern or outer section (Ronkonkoma Ridge) and the other forming the western or inner section (Harbor Hill Ridge).