4

AIRPHOTO INTERPRETATION FOR TERRAIN EVALUATION

4.1 INTRODUCTION

Various terrain characteristics are important to soil scientists, geologists, geographers, civil engineers, urban and regional planners, landscape architects, real estate developers, and others who wish to evaluate the suitability of the terrain for various land uses. Because terrain conditions strongly influence the capability of the land to support various species of vegetation, an understanding of airphoto interpretation for terrain evaluation is also important for botanists, foresters, wildlife ecologists, and others concerned with vegetation mapping and evaluation.

The principal terrain characteristics that can be estimated by means of airphoto interpretation are bedrock type, landform, soil texture, site drainage conditions, susceptibility to flooding, and depth of unconsolidated materials over bedrock. In addition, the slope of the land surface can be estimated by airphoto interpretation and measured by photogrammetric methods (Chapter 5).

In this chapter, we consider the terrain characteristics and airphoto identification of most of the common bedrock types and associated residual soils, followed by a consideration of transported soils and organic soils. The airphoto interpretation process described herein emphasizes terrain characteristics that are visible on stereoscopic aerial photographs. The geological terminology employed follows that set forth in the American Geological Institute *Dictionary of Geological Terms* [1].

4.2 SOIL CHARACTERISTICS

The term "soil" has specific scientific connotations to different groups involved

with soil surveying and mapping. For example, engineers and agricultural soil scientists each have a different concept of soils and use a different terminology in describing soils. Most engineers consider all unconsolidated earth material lying above bedrock to be "soil." Agricultural soil scientists regard "soil" as a material that develops from a geologic parent material through the natural process of weathering and contains a certain amount of organic material and other constituents that support plant life. For example, a ten meter thick deposit of glacial till over bedrock might be extensively weathered and altered to a depth of one meter. The remaining nine meters would be relatively unaltered. An engineer would consider this a soil deposit ten meters thick lying over bedrock. A soil scientist would consider this a soil layer one meter thick lying over glacial till parent material. We use the soil science (pedalogical) concept of soil in this chapter.

Through the processes of weathering, including the effects of climate and plant and animal activity, unconsolidated earth materials develop distinct layers that soil scientists call *soil horizons*. The top layer is designated the *A horizon* and called the *surface soil*, or *topsoil*. It can range from about 0 to 60 cm in thickness and is typically 15 to 30 cm. The A horizon is the most extensively weathered horizon. It contains the most organic matter of any horizon and has had some of its fine-textured particles washed down into lower horizons. The second layer is designated the *B horizon* and called the *subsoil*. It can range from 0 to 250 cm in thickness and usually is 45 to 60 cm. The B horizon contains some organic matter and is the layer of accumulation for the fine-textured particles washed down from the A horizon. The portion of the soil profile occupied by the A and B horizons is called the *soil* (or *solum*) by soil scientists. The *C horizon* is the underlying geologic material from which the A and B horizons have developed and is called the *parent material* (or *initial material*). The concept of soil profile development into distinct horizons is vitally important for agricultural soils mapping and productivity estimation, as well as for many developmental uses of the landscape.

There are three principal origins of soil materials. *Residual soils* are formed in place from bedrock by the natural process of weathering. *Transported soils* are formed from parent materials that have been transported to their present location by wind, water, and/or glacial ice. *Organic soils* (muck and peat) are formed from decomposed plant materials in a very wet environment, typically in shallow lakes or areas with a very high ground water table.

Soils consist of combinations of solid particles, water, and air. Particles are given size names, such as gravel, sand, silt, and clay, based on particle size. Particle size terminology is not standardized for all disciplines and several classification systems exist. Typical particle size definitions for engineers and agricultural soil scientists are shown in Table 4.1. For our purposes, the differences in particle size definitions between engineers and soil scientists for gravel, sand, silt, and clay are relatively unimportant. We use the soil science

Table 4.1 Soil Particle Size Designations

Soil Particle Size Name	Soil Particle Size: Engineering Definition	Soil Particle Size: Agricultural Soil Science Definition
Gravel	2.0 to 76.2 mm	2.0 to 76.2 mm
Sand	0.074 to 2.0 mm	0.05 to 2.0 mm
Silt	0.005 to 0.074 mm	0.002 to 0.05 mm
Clay	below 0.005 mm	below 0.002 mm

definition because it has a convenient system for naming combinations of particle sizes.

Figure 4.1 shows the system used by soil scientists to give textural names to specific combinations of sand, silt and clay. When a soil contains a significant amount of gravel, the term "gravelly" (20 to 50 percent gravel) or "very gravelly" (more than 50 percent gravel) is used in addition to the basic textural name. For example, a soil containing 60 percent sand, 30 percent silt, and 10 percent clay would be called "sandy loam." A soil containing 60 percent gravel, 24 percent sand, 12 percent silt, and 4 percent clay would be called "very gravelly sandy loam." Note that the proportions of sand, silt, and clay are the same for both examples.

We consider materials containing more than 50 percent silt and clay to be *fine-textured* and materials containing more than 50 percent sand and gravel to be *coarse-textured*.

The descriptions of many of the stereopair illustrations contained in this chapter include reference to the soil texture, soil drainage condition, and depth to bedrock of the terrain shown in the illustrations. In the case of residual soils, where the depth to bedrock is commonly only 1 to 2 m, the textures specified are generally representative of the B and C horizon textures. In the case of transported soils, where the weathered soil profile is commonly only a small fraction of the total thickness of the unconsolidated transported material (e.g., a 30 meter high river terrace might have a weathered profile only one meter thick), emphasis is on describing the texture of the parent material. Not all the information given in figure descriptions was obtained solely by airphoto interpretation. In cases where specific soil information is given, USDA-SCS soil survey reports were consulted for information regarding soil texture, drainage class, and depth to bedrock.

Soils have characteristic drainage conditions that depend on surface runoff, soil permeability, and internal soil drainage. We use the USDA [20] soil drainage classification system for soils in their natural condition, with the following seven soil drainage classes:

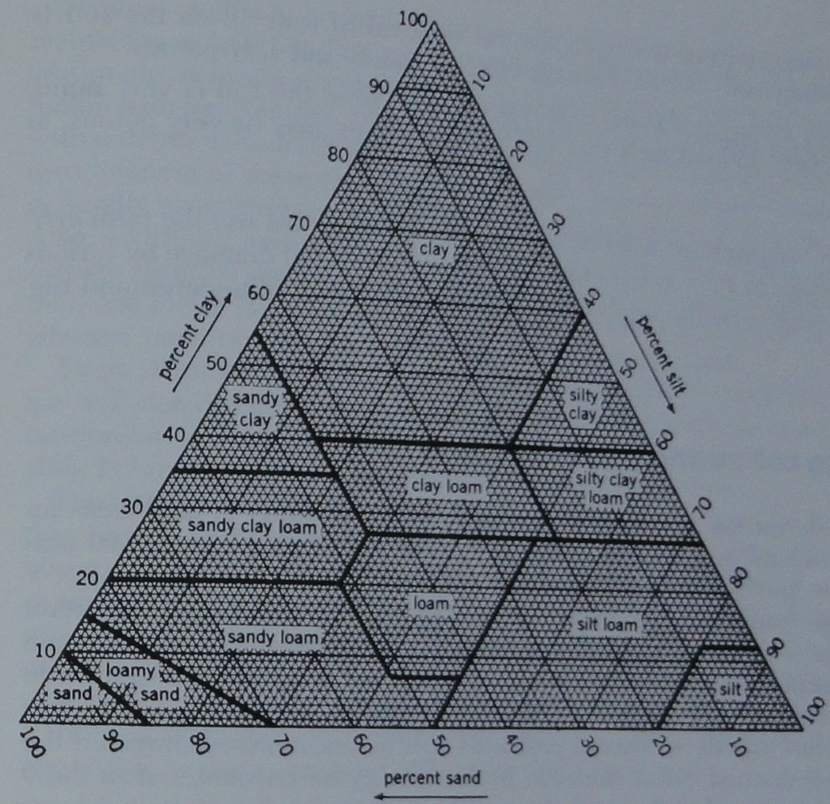

Figure 4.1 USDA textural triangle chart showing the percentages of sand, silt, and clay in the basic USDA soil textural classes. (After USDA [20].)

Very poorly drained. Natural removal of water from the soil is so slow that the water table remains at or near the surface most of the time. Soils of this drainage class usually occupy level or depressed sites and are frequently ponded.

Poorly drained. Natural removal of water from the soil is so slow that it remains wet for a large part of the time. The water table is commonly at or near the ground surface during a considerable part of the year.

Somewhat poorly drained. Natural removal of water from the soil is slow enough to keep it wet for significant periods but not all the time.

Moderately well drained. Natural removal of water from the soil is somewhat slow so that the soil is wet for a small but significant part of the time.

Well drained. Natural removal of water from the soil is at a moderate rate without notable impedance.

Somewhat excessively drained. Natural removal of water from the soil is rapid. Many soils of this drainage class are sandy and very porous.

Excessively drained. Natural removal of water from the soil is very rapid. Excessively drained soils may be on steep slopes, may be very porous, or both.

The above descriptions refer to natural soil drainage. We use the term *artificial drainage* to refer to the enhancement of natural soil drainage by various human activities including ditching and the installation of underground tile drains.

4.3 LAND USE SUITABILITY EVALUATION

Terrain information can be used to evaluate the suitability of land areas for a variety of land uses. Our emphasis is on suitability for developmental purposes, principally urban and suburban land uses.

The topographic characteristics of an area are one of the most important determinants of the suitability of an area for development. For subdivision development, slopes in the 2 to 6 percent range are steep enough to provide for good surface drainage and interesting siting, and yet flat enough so that no significant site development problems will be encountered provided the soil is well drained. Some drainage problems may be encountered in the 0 to 2 percent range, but these can be readily overcome unless there is a large expanse of absolutely flat land with insufficient internal drainage. The site plan in the 6 to 12 percent range may be more interesting than in the 2 to 6 percent range, but will be more costly to develop. Slopes over 12 percent present problems in street development and lot design and also pose serious problems when septic tanks are used for domestic sewage disposal. Severe limitations to subdivision development occur on slopes over 20 percent. For industrial park and commercial sites, slopes of not more than 5 percent are preferred.

The soil texture and drainage conditions also affect land use suitability. Well-drained, coarse-textured soils present few limitations to development. Poorly drained or very poorly drained, fine-textured soils can present severe limitations. Shallow groundwater tables and poor soil drainage conditions cause problems in septic tank installation and operation, in cellar and foundation excavation, and in keeping cellars water-free after construction. In general, depths to the water table of at least 2 meters are preferred. Depths of 1 to 2 meters may be satisfactory where public sewage disposal is provided and buildings are constructed without basements.

Shallow depths to bedrock cause problems in septic tank installation and maintenance, in utility line construction, in cellar and foundation excavation, and in street location and construction, especially when present in combination with steep slopes. Depths to bedrock over 2 meters are preferred. Sites with a depth to bedrock of 1 to 2 meters are generally unsatisfactory but the development of these areas may be feasible in some cases. These sites are generally unsatisfactory where septic tank sewage disposal is to be provided. Also, additional excavation costs are involved where basements and public sewage disposal facilities are to be constructed. A depth to bedrock of less than one meter presents serious limitations to development and is an unsatisfactory condition in almost all cases of land development.

Slope stability problems occur with certain soil-slope conditions. Although we will not discuss techniques for slope stability analysis using airphoto interpretation, it should be mentioned that numerous areas of incipient landslide failure have been detected by airphoto interpretation.

Despite the emphasis here on land development, it must be recognized that certain land areas may be worthy of preservation in their natural state because of outstanding topographic or geologic characteristics or because rare or endangered plant or animal species occupy those areas. In additional, the maintenance of prime agricultural land for agricultural rather than developmental use must be an important consideration in all land use planning decisions. Similar concerns also apply to the preservation of wetland systems. Various airphoto interpretation techniques discussed in Chapters 3 and 4 are applicable to the assessment of land for these purposes.

4.4 ELEMENTS OF AIRPHOTO INTERPRETATION FOR TERRAIN EVALUATION

Airphoto interpretation for terrain evaluation is based on a systematic observation and evaluation of key elements that are studied stereoscopically. These are: topography, drainage pattern and texture, erosion, photo tone, and vegetation and land use.

Topography

Each landform and bedrock type described has its own characteristic topographic form, including a typical size and shape. In fact, there is often a distinct topographic change at the boundary between two different landforms.

With vertical photographs having a normal 60 percent overlap, most individuals see the terrain exaggerated in height about three or four times. Consequently, slopes appear steeper than they actually are. The specific amount

of vertical exaggeration observed in any given stereopair is a function of the geometric conditions under which the photographs are viewed and taken. The ground distance between the photo centers at the times of exposure is called the *air base*. The ratio between the air base and the flying height above ground determines the vertical exaggeration. The larger the *base-height ratio*, the greater the vertical exaggeration. Table 4.2 lists various actual and apparent slopes based on the rule-of-thumb that

$$\tan(\text{apparent slope angle}) = \tan(\text{true slope angle}) \times 3$$

Drainage Pattern and Texture

The drainage pattern and texture seen on aerial photographs are indicators of landform and bedrock type and also suggest soil characteristics and site drainage conditions.

Six of the most common drainage patterns are illustrated in Figure 4.2. The *dendritic drainage pattern* is a well-integrated pattern formed by a main stream with its tributaries branching and rebranching freely in all directions and occurs on relatively homogeneous materials such as flat-lying sedimentary rock and granite. The *rectangular drainage pattern* is basically a dendritic pattern modified by structural bedrock control such that the tributaries meet at right angles and is typical of flat-lying massive sandstone formations with a well-developed joint system. The *trellis drainage pattern* consists of streams having one dominant direction, with subsidiary directions of drainage at right angles, and occurs in areas of folded sedimentary rocks. The *radial*

Table 4.2 Slope Exaggeration on Stereo Airphotos

Actual Terrain Slope	Approximate Apparent Slope on Stereo Airphotos
0°	0°
2°	6°
5°	15°
10°	28°
15°	39°
30°	60°
45°	72°
60°	79°
90°	90°

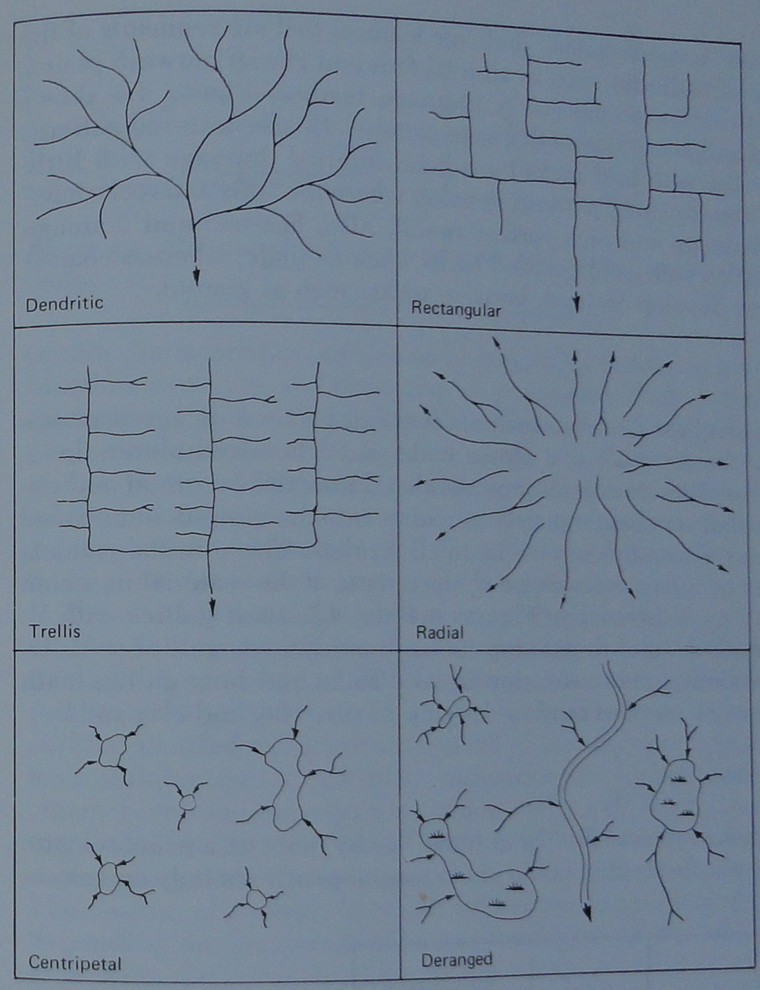

Figure 4.2 Six basic drainage patterns.

drainage pattern is formed by streams that radiate outward from a central area as is typical of volcanoes and domes. The *centripetal drainage pattern* is the reverse of the radial drainage pattern where drainage is directed toward a central point and occurs in areas of limestone sinkholes, glacial kettle holes, volcanic craters, and other depressions. The *deranged drainage pattern* is a disordered pattern of aimlessly directed short streams, ponds, and wetland areas typical of ablation glacial till areas.

The previously described drainage patterns are all "destructional" drainage patterns resulting from the erosion of the land surface; they should not

be confused with "constructional" drainage features that are remnants of the mode of origin of landforms such as alluvial fans and glacial outwash plains.

Coupled with drainage pattern is drainage texture. Figure 4.3 shows *coarse-textured* and *fine-textured* drainage patterns. Coarse-textured patterns develop where the soils and rocks have good internal drainage with little surface runoff. Fine-textured patterns develop where the soils and rocks have poor internal drainage and high surface runoff. Also, fine-textured drainage patterns develop on soft, easily eroded rocks, such as shale, whereas coarse-textured patterns develop on hard, massive rocks, such as granite.

Erosion

Gullies are the smallest drainage features that can be seen on aerial photographs and may be as small as a meter wide and a hundred meters long. Gullies result from the erosion of unconsolidated material by runoff and develop where rainfall cannot adequately percolate into the ground, but instead collects and flows across the surface in small rivulets. These initial rivulets enlarge and take on a particular shape characteristic of the material in which they are formed. As illustrated in Figures 4.4 and 4.5, short gullies with V-shaped cross sections tend to develop in sand and gravel; gullies with U-shaped cross sections tend to develop in silty soils; and long gullies with gently rounded cross sections tend to develop in silty clay and clay soils.

Photo Tone

The term *photo tone* refers to the "brightness" at any point on a panchromatic photograph. The absolute value of the photo tone depends not only on certain

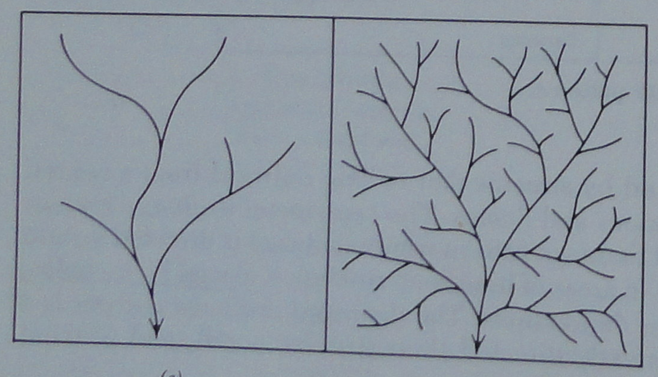

Figure 4.3 Illustrative drainage patterns. (*a*) Coarse-textured dendritic pattern. (*b*) Fine-textured dendritic pattern.

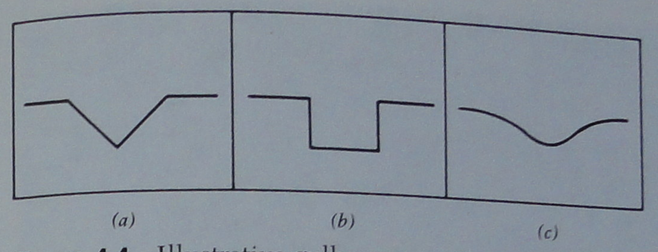

Figure 4.4 Illustrative gully cross sections. (*a*) Sand and gravel. (*b*) Silt. (*c*) Silty clay or clay.

terrain characteristics but also on photographic factors such as film-filter combination, exposure, and photographic processing. Photo tone also depends on meteorological and climatological factors such as atmospheric haze, sun angle, and cloud shadows. Because of the effect of these nonterrain-related factors, photo interpretation for terrain evaluation must rely on an analysis of *relative* tone values, rather than absolute tone values. Relative tone values are important because they often form distinct photographic patterns that may be of great significance in airphoto interpretation.

The effect of terrain conditions on relative photo tone is illustrated in Figure 4.6. In the case of bare soils (nonvegetated soils), the lighter-toned areas tend to have a topographically higher position, a coarser soil texture, a lower soil moisture content, and a lower organic content. Figure 4.6 shows the striking mottled tonal pattern typical of fine-textured glacial till soils. The tonal differences are caused by differences in sunlight reflection due principally to the varying moisture content of the soil. The lighter-toned areas are somewhat poorly drained silt loam soils on rises ⅓ to 1 meter above the surrounding darker-toned areas of very poorly drained silty clay loam soils. The degree of contrast between lighter and darker-toned bare soils varies depending on the overall moisture conditions of the soil, as illustrated in Plate VII.

The sharpness of the boundary between lighter and darker-toned areas is often related to the soil texture. Coarser-textured soils will generally have sharper gradations between light and dark tones while finer-textured soils will generally have more gradual gradations. These variations in tonal gradients result from differences in capillary action occurring in soils of different textures.

Our discussion of airphoto interpretation for terrain evaluation relates primarily to panchromatic film because this film type has historically received the most use for this purpose. Subtle differences in soil and rock colors can be more readily detected using color film as compared with panchromatic film and subtle differences in soil moisture and vegetation vigor can be more readily detected using color infrared film. Because there is a wide variety of

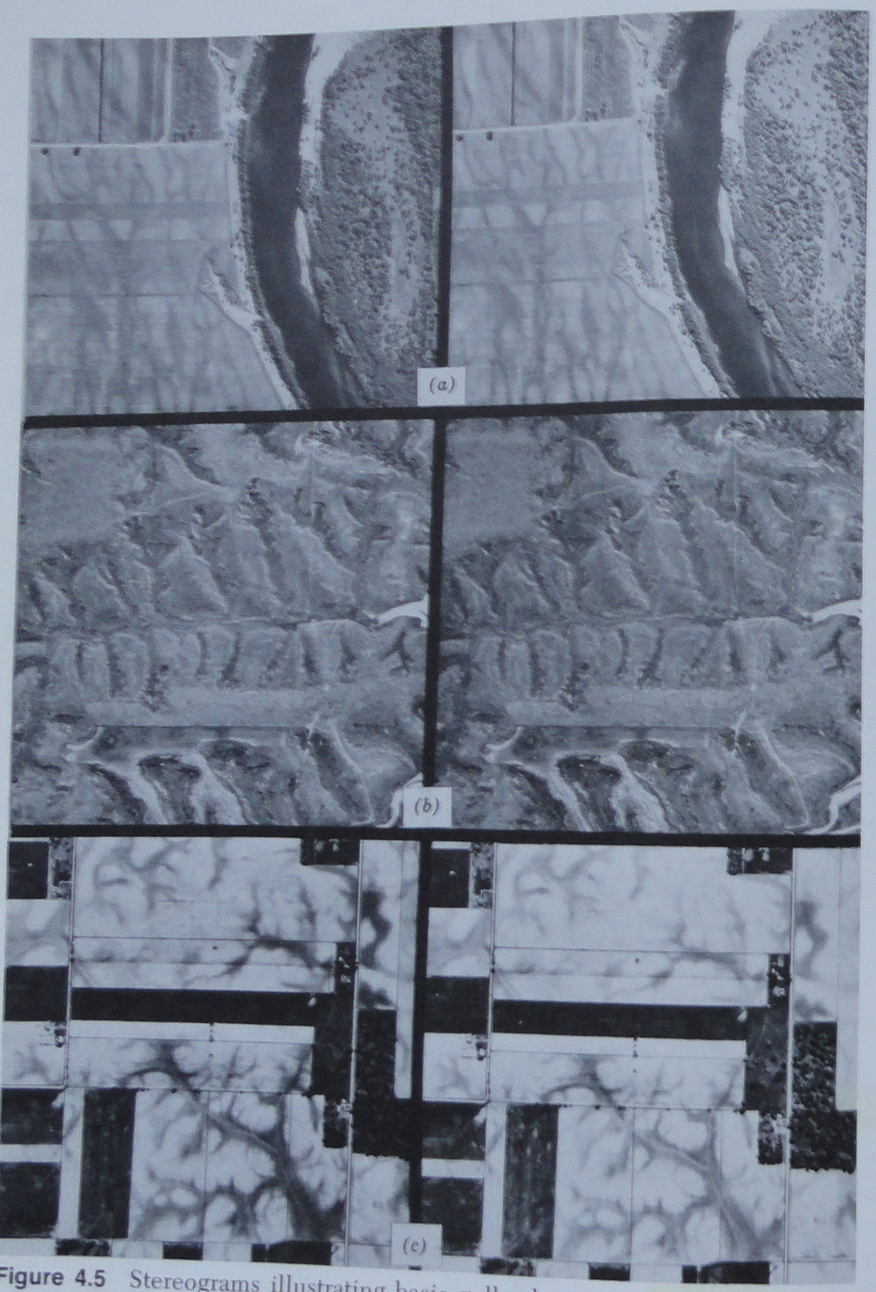

Figure 4.5 Stereograms illustrating basic gully shapes. (*a*) Sand and gravel terrace, Dunn County, Wisconsin. (*b*) Loess (wind-deposited silt), Buffalo County, Nebraska. (*c*) Silty clay loam glacial till, Madison County, Indiana. 1:20,000. (USDA-ASCS photos.)

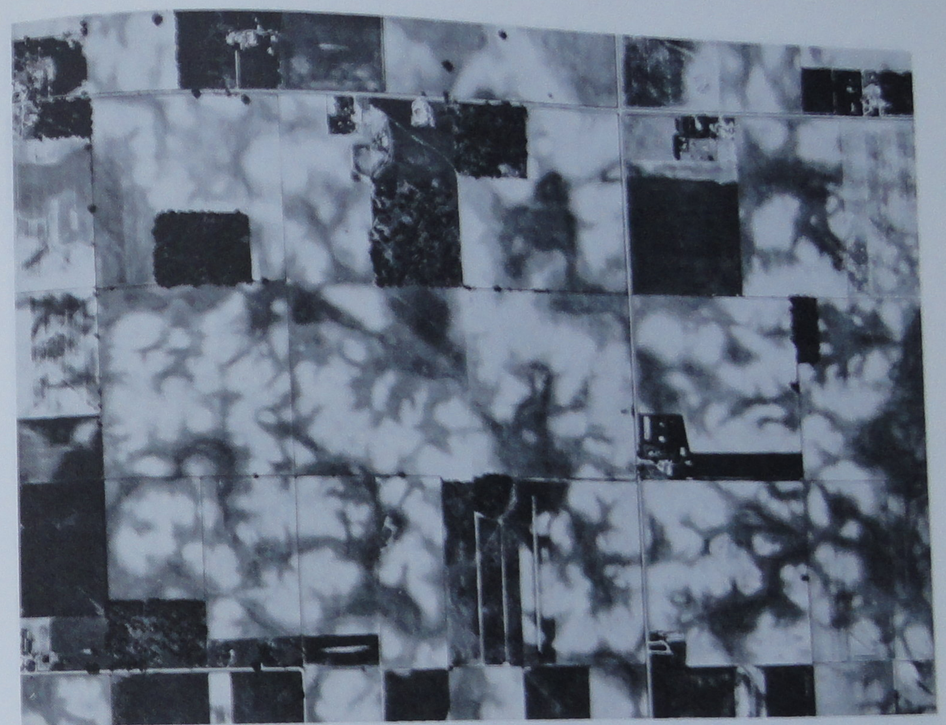

Figure 4.6 Airphoto illustrating effect of terrain conditions on relative photo tones. Madison County, Indiana. 1:16,000. (USDA-ASCS photo.)

soil and vegetation colors possible on color and color infrared films, it is not possible to consider them all here. Therefore, our discussion of *photo tone* will describe tone as the shades of gray seen on panchromatic photographs. Persons working with color or color infrared photographs of specific geographic regions at specific times of the year can work out their own criteria for *tone and color* evaluation following the principles in this chapter.

Vegetation and Land Use

Differences in natural or cultivated vegetation often indicate differences in terrain conditions. For example, orchards and vineyards are generally located on well drained soils, whereas truck farming activities often take place on highly organic soils such as muck and peat deposits. In many cases, however, vegetation and land use obscure differences in terrain conditions and the interpreter must be careful to draw inferences only from meaningful differences in vegetation and land use.

Figure 4.7*a* shows a very poorly drained area of organic soils (darker-toned

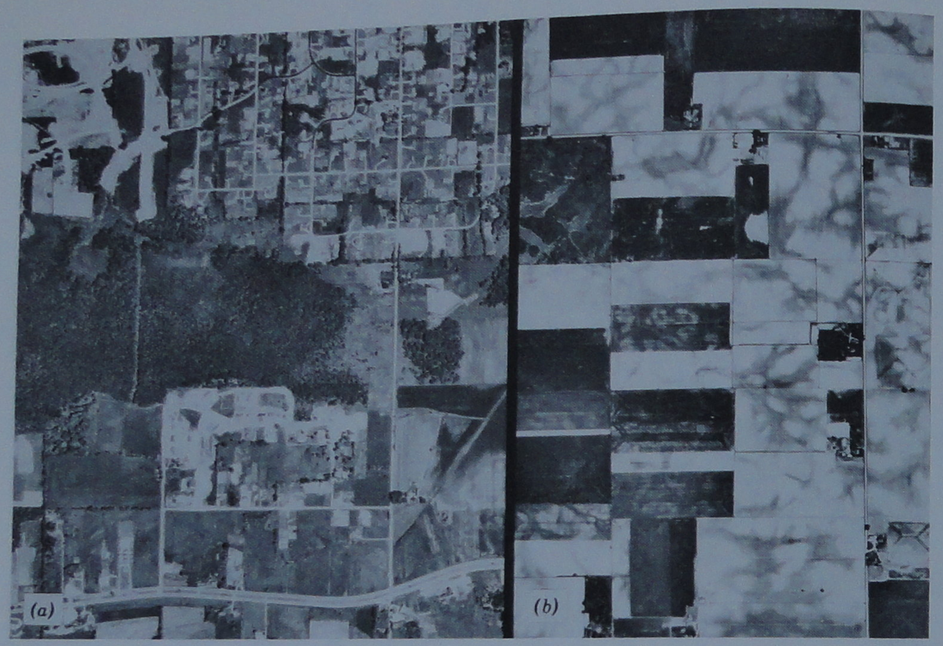

Figure 4.7 Airphotos illustrating vegetation and land use paterns. (*a*) Waukesha County, Wisconsin. (*b*) Madison County, Indiana. 1:23,000. (USDA-ASCS photos.)

area running across center of photo) surrounded by a moderately well drained area of glacial till soils. The distinct differences in vegetation and land use on these soils reflect the variations in terrain conditions associated with these soil materials.

The vegetation cover in agricultural areas changes during the year and, during the summer growing season, dense cultivated vegetation commonly obscures tonal patterns due to soil differences. Figure 4.7*b* shows an area of fine-textured glacial till similar to that shown in Figure 4.6. The soil patterns are similar across the entire area of the photograph but the variations in crop patterns cause a very different appearance in different fields. The mottled tone pattern typical of glacial till is clearly seen in the bare soil fields, but is obscured in the fields with significant crop cover.

4.5 THE AIRPHOTO INTERPRETATION PROCESS

Through an analysis of the elements of photo interpretation (topography, drainage pattern and texture, erosion, photo tone, vegetation, and land use), the photo interpreter can identify different terrain conditions and can determine the boundaries between them. Initially, photo interpreters will need to consider carefully each of the above elements individually and in combination in order to estimate terrain conditions. After some experience, these elements are often applied subconsciously as the interpreter develops the facility to recognize certain recurring airphoto patterns almost instantaneously. In complex areas, the interpreter should not make snap decisions about terrain conditions, but should carefully consider the topography, drainage pattern and texture, erosion, photo tone, vegetation, and land use characteristics exhibited on the aerial photographs.

In the remainder of this chapter, we examine each of the principal bedrock and transported soil types common on the earth's surface, as well as organic deposits. For each of these, we consider geologic origin and formation, soil and/or bedrock characteristics, implications for land use planning, and airphoto identification using the elements of airphoto interpretation for terrain evaluation. Our illustrations are limited to occurrences in the United States. We emphasize the recognition of clear-cut examples of various bedrock and transported soil types. In nature, there are many variations to each type. Interpreters working in specific localities can use the principles set forth here to develop their own photo interpretation keys.

In cases where distinctions in airphoto appearance must be made for different climatic situations, we will speak of "humid" and "arid" climates. We will consider *humid climates* to occur in areas that receive 50 cm or more rainfall per year and *arid climates* to occur in areas that receive less than 50 cm per year rainfall. In the United States, farming without irrigation is feasible in areas with a rainfall of about 50 cm per year or more. Areas receiving less than 50 cm per year rainfall generally require irrigation for farming.

Even the most searching and capable airphoto analysis can benefit from field verification as the airphoto interpretation process is seldom expected to stand alone. The photo interpreter should consult existing topographic, geologic, and soil maps and should conduct a selective field check. The principal benefits of airphoto interpretation for terrain evaluation should be a savings in time, money, and effort. The use of airphoto interpretation techniques can allow for terrain mapping during periods of unsuitable weather for field mapping and can provide for more efficient field operations.

4.6 SEDIMENTARY ROCKS

The principal sedimentary rock types to be considered are sandstone, shale, and limestone. Sedimentary rocks are by far the most common rock type exposed at the earth's surface and extend over approximately 75 percent of the earth's land surface (igneous rocks extend over approximately 20 percent and metamorphic rocks over about 5 percent).

Sedimentary rocks are formed by the consolidation of layers of sediments

that have settled out of water or air. Sediments are converted into coherent rock masses by lithification, a process that involves cementation and compaction by the weight of overlying sediments.

Clastic sedimentary rocks are rocks containing discrete particles derived from the erosion, transportation, and deposition of pre-existing rocks and soils. The nature of the constituent particles and the way in which they are bound together determine the texture, permeability, and strength of the rocks. Clastic sedimentary rocks containing primarily gravel-size particles are called *conglomerate*, those containing primarily sand-sized particles are called *sandstone*, those containing primarily silt-sized particles are called *siltstone*, and those containing primarily clay-sized particles are called *shale*.

Limestone has a high calcium carbonate content and is formed from chemical or biochemical action. Chemically formed limestone results from the precipitation of calcium carbonate from water. Biochemically formed limestone results from chemical processes acting on shells, shell fragments, and plant materials.

The principal sedimentary rock characteristics that affect the airphoto appearance of the terrain are *bedding*, *jointing*, and *resistance to erosion*.

Sedimentary rocks are typically stratified or layered as the result of variations in the depositional process. The individual strata or layers are called *beds*. The top and bottom of each bed have more or less distinct surfaces, called bedding planes, that delineate the termination of one bed and the beginning of another with somewhat different characteristics. Individual beds may range in thickness from a few millimeters to many meters. Beds in their initial condition usually are nearly horizontal but may be tilted to any angle by subsequent movements of the earth's crust.

Joints are cracks through solid bodies of rock with little or no movement parallel to joint surfaces. Joints in sedimentary rocks are primarily perpendicular to bedding planes and form plane surfaces that may intersect other joint planes. Several systematic joints constitute a joint set and when two or more sets are recognized in an area, the overall pattern is called a joint system. Because joints are planes of weakness in rocks, they often form surfaces clearly visible on aerial photographs, especially in the case of sandstone. Streams often follow joint lines and may zig-zag from one joint line to another.

The *resistance to erosion* of sedimentary rocks depends on rock strength, permeability, and solubility. Rock strength depends principally on the strength of the bonding agent holding the individual sediment particles together and on the thickness of the beds. Thick beds of sandstone cemented by quartz are very strong and may be used as building materials. Thin beds of shale are often so weak that they can be shattered by hand into flakes and plates. Rock permeability refers to the ability of the rock mass to transmit

water and depends on the size of the pore spaces between sediment particles and on the continuity of their connections. Sandstone is generally a very permeable rock. Shale is usually quite impermeable and water moves principally along joint planes rather than in sediment void spaces. Limestones high in calcium carbonate are soluble in water and may dissolve under the action of rainfall and ground water movement.

We first consider the characteristics of sandstone, shale, and limestone, and then examine the characteristics of interbedded sedimentary rocks, both horizontally bedded and tilted.

Sandstone

Sandstone deposits commonly occur in beds a few meters thick interbedded with shale and/or limestone. We discuss such occurrences later in this section. Here we are concerned primarily with sandstone formations about ten meters or more in thickness.

Sandstone *bedding* is often prominent on airphotos, especially when the sandstone beds occur over softer, more easily eroded formations such as shale. *Jointing* is prominent, with a joint system consisting of two or three dominant directions. The *resistance to erosion* varies, depending on the strength of the cementing agent. Sandstone cemented with iron compounds and silica is typically very strong, whereas sandstone cemented with carbonates is generally quite weak. Since sandstone is very permeable, most rainfall percolates downward through the rock rather than becoming erosion-producing surface runoff. Sandstone cemented with carbonates may weaken as percolating water dissolves the cementing agent.

In arid areas, there is seldom a residual soil cover over sandstone because any weathered sand particles are removed by wind erosion. In humid areas, the depth of residual soil cover depends on the strength of the cementing agent, but is commonly less than one meter and seldom more than two meters. The residual soil texture in humid areas depends on the particle size of the sandstone and on the strength of the cementing agent. Weakly cemented sandstone weathers to sand while residual soils formed from strongly cemented sandstone may contain some silt and clay. Residual soils are typically well drained to excessively drained sand, loamy sand and sandy loam.

Areas of massive sandstone beds with a residual soil cover are commonly undeveloped because of a combination of their typically rugged topography and shallow depths to bedrock. Buried sandstone strata are often an excellent source of groundwater for both individual homeowners and municipalities. Well-cemented sandstone rock is often used as building stone for residential construction.

Airphoto Identification of Horizontally Bedded Sandstone. *Topography*: Bold, massive, relatively flat-topped hills with nearly vertical or very steep hillsides. *Drainage*: Coarse-textured, joint-controlled, modified dendritic pattern; often a rectangular pattern caused by perpendicular directions of joint sets. *Erosion*: Few gullies; V-shaped if present in residual soil. *Photo tone*: Generally light-toned due to light rock color and excellent internal drainage of both residual soil and sandstone rock. Reddish sandstone in arid areas may photograph with a somewhat dark tone on panchromatic film. A dense tree cover over sandstone in humid areas generally appears dark, but in this case the interpreter is looking at the tree canopy rather than the soil or rock surface. *Vegetation and land use*: Sparse vegetation in arid areas. Commonly forested in humid areas as residual soil is too well drained to support crops. In a humid climate, flat-topped sandstone ridges with a loess cover (Section 4.9) are often farmed. *Other*: Sandstone is sometimes mistakenly identified as granite (Section 4.7).

Figure 4.8 Horizontally bedded sandstone in an arid climate. Southern Utah, September 1952. 1:20,000. (USGS photos. Stereogram.)

Figure 4.8 shows horizontally bedded sandstone in an arid climate interbedded with a few thin shale beds. The bedding can best be seen by inspecting the valley walls where the deeply incised stream cuts across the terrain. The direction of the major joint set is nearly vertical on the page; a secondary direction is perpendicular to the major joint set. These joint sets only partially control the direction of flow of the major stream, but strongly influence the direction of secondary drainage.

Figure 4.9 shows horizontally bedded sandstone in an arid climate. There is virtually no interbedded shale and the photo tone is very light. As in the previous figure, the joint sets are prominent. Photo interpreters must be careful to distinguish between bedding and jointing in order to properly identify the attitude of the beds (horizontally bedded or tilted). In Figure 4.9, the two principal directions of jointing are clearly expressed, while the bedding is more subtle.

Figure 4.10 shows horizontally bedded sandstone in a humid climate. Note the massive hills and the nearly continuous tree cover. The residual soils here are well drained sandy loam with many sandstone rock fragments at least 50 cm deep over sandstone bedrock.

Figure 4.9 Horizontally bedded sandstone in an arid climate. Garfield County, Utah, July 1960. 1:30,800 (USDA-ASCS photos. Stereogram.)

Figure 4.10 Horizontally bedded sandstone in a humid climate McKean County, Pennsylvania, October 1958. 1:33,300. (USDA-ASCS photos. Stereogram.)

Shale

Deposits of shale are common throughout the world, as both thick deposits and thin deposits interbedded with sandstone and limestone. Shale *bedding* is very extensive with beds typically one to twenty cm in thickness. Bedding is not always visible on aerial photographs. However, if beds with a distinct difference in color or resistance to erosion are present, or if shale is interbedded with sandstone or limestone, bedding may be seen. The effect of *jointing* is not always strong enough to alter the surface drainage system into a significantly joint-controlled pattern. The *resistance to erosion* is low, compared with other sedimentary rock types. Since shale is relatively impermeable, most rainfall runs off the ground surface causing extensive erosion.

The depth of residual soil cover is generally less than one meter and seldom more than two meters. The residual soil is high in silt and clay, with textures typically silt loam, silty clay loam, silty clay, and clay. Internal soil drainage is typically moderately well drained or poorer, depending on soil texture and on soil and rock structure.

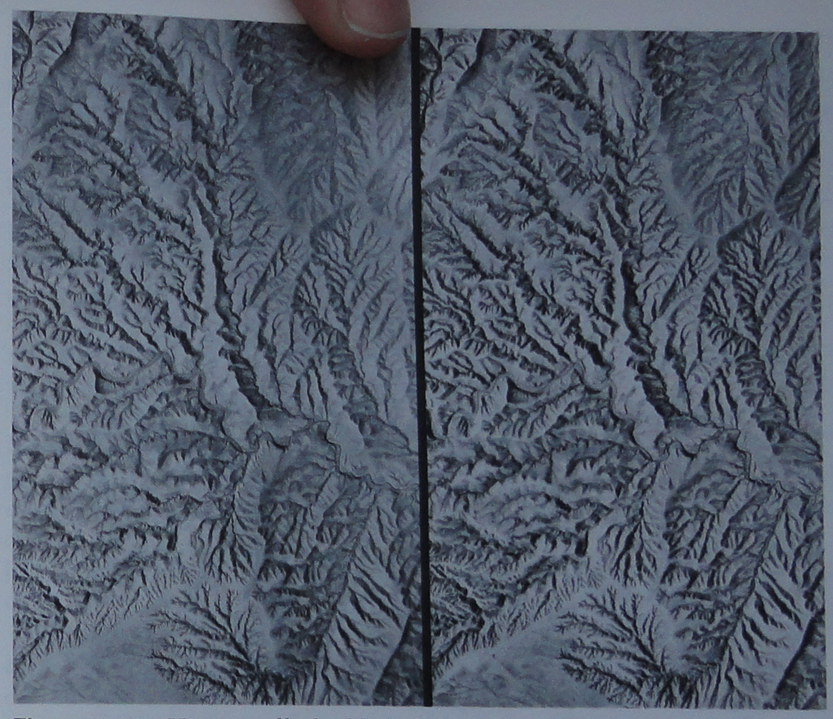

Figure 4.11 Horizontally bedded shale in an arid climate. Utah, November 1952. 1:26,700. (USGS photos. Stereogram.)

Although the topography in shale areas is generally favorable to urban development, the soil drainage and depth to bedrock conditions may limit residential development by causing problems in basement excavation and in septic tank installation and maintenance. The groundwater supply is extremely variable in shale bedrock. If the shale is strongly jointed, groundwater may be available. In many cases, however, it will be necessary to drill through the shale into an underlying water-bearing stratum.

Airphoto Identification of Horizontally Bedded Shale. *Topography*: In an arid climate, minutely dissected terrain with steep stream/gully side slopes resulting from rapid surface runoff associated with short-duration heavy rainfall. In a humid climate, gently to moderately sloping, softly rounded hills. *Drainage*: A dendritic pattern with gently curving streams; fine-textured in arid climates and medium-to-fine-textured in humid climates. *Erosion*: Gullies in residual soil have gently rounded cross sections. *Photo tone*: Varies widely, generally dark-toned com-

Figure 4.12 Horizontally bedded shale in a humid climate. Hunterdon County, New Jersey, June 1963. 1:36,400. (USDA-ASCS photos. Stereogram.)

pared with sandstone and limestone. Differences in photo tone may outline bedding. *Vegetation and land use*: Arid areas usually barren, except for desert vegetation. Humid areas intensively cultivated or heavily forested. *Other*: Shale is sometimes mistakenly identified as loess (Section 4.9).

Figure 4.11 shows horizontally bedded shale in an arid climate. A comparison with Figure 4.8 illustrates the contrast in bedding, jointing, and resistance to erosion between shale and sandstone.

Figure 4.12 shows horizontally bedded shale in a humid climate. Note the well-developed medium-textured dendritic drainage pattern. The banding

seen in various portions of the photograph is caused by differences in the residual soil texture and moisture conditions resulting from variations in the composition of the individual shale beds. The residual soils here are moderately well drained shaly silt loam 50 to 100 cm deep over shale bedrock.

Limestone

Limestone consists mainly of calcium carbonate, which is soluble in water. Limestone that contains a significant amount of calcium carbonate and magnesium carbonate (or calcium magnesium carbonate) is called dolomitic limestone, or dolomite, and is less soluble in water. Limestone occurs throughout the world. An area of very soluble limestone occurs in the United States in a region spanning portions of Indiana, Kentucky, and Tennessee.

Limestone *bedding* is generally not prominent on airphotos unless the limestone is interbedded with sandstone or shale. *Jointing* is strong and determines the location of many of the pathways for subsurface drainage. However, jointing is generally not prominent on airphotos of limestone in a humid climate. The *resistance to erosion* varies, depending on the solubility and jointing of the rock. Since calcium carbonate is soluble in water, many limestone areas have been severely eroded by rainfall and groundwater action.

The ground surface in areas of soluble limestone in humid climates is typically dotted with literally thousands of roughly-circular depressions called *sinkholes*. They form when surface runoff drains vertically through the rock along joint planes and the intersections of joint planes, gradually enlarging the underground drainageways by solution and causing the ground surface to collapse and form sinkholes.

There is generally only a shallow residual soil cover over limestone in arid areas where limestone often caps ridges and plateaus. In humid areas, the depth of residual soil cover is extremely variable and depends on the amount of solution weathering. Generally, residual soil depth ranges from two to four meters for soluble limestone (which typically occurs as valleys or plains) and is somewhat less for dolomite (which may cap ridges and plateaus). The residual soil in humid areas contains a great deal of clay. Soil textures of clay, silty clay, clay loam, and silty clay loam are common. Soils are often well drained, except in sinkhole bottoms, due to soil structure and solution openings in the underlying rock. If these soils are extensively disturbed by human activity—such as subdivision development—soil drainage can become very poor.

Although limestone areas may be generally satisfactory for urban development, there are limiting characteristics that must be carefully considered. Because the residual soils contain a great deal of clay, they are relatively poor foundation soils. Often, it will be necessary to locate foundations directly on

Figure 4.13 Horizontally bedded soluble limestone in a humid climate. Harrison County, Indiana, May 1960. 1:20,000. (USDA-ASCS photos. Stereogram.)

bedrock for proper building support. Although the soils are well drained in a natural condition, there may be problems with septic tank operation because of a low percolation rate in the disturbed soil. Groundwater may be difficult to locate and may be very "hard." In addition, effluent from septic tanks can often contaminate the groundwater. There is usually considerable variation in topography, depth to bedrock, and soil drainage conditions, requiring careful soils exploration and mapping before development proceeds. Sinkhole collapse under heavy loads such as construction equipment, highways and airport runways is a serious problem in some limestone areas.

Airphoto Identification of Horizontally Bedded Limestone. This discussion refers to soluble limestone in humid climates. *Topography*: A gently rolling surface broken by numerous roughly-circular sinkholes that are typically 3 to 15 m in depth and 5 to 50 m in diameter. *Drainage*: Centripetal drainage into individual sinkholes. Very few surface streams. Surface streams from adjacent landforms or rock types may disappear underground via sinkholes when streams reach the limestone. *Erosion*: Gullies with gently rounded cross sections develop in the fine-textured residual soil. *Tone*: Mottled tone due to extensive sinkhole development. *Vegetation and land use*: Typically farmed, except for sinkhole bottoms that are often wet or contain standing water a portion of the year. *Other*: Limestone with extensive sinkhole development might be mistakenly identified as ablation till (Section 4.10). Dolomitic limestone is more difficult to identify than soluble limestone. It is generally well drained and has subtle sinkholes.

Figure 4.13 shows horizontally bedded soluble limestone in a humid climate. Note the extensive sinkhole development (up to 40 sinkholes per square kilometer are present) and the complete lack of surface streams. The residual soils here are well drained silty clay loam and silty clay 1.5 to 3 m deep over limestone bedrock.

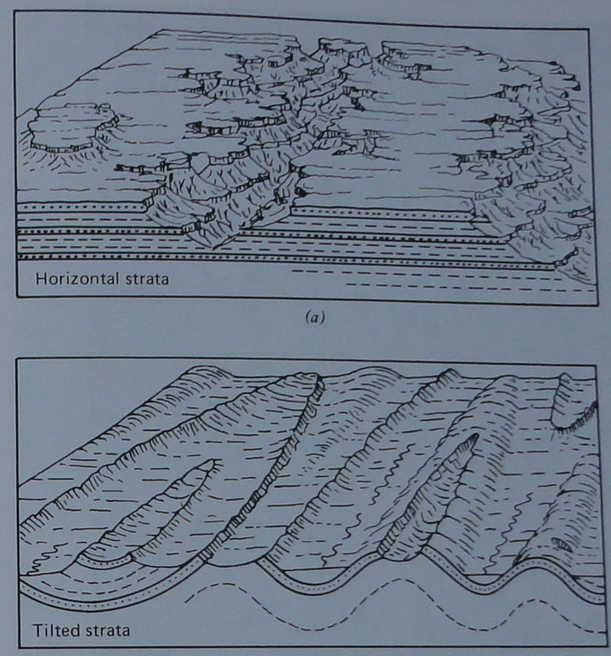

Figure 4.14 Schematic diagram showing the physiographic expression of horizontal and tilted sedimentary rock strata (Original drawn by A. N. Strahler [17].)

Figure 4.15 Horizontally bedded sandstone over shale in an arid climate. Chapin Mesa, Mesa Verde National Park, Colorado. September 1965. 1:49,200. (USGS photos. Stereogram.)

Interbedded Sedimentary Rocks

Rock formations with alternating layers of different sedimentary rock types are called *interbedded sedimentary rocks*. The appearance of the resulting terrain depends on the thickness of the beds and their attitude (horizontal or tilted). As illustrated in Figure 4.14, horizontal strata of differing resistance to erosion result in a stair-stepped terrain, often with steeply incised streams, and folded strata result in a series of linear, often curving, ridges and valleys. The resistant strata that form plateaus and ridges are typically sandstone in humid climates and sandstone or limestone in arid climates.

Airphoto Identification of Horizontally Bedded Interbedded Sedimentary Rocks. *Topography*: When resistant strata are on the order of 10 meters or more in thickness, a distinct stair-stepped terrain is evident

Figure 4.16 Horizontally bedded sandstone over shale in an arid climate. Montezuma County, Colorado, September 1965. 1:32,000. (USGS photos. Stereogram.)

on the photographs. When the thickness of resistant strata is only a few meters, the terrain will be stair-stepped, but slope changes may be difficult to observe on airphotos at commonly utilized scales (1:20,000 and smaller). In humid climates, topographic differences between the terrain on different rock types are typically more subdued than in arid climates. *Drainage*: Typically dendritic, with density determined by relative amounts of sandstone, shale, and limestone. *Erosion*: Varies with residual soil type. *Photo tone, vegetation, and land use*: Differences in photo tone that appear as contours on hillsides often help accentuate the presence of different sedimentary beds. These tonal differences may be caused by differences in vegetation type and vigor over different rock types, or by differences in rock and residual soil cover in nonvegetated areas. Figure 4.12 illustrated banding due to differences in crop growth over shale beds of varying residual soil texture and moisture conditions. In a similar fashion, sandstone and shale interbedded in a humid climate

Figure 4.17 Horizontally bedded sandstone and shale in a humid climate. Green County, Pennsylvania, August 1958. 1:30,800. (USDA-ASCS photos. Stereogram.)

might have a forest cover over the sandstone and agricultural land use over the shale. In addition, in agricultural areas, strip farming and contour plowing can help accentuate the appearance of horizontally bedded sedimentary rocks, although it must be recognized that changes in strip crops do not necessarily occur at the changes between rock types. *Other*: Horizontally bedded sandstone over shale is sometimes mistakenly identified as flood basalt over shale (Section 4.7).

Figure 4.15 shows horizontally bedded sandstone over shale in an arid climate (near area shown in Figure 4.15). Note the numerous alternations of layers of sandstone and shale in the cap rock that is underlain by soft shale. pattern. Two distinct light-toned beds of resistant sandstone with a thin shale bed between them form the cap rock and are underlain by less resistant darker-toned beds of shale. The forest cover is greater than would normally

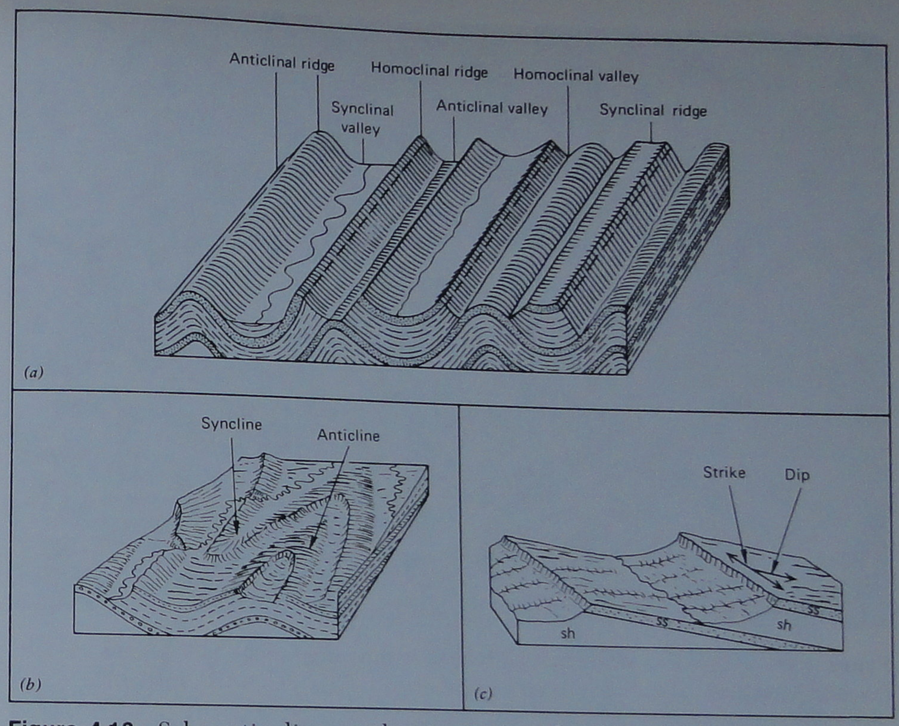

Figure 4.18 Schematic diagram showing topographic forms associated with tilted sedimentary rock strata. (*a* From Thornbury [18]; *b* original drawn by E. Raisz [7]; *c* original drawn by A. N. Strahler [17].)

be expected on sandstone in an arid climate (the area shown receives 45 cm per year rainfall) because the plateau is covered with loess, a fertile wind-deposited silt (Section 4.9).

Figure 4.16 shows horizontally bedded sandstone over shale in an arid climate (near Figure 4.15). Note the numerous alternations of layers of sandstone and shale in the cap rock that is underlain by soft shale.

Figure 4.17 shows horizontally bedded sandstone and shale in a humid climate. Here, the alternating beds of sandstone and shale are relatively thin and slope changes on hillsides can be seen by careful inspection of the stereogram. The relief is more rugged than would be expected for shale and less rugged than for sandstone. The drainage texture is coarser than for shale and finer than for sandstone. There are more forested areas than would be expected for shale and more agricultural land than for sandstone. These observations lead the interpreter to conclude that sandstone and shale are present

Figure 4.17 Horizontally bedded sandstone and shale in a humid climate. Green County, Pennsylvania, August 1958. 1:30,800. (USDA-ASCS photos. Stereogram.)

might have a forest cover over the sandstone and agricultural land use over the shale. In addition, in agricultural areas, strip farming and contour plowing can help accentuate the appearance of horizontally bedded sedimentary rocks, although it must be recognized that changes in strip crops do not necessarily occur at the changes between rock types. *Other*: Horizontally bedded sandstone over shale is sometimes mistakenly identified as flood basalt over shale (Section 4.7).

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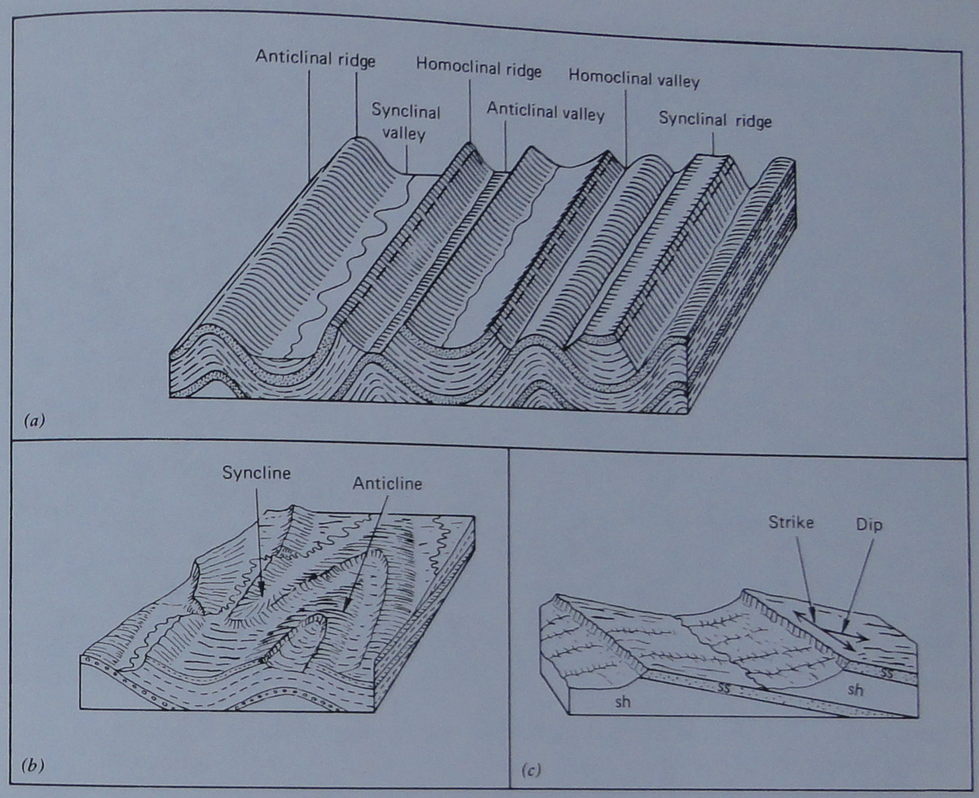

Figure 4.18 Schematic diagram showing topographic forms associated with tilted sedimentary rock strata. (*a* From Thornbury [18]; *b* original drawn by E. Raisz [7]; *c* original drawn by A. N. Strahler [17].)

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Figure 4.19 Radar image illustrating folded sedimentary rocks in a humid climate. Ouchita Mountains, Le Flore County, Oklahoma. 1:170,000. (NASA image.)

in roughly equal amounts. Numerous tonal differences can be seen as hillside contours, indicating the horizontal nature of the bedding.

We refer to sedimentary rocks that have been folded or warped from their original horizontal bedding planes as *tilted sedimentary rocks*. Figure 4.18 illustrates how tilted sedimentary rocks can form linear ridges and valleys with occurrences of folded bedding convex upward referred to as *anticlines* and those of folded bedding convex downward as *synclines*. When the longitudinal axes of anticlines and synclines are horizontal, ridges of resistant sedimentary rock can run parallel for many kilometers (Figure 4.18*a*). When the axes are plunging, ridges curve in a zig-zag fashion, as illustrated in Figure 4.18*b*.

The terms *strike* and *dip* are used to indicate the direction and amount of inclination of tilted sedimentary beds. As illustrated in Figure 4.18*c*, a horizontal line along the beds gives the *direction of strike* (conventionally expressed as a compass direction). The *direction of dip* is perpendicular to the direction of strike and points downslope. The *amount of dip* is the inclination of the beds from the horizontal, measured along the direction of dip. If we assume that the ridges in Figure 4.18*c* run NW-SE, we would say that the direction of strike of the beds is NW-SE and the direction of dip of the beds

Figure 4.20 Tilted interbedded sandstone and shale (anticline) in an arid climate. Fremont County, Wyoming, October 1948. 1:47,200. (USGS photos. Stereogram.)

is NE. The amount of dip of the beds is about 10 degrees. Since the direction of strike and dip are perpendicular, we could fully describe the attitude of these beds as dipping to the NE at 10 degrees.

Airphoto Identification of Tilted Interbedded Sedimentary Rocks. *Topography*: A series of straight or curving ridges. *Drainage*: A trellis drainage pattern with major streams running along valley bottoms and secondary streams flowing down dip and scarp slopes and joining the major streams at right angles, as shown in Figure 4.18*c*. *Erosion*: Varies with residual soil type. *Photo tone*: Varies with rock type. *Vegetation and land use*: Varies with rock type; a typical occurrence for tilted sedimentary rocks in a humid area would be forested sandstone ridges and farmed shale valleys.

Figure 4.19 is a radar image (Chapter 9) illustrating a plunging anticline and syncline in a humid climate. The linear forested bands are sandstone ridges that form an anticline at the top portion of the image and a syncline at the bottom portion. Note that in a plunging anticline, the beds dip away from the axis of the fold, whereas in a plunging syncline, the beds dip toward the axis of the fold.

Figure 4.20 shows a tightly folded anticline in an arid climate. The anticline is composed of alternating beds of sandstone (ridges) and shale (valleys) that dip outward from the center of the anticline.

Figure 4.21 is a stereo-triplet showing an anticline in a humid climate. The anticline is a wooded ridge consisting of sandstone with some interbedded shale. In the right-hand stereopair, the beds are dipping to the right; in the left-hand pair to the left. The soils on the wooded anticline are well drained stony silt loam 1.0 to 1.5 m deep over sandstone and shale bedrock. Soils in the farmed portion of the central valley and the farmed area to the right of the anticline are moderately well drained silt loam and silty clay loam 1.0 to 2.5 m deep over shale bedrock. Soils on the wooded hills near the bottom center of the figure are well drained sandy loam 30 to 50 cm deep over sandstone.

4.7 IGNEOUS ROCKS

Igneous rocks are formed by the cooling and consequent solidification of magma, a molten mass of rock material. Igneous rocks are divided into two groups: intrusive and extrusive. *Intrusive igneous rocks* are formed when magma does not reach the earth's surface but solidifies in cavities or cracks it has made by pushing the surrounding rock apart, or by melting or dissolving it. *Extrusive igneous rocks* are formed when magma reaches the ground surface.

Intrusive igneous rocks commonly occur in large masses in which the molten magma has cooled very slowly and solidified into large crystals. The crystal grains interlock closely to produce a dense, strong rock that is free of cavities. Erosion of overlying materials exposes intrusive igneous rocks.

Extrusive igneous rocks occur as various volcanic forms, including lava flows, lava cones, cinder and spatter cones, tuff cones, and volcanic ash deposits. These rocks have cooled more rapidly than intrusive rocks and consequently have smaller crystals.

Figure 4.21 Tilted interbedded sandstone and shale (anticline) in a humid climate. Logan County, Arkansas, January 1961. 1:32,300. (USDA-ASCS photos. Stereo-triplet.)

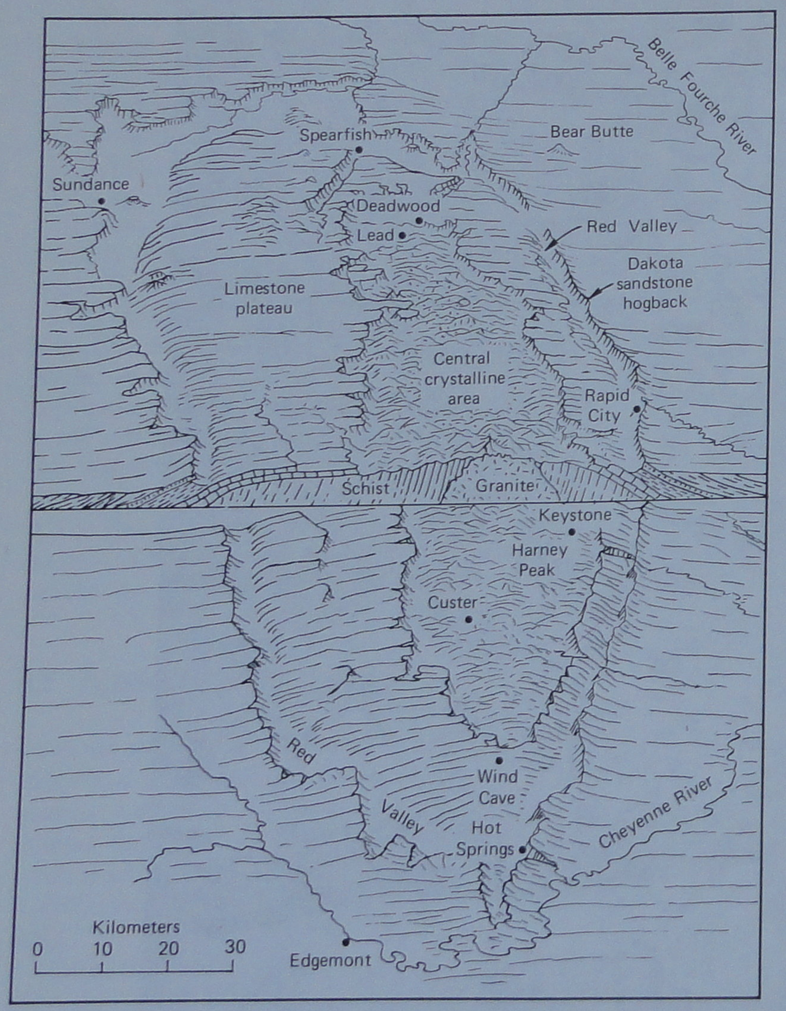


Figure 4.22 Schematic diagram illustrating granitic core and upwarped sedimentary rocks, Black Hills, South Dakota. (Original drawn by A. N. Strahler [17].)

Intrusive Igneous Rocks

Intrusive igneous rocks range from granite, a light-colored, coarse-grained rock consisting principally of quartz and feldspar, to gabbro, a dark-colored, coarse-grained rock consisting principally of ferromagnesian minerals and feldspar. There are many intrusive igneous rocks intermediate between granite and gabbro in composition, such as granodiorite and diorite. We consider

only the broad class of intrusive igneous rocks called *granitic rocks*, a term used to describe any coarse-grained, light-colored, intrusive igneous rock.

Granitic rocks typically occur as large masses such as the Sierra Nevada Mountains and the Black Hills of South Dakota. Figure 4.22 illustrates the occurrence of granite in the Black Hills. The intrusive mass has warped the overlying sedimentary rocks upward and subsequent erosion has left a central area of crystalline rocks surrounded by tilted sedimentary rocks. The intense heat and pressure of the magma altered some of the sedimentary rocks into a metamorphic rock known as schist. The central core contains granitic rocks.

Granitic rocks occur as massive, *unbedded* formations. They are often strongly fractured into a series of irregularly oriented *joints* as a result of cooling from a molten state and/or pressure relief as overburden is eroded. Granitic rocks have a high *resistance to erosion*. As they weather, they tend to break or peel in concentric sheets through a process called exfoliation.

In arid areas, the depth of residual soil cover over granitic bedrock is typically very thin (less than ½ meter), except in fracture zones where it may be thicker. In humid areas, the depth to bedrock is typically 1 to 2 meters. The residual soil texture in humid areas is typically loamy sand, sandy loam, or sandy clay loam. Granitic rocks yield essentially no water, except in fracture zones. Limited water may be available from the sandy soil above the solid rock.

Areas of massive granitic rocks with residual soil cover are typically not well suited to urban development because of a combination of rugged topography, shallow depth to bedrock, and poor groundwater supply.

Airphoto Identification of Granitic Rocks. *Topography*: Massive, rounded, unbedded, dome-like hills with variable summit elevations and steep side slopes. Often strongly jointed with an irregular and sometimes gently curving pattern. Joints may form topographic depressions in which soil and vegetation accumulate and along which water tends to flow. *Drainage and erosion*: Coarse-textured dendritic pattern with a tendency for streams to curve around the bases of dome-like hills. Secondary drainage channels form along joints. Few gullies, except in areas of deeper residual soil. *Photo tone*: Light-toned due to light rock color. Darker-toned in depressions which form along joints. *Vegetation and land use*: Sparse vegetation in an arid climate. Often forested with some bare rock outcrops in a humid climate. Vegetation may be concentrated in depressions that form along some joints. *Other*: Granitic rocks are sometimes mistakenly identified as horizontally bedded sandstone (Section 4.6). The principal differences in airphoto identification of granitic rocks versus sandstone can be summarized as follows. (1)

Figure 4.23 Granitic rock in an arid climate. Wyoming, July 1947. 1:37,300. (USGS photos. Stereogram.)

Evidences of bedding: Granitic rocks are unbedded; sandstone is bedded. (2) *Topography*: Granitic outcrops have variable summit elevations, sandstone caprocks form plateaus; granitic rocks have rounded cliffs, sandstone has vertical cliffs; granitic microfeatures are rounded, sandstone microfeatures are blocky. (3) *Joint pattern*: Granitic rocks have an irregular joint pattern with some distinct linear depressions; sandstone has a joint system consisting of two or three principal directions.

Figure 4.23 shows granitic rocks in an arid climate with very little soil or vegetative cover. Note the massive, unbedded formation with rounded cliffs. Note also that a number of joints are enlarged and form depressions with some soil and vegetative cover.

Figure 4.24 shows granitic rocks in an area with 50 cm per year rainfall. There is some soil cover and considerable forest cover. Note that the bare rock outcrops have variable elevations, rounded forms, and a somewhat irregular joint system.

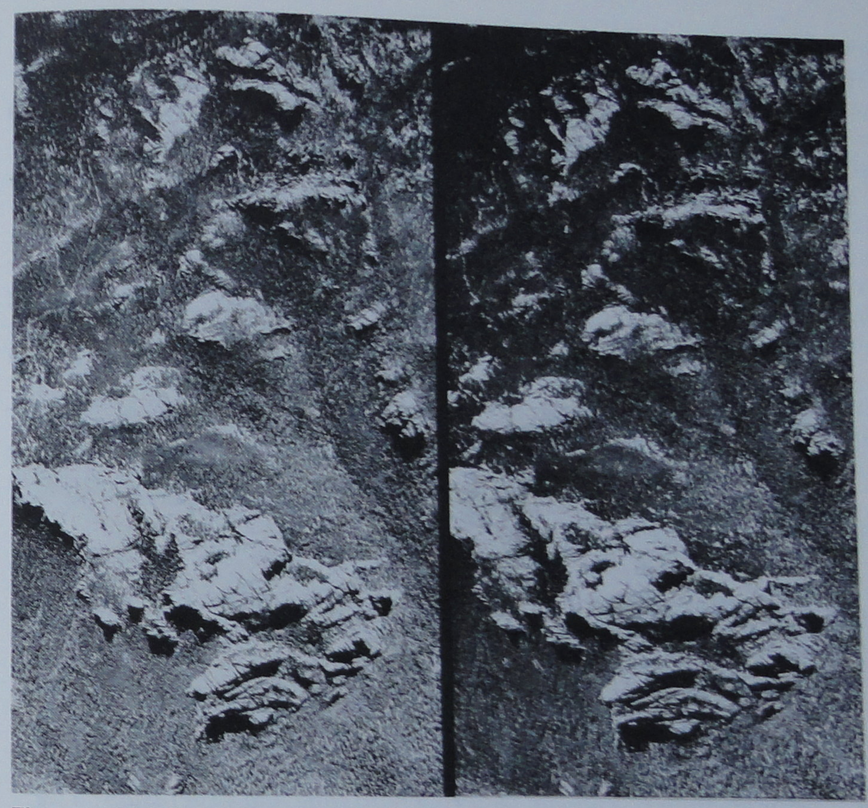


Figure 4.24 Granitic rocks. Black Hills, Pennington County, South Dakota. August 1962. 1:20,000. (USDA-ASCS photos. Stereogram.)

Extrusive Igneous Rocks

Extrusive igneous rocks consist principally of lava flows and pyroclastic materials. Lava flows are the rock bodies formed from the solidification of molten rock that issued from volcanic cones or fissures with little or no explosive activity. In contrast, pyroclastic materials, such as cinders and ash, were ejected from volcanic vents.

The form of lava flows depends principally on the viscosity of the flowing lava. The viscosity of lava increases with the proportion of silica (SiO_2) and alumina (Al_2O_3) in the lava. The least viscous (most fluid) lavas are the basaltic lavas, which contain about 65 percent silica and alumina. Andesitic lavas are intermediate in viscosity and contain about 75 percent silica and alumina. Rhyolitic lavas are very viscous and contain about 85 percent silica and alumina.

Several basic volcanic forms are recognized.

Strato volcanoes (also called composite volcanoes) are steep-sided, cone-shaped, volcanoes composed of alternating layers of lava and pyroclastic materials. The lava is typically andesitic or rhyolitic and side slopes can be 30 degrees or more. Many strato volcanoes are graceful cones of striking beauty and grandeur. Each of the following mountains is a strato volcano: Lassen (California), Shasta (California), Hood (Oregon), Ranier (Washington), Fuji-yama (Japan), Vesuvius (Italy), and Kilimanjaro (Tanzania).

Shield volcanoes (also called Hawaiian-type volcanoes) are broad, gently sloping volcanic cones of flat domical shape built chiefly of overlapping basaltic lava flows. Side slopes generally range from about 4 to 10 degrees. The Hawaiian volcanoes, such as Haleakala, Mauna Kea, Mauna Loa, and Kilauea, are shield volcanoes.

Flood basalt (also called plateau basalt) consists of large-scale eruptions of very fluid basalt that build broad, nearly level plains, some of which are at high elevation. Extensive flood basalt flows form the Columbia River and Snake River plains of the northwest United States.

Airphoto Identification of Lava Flows (excluding Flood Basalt). *Topography*: A series of tongue-like flows that may overlap and interbed, often with associated cinder and spatter cones. Viscous lavas (andesite and rhyolite) form thick flows with prominent, steep edges. Fluid lavas (basalt) form thin flows, seldom exceeding 15 m in thickness. *Drainage and erosion*: Lava is well drained internally and there is seldom a well-developed drainage pattern. *Photo tone and vegetation*: The color of unweathered, unvegetated, lava is dark-toned in the case of basalt, medium-toned for andesite, and light-toned for rhyolite. In general, recent unvegetated flows are darker-toned than weathered, vegetated flows. *Land use*: Recent flows are seldom farmed or developed.

Figure 4.25 shows a viscous lava flow that emanated from Mt. Shasta, California. This flow is 60 m thick and has a 25 degree slope on its front face.

Figure 4.26 shows basaltic lava flows with a six degree slope on the southwest flank of Mauna Loa, a 4200 m high (above sea level) active shield volcano on the island of Hawaii. The darker-toned, unvegetated areas are lava flows dating to 1907 (center of figure) and 1887 (lower portion of figure). The surrounding lighter-toned, sparsely vegetated areas are older flows. The recent flows have a rough surface, excessive internal drainage, and essentially no soil cover or vegetation. This area receives an annual rainfall of 125 cm, but the terrain is dry because of the excessive drainage and strong winds. Note the extensive subdivision being carved into these lava flows in a grid pattern with no apparent sensitivity to terrain conditions and no apparent consider-

Figure 4.25 Viscous lava flow in an arid climate. Siskiyou County, California, August 1955. 1:33,300. (USDA-ASCS photos. Stereogram.)

ation of the future volcanic activity that will some day cover the area of this subdivision.

Pyroclastic materials include cinders, spatter, and ash which form cinder cones, spatter cones, and tuff cones.

Cinders are irregular, spongy fragments of lava, approximately 4 to 32 mm in size, ejected by volcanic explosions. Cinders are usually solid (cooled) when they strike the ground and form *cinder cones* (steep-sided, cone-shaped hills of cinders that have piled up around volcanic vents). Cinder cones are usually less than 300 m high and typically have a bowl or funnel shaped depression (crater) at the summit. Side slopes are typically very smooth, unless eroded, and stand at the natural angle of repose of loose cinders. Lava flows often issue from near the base of cinder cones.

Spatter is volcanic ejecta thrown out in a very fluid condition with fragments that remain partly fluid when they strike the ground, so that they flatten out and often stick together. Spatter forms *spatter cones* (steep-sided cones built by the accumulation of spatter). Spatter cones are smaller and steeper-sided than cinder cones, typically less than 15 m high, and are often found along volcanic *rift zones* (highly fractured linear belts on the flanks of volcanoes). Lava flows often issue from near the base of spatter cones.

Volcanic *ash* consists of fine-grained volcanic ejecta, 4 mm or smaller in

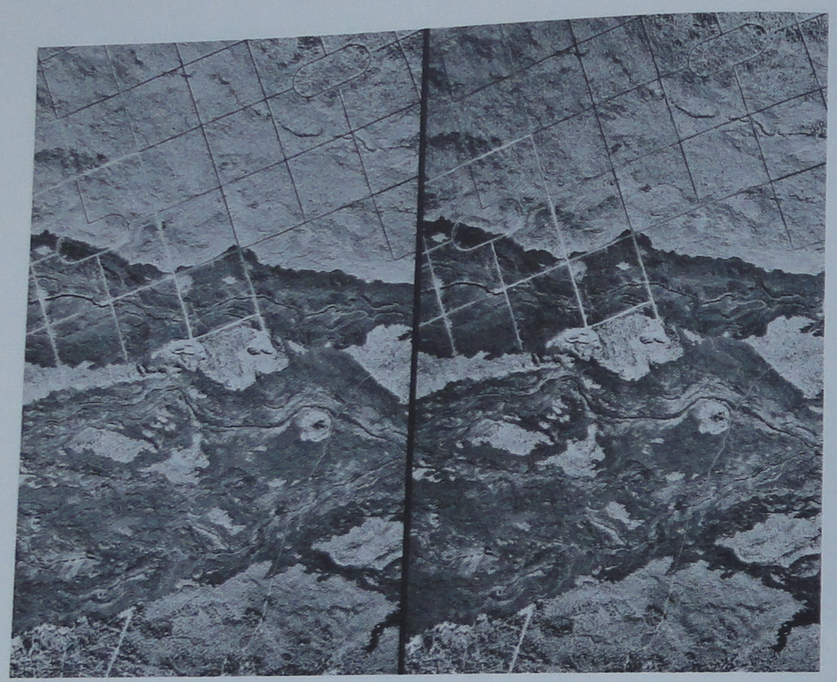


Figure 4.26 Basaltic lava flow. Mauna Loa Volcano, Island of Hawaii, March 1965. 1:36,400. (USDA-ASCS photos. Stereogram.)

size. Consolidated volcanic ash is called *tuff*, which forms *tuff cones* around volcanic vents. Tuff cones are relatively uncommon. In Hawaii, they form as the result of moderately explosive eruptions near the ocean when molten magma encounters either sea water or groundwater, causing the explosive eruption. Tuff cones are much broader in proportion to their height than cinder or spatter cones and their craters are broad and saucer-shaped.

Figure 4.27 shows cinder cones in the summit crater of Haleakala Volcano. Note their smooth side slopes and the lava flow that emanated from the base of the cinder cone near the top of the figure. There is very little vegetation on the cinder cones. The rainfall is about 50 cm per year but the cinder cones are excessively drained and have virtually no residual soil.

Figure 4.28 shows several volcanic forms in Craters of the Moon National Monument. It is estimated that lava erupted here for many thousands of years and ceased about 1600 years ago. A large, smooth-sided cinder cone 150 m high is at the upper left. A series of spatter cones along a rift zone runs diagonally from lower left to upper right through the center of the figure. A series of basaltic lava flows is at the lower right.

Figure 4.27 Cinder cones and lava flows. Haleakala National Park, Island of Maui, Hawaii, January 1965. 1:28,600. (USDA-ASCS photos. Stereogram.)

Figure 4.29 shows a tuff cone, the world-famous Diamond Head in Honolulu. This tuff cone was formed an estimated 100,000 years ago. This crater is much larger and flatter than a cinder cone crater. The average height of the uneven rim is 125 m, but it rises to 225 m at the lower right because the prevailing wind at the time of formation was from upper left to lower right. The annual rainfall here is just under 50 cm per year.

Flood basalt deposits result from horizontal and overlapping flows of very fluid lava that issue from fissures. Commonly, the lava flows over an older eroded land surface and gradually buries hills and valleys, transforming the terrain into a relatively featureless plain. Individual flows are typically 15 to 30 m thick, sometimes much thicker. At times, flood basalt flows are interbedded with fluvial and lacustrine soils or with residual soils, indicating that, in places, considerable time elapsed between successive flows. Flood basalts are also called *plateau basalts* because they build broad, nearly level plains, some of which are at high elevation.

Flood basalt deposits are extensive in the northwest United States. The

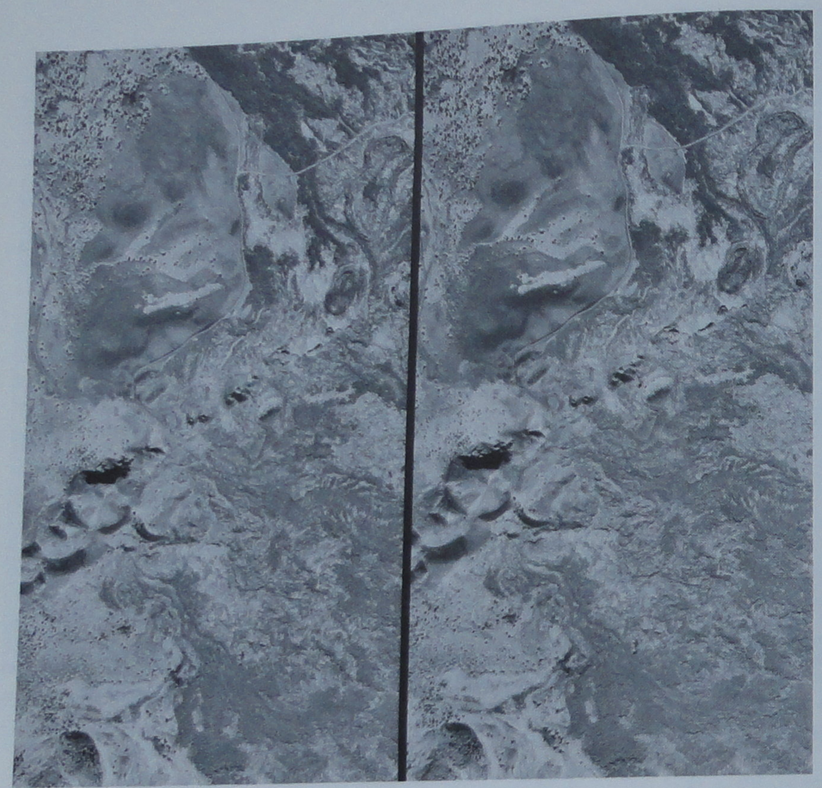


Figure 4.28 Cinder cones, spatter cones, and lava flows in an arid climate. Craters of the Moon National Monument, Idaho, July 1959. 1:26,700. (USDA-ASCS photos. Stereogram.)

flood basalts of the Columbia River Plain are about 60 million years old and cover an area of about 400,000 km² in Washington, Oregon, and Idaho with an average thickness of 625 m and a maximum thickness greater than 3000 m. The Snake River Plain in Idaho is a similar mass of younger flood basalt. The nature of these plateaus is best seen along the side walls of the deep valleys cut into the flood basalt by the Columbia and Snake Rivers.

Flood basalt deposits typically exhibit columnar jointing, as illustrated in Figure 4.30. These joints form when the basalt, which solidified at several hundred degrees Celsius, cools to ambient air temperature and further contracts and cracks. The columns are typically six-sided and ¼ to 1 m wide. Flood basalt deposits are well drained internally because of the strong columnar jointing. In fact, several major streams flowing from the mountains just

Figure 4.29 Tuff cone. Honolulu, Hawaii, February 1965. 1:25,000. (USDA-ASCS photos. Stereogram.)

north of the Snake River Plain disappear underground when they reach the flood basalt and emerge nearly 200 km away as springs in the side of the basalt-walled Snake River Canyon.

Airphoto Identification of Flood Basalt. *Topography*: A nearly level surface, often cut by major streams that form deep valleys. Sometimes found as high plateaus. Columnar jointing (just barely visible at a photo scale of 1:20,000) can be seen on valley and escarpment walls. *Drainage*: Very few surface streams because of the excellent internal drainage. *Erosion*: Gullies generally not prominent, except in areas of deeper residual soil. *Photo tone*: Basalt rock has a dark tone. This dark tone is usually best seen along valley walls and escarpment faces as the ground surface often has some vegetation, especially when a soil cover is present. *Land use*: In arid areas, flood basalt with a soil cover is often farmed in areas near streams where the land can be irrigated. In nonirrigated arid areas, flood basalt plains are used for very low density grazing or

Figure 4.30 Exceptionally well-developed columnar jointing, Devil's Postpile National Monument, California, June 1971.

left idle. *Other features*: Landslides are often found along flood basalt cliffs, especially where streams undercut the base of the slopes. *Other*: Flood basalt plateaus are sometimes mistakenly identified as sandstone-capped plateaus (Section 4.6). The principal differences in airphoto identification of flood basalt plateaus versus sandstone-capped plateaus can be summarized as follows. (1) *Tone of bare rock*: Basalt is dark-toned; sandstone is light-toned. (2) *Rock jointing*: Flood basalt exhibits columnar jointing; sandstone has extensive joint systems with two or three principal directions. As a result, flood basalt canyon and cliff edges have a serrated appearance, while sandstone canyon and cliff edges have a blocky appearance. (3) *Drainage*: Flood basalt has principally internal drainage; sandstone has a low-density modified dendritic pattern (rectangular or angular).

Figure 4.31 shows an irrigated area of flood basalt on the Snake River Plain. Note the sinuous dark-toned irrigation canal at the upper left. The rock can be identified as flood basalt because of the characteristics exhibited along the

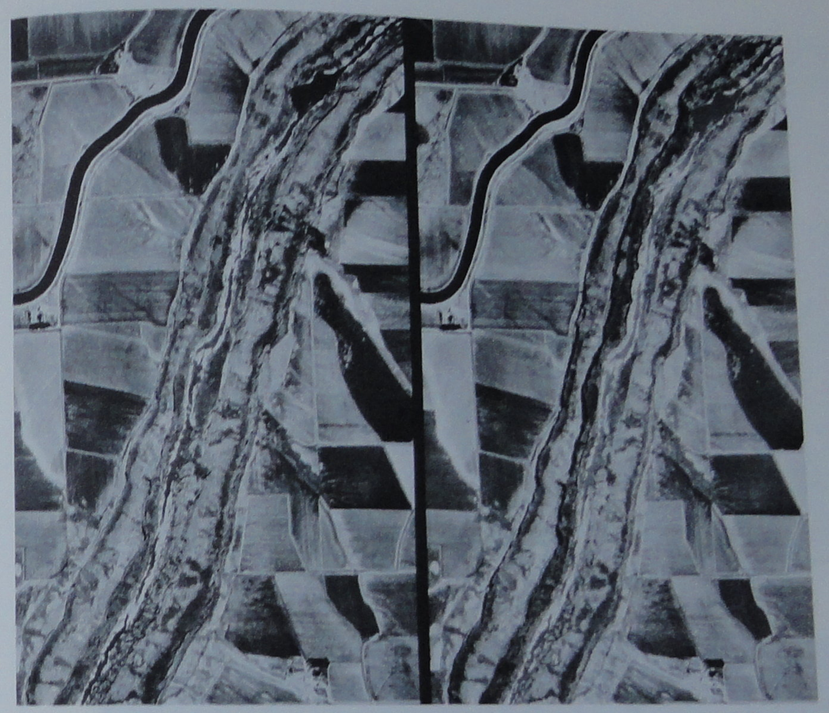


Figure 4.31 Flood basalt, irrigated plateau in an arid climate. Jerome and Twin Falls Counties, Idaho, July 1957. 1:20,000 (USDA-ASCS photos. Stereogram.)

sides of the canyon, which cuts through several individual flows. The serrated edges of the canyon walls are caused by columnar jointing. The rock on the sunlit portions of the canyon walls is dark-toned (be careful not to confuse shadows with dark-toned materials!).

Figure 4.32 shows columnar jointing in flood basalt a few kilometers west of the area shown in Figure 4.31. Figure 4.32*b* is a close-up showing individual columns approximately ⅓ m across. Clusters of columns 1 to 2 m across break off as a unit and fall to the base of the cliffs, leaving serrated canyon edges such as those in Figure 4.31.

Figure 4.33 shows a flood basalt plateau in an arid climate. The basalt flow originally covered a larger area than presently shown, but erosion of the plateau is steadily reducing its size. Weathering of the softer underlying rock has resulted in landslide failures along the basalt cap. The edges of the basalt cliffs have a dark tone and exhibit columnar jointing.

Figure 4.32 Flood basalt. Snake River Canyon near Twin Falls, Idaho, August 1977. (*b* is a stereogram.)

4.8 METAMORPHIC ROCKS

Common metamorphic rocks are quartzite, slate, marble, gneiss, and schist. They are formed from pre-existing sedimentary or igneous rocks due principally to the action of heat and pressure. Occasionally, chemical action or shearing stresses are also involved. The minerals in any rock are generally stable under a limited range of temperature and pressure. When high temperatures and pressures are imposed, the pre-existing rocks undergo a metamorphosis and a new mineral composition, texture, and/or structure results. Minimum conditions for metamorphic change are estimated at temperatures in excess of 100°C along with a pressure equal to that found 3 km below the earth's surface. Maximum conditions are estimated to be a temperature of 800°C and a pressure equal to that found 35 km below the earth's surface. Above these conditions, magma is formed, resulting in igneous rocks.

Most metamorphic rocks have a distinct banding that can be seen via field observations and which sets them apart from sedimentary and igneous rocks.

Metamorphic rocks can be found throughout the world. However, since their extent is limited, the airphoto identification of metamorphic rocks is not covered here. In addition, the airphoto identification of metamorphic rocks is more difficult than for sedimentary and igneous rocks and interpretive techniques for metamorphic rocks are not well established.

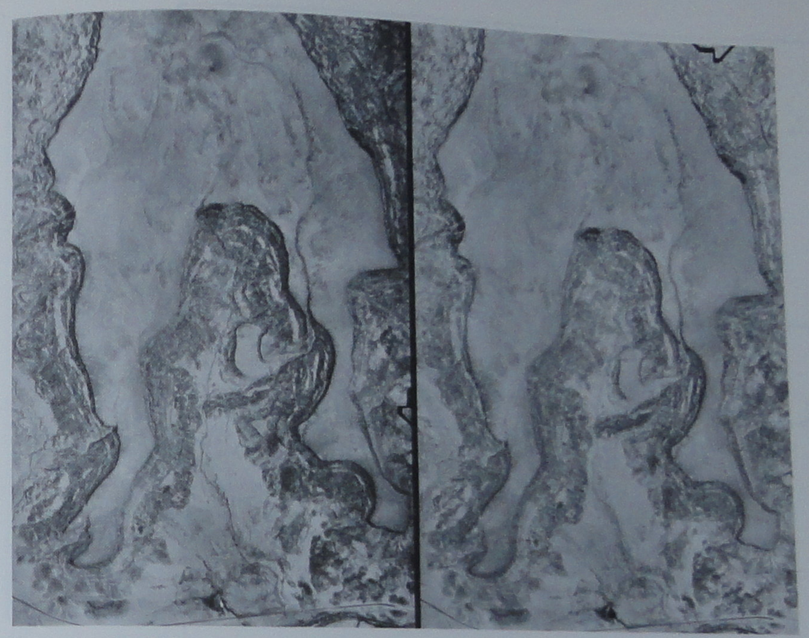


Figure 4.33 Flood basalt plateau in an arid area. New Mexico, May 1955. 1:68,000. (USGS photos. Stereogram.)

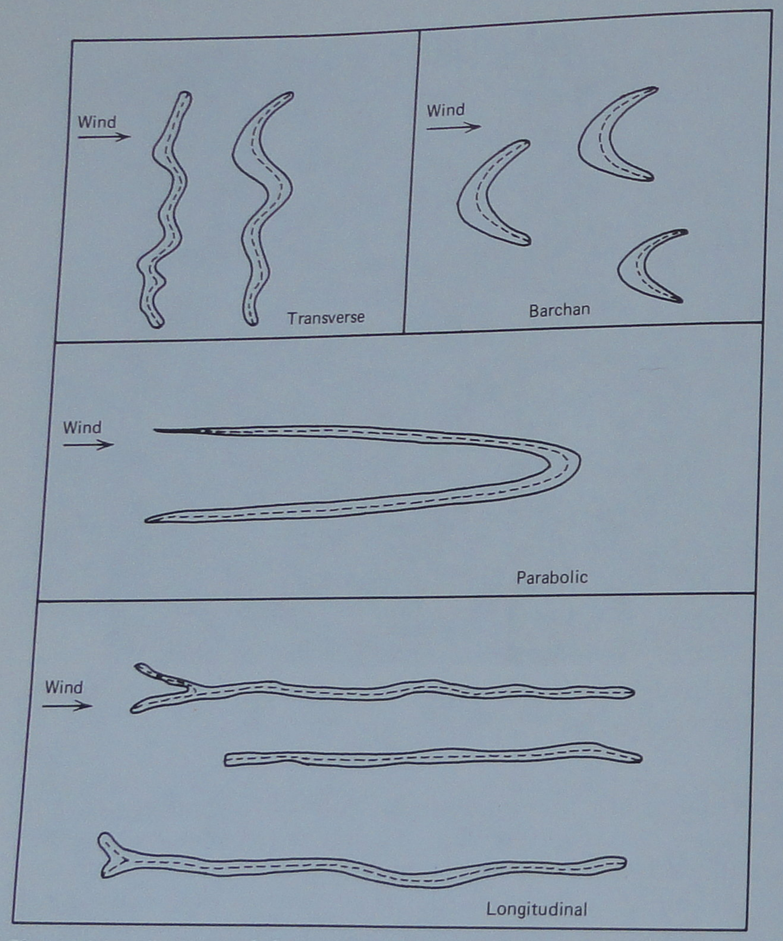


Figure 4.34 Basic sand dune shapes. Dune crests shown in dashed lines.

4.9 AEOLIAN DEPOSITS

Aeolian deposits are created by the erosion, transportation, and deposition of unconsolidated materials by the wind. The principal aeolian deposits are sand dunes and loess.

Sand Dunes

Sand dunes are mounds, hills, or ridges of windblown sand. They are found where there is a source of sand, a wind strong enough to erode and transport

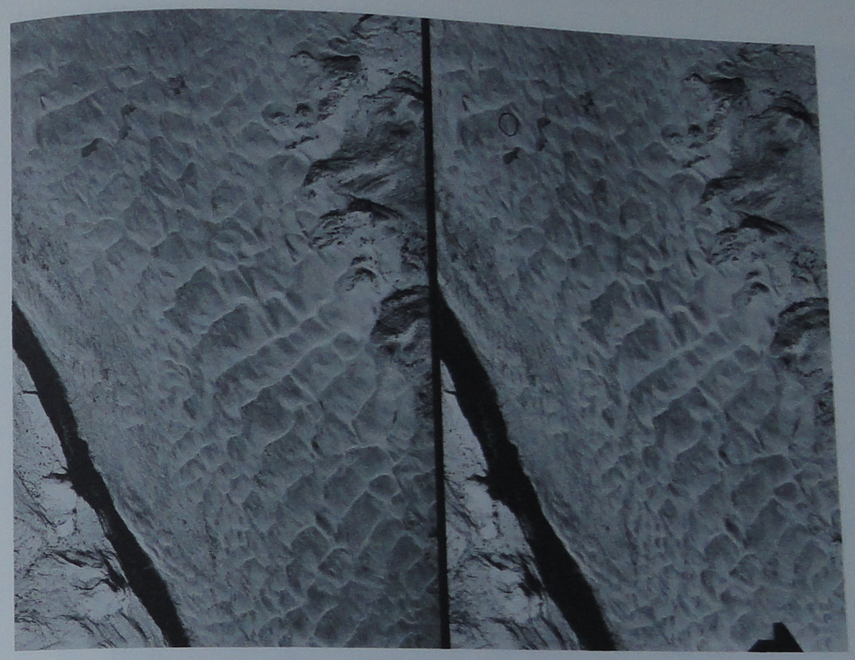


Figure 4.35 Transverse sand dunes in an arid climate. Navajo County, Arizona, September 1951. 1:26,700. (USGS photos. Stereogram.)

sand-sized particles, and a land surface on which to deposit the sand. These conditions are commonly found inland from sandy beaches with onshore winds, close to streams with sandy bottoms exposed during the dry season, and in desert areas where the disintegration of sandstone and other rocks provides the sand. In addition, glacial outwash deposits and sandy glacial lakebed areas often provide a source of sand.

Because wind velocities are seldom strong enough to lift sand-sized particles more than 1 to 2 m from the ground surface, sand grains are transported by "saltation," a process whereby the grains travel by bouncing and rolling generally within about ½ to 1 m above the ground surface.

Sand dunes tend to form with an asymmetrical cross section, with a slope of 5 to 10 degrees on the windward slope and 30 to 34 degrees on the leeward slope. Unless stabilized by vegetation, sand dunes tend to migrate downwind because sand particles are blown from the windward to the leeward side of the dunes. Sand dune movement is generally less than 30 m per year.

Sand dunes vary in shape depending on such factors as the quantity and particle size of the sand, the strength and direction of the wind, and the vegetation conditions. The basic sand dune shapes to be discussed are transverse, barchan, parabolic, and longitudinal, as illustrated in Figure 4.34.

Figure 4.36 Barchan sand dunes in an arid climate. Imperial County, California, November 1959. 1:20,000 (USDA-ASCS photos. Stereogram.)

Transverse dunes tend to form in areas where there is a large supply of sand and little vegetation. These dunes often cover large areas and develop a wavelike form with sinuous ridges and troughs perpendicular to the direction of prevailing wind. Transverse sand dunes have an asymmetrical cross section with a width about seven times their height. They have a typical height of 5 to 15 m, with a maximum of about 100 m. Transverse dunes may grade into barchan dunes as the sand supply lessens.

Crescent-shaped *barchan dunes* tend to form in areas where there is a limited amount of sand and little vegetation. The tips, or horns, of the barchan dunes point downwind and sand grains are swept around the barchan as well as up and over the crest. The dune cross section is asymmetrical at the crest, but may become nearly symmetrical on the horns. Barchan dunes have a typical height of 5 to 15 m, up to a maximum of about 30 m. Barchan dunes migrate readily, with smaller dunes moving faster than larger dunes. Near the sand source, there is often a dune complex of transverse and barchan

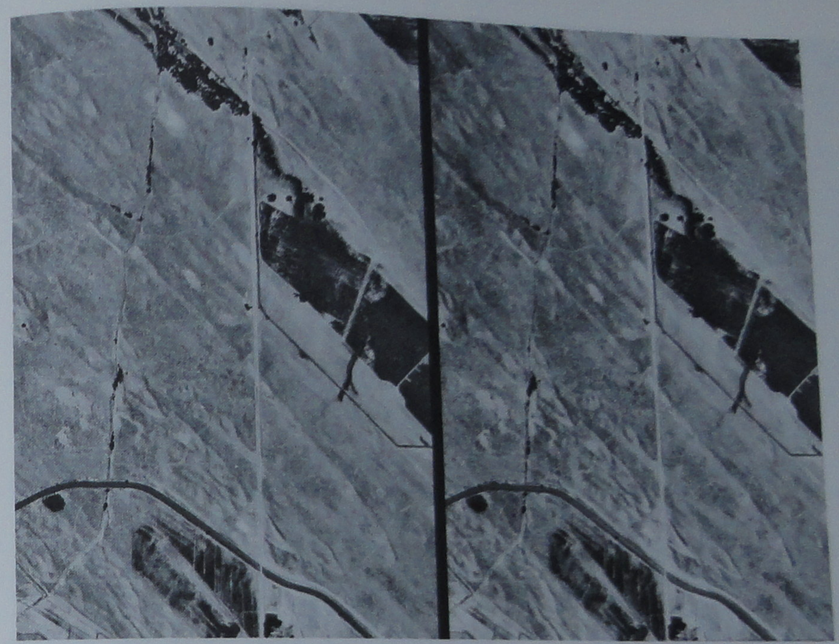


Figure 4.37 Parabolic sand dunes in an arid climate. Bingham County, Idaho, June 1960. 1:20,000. (USDA-ASCS photos. Stereogram.)

dunes. Individual, often extremely well-developed barchan dunes tend to develop some distance downwind from the source.

Parabolic dunes have a crescent shape with long horns pointed into the wind. They typically form where vegetation anchors portions of the horns, allowing the center of the dune to migrate resulting in a hairpin-shaped dune. Once the basic parabolic shape has formed, most parabolic dunes are fixed in place and do not migrate. The dune cross section is asymmetrical at the crest and nearly symmetrical on the horns. Parabolic dunes typically have a height up to 15 m.

Longitudinal dunes are long, nearly straight ridges of sand that form parallel to the direction of the wind. They are found where strong prevailing winds converge and blow in a constant direction. The dune cross section is symmetrical, with a width several times the height. Longitudinal dunes are typically less than 15 m high and several kilometers long. However, in large desert areas, they may be as high as 200 m and as long as 300 km. Such massive longitudinal dunes are often called seif dunes.

Nearly 100 percent of the particles found in sand dunes fall within the very narrow range of 0.05 to 0.5 mm, attesting to the excellent sorting power of

Figure 4.38 Longitudinal sand dunes in an arid climate. Great Sand Dunes National Monument, Colorado, September 1955. 1:20,000. (USDA-ASCS photos. Stereogram.)

the wind. When soils develop on stabilized sand dunes, they tend to be thin, sandy, and excessively well drained.

Sand dunes are generally unfavorable locations for urban development due to the possibility of blowing sand and migrating dunes. However, at times sand dune areas are developed, as in the case of many lakeshore sites. Many sand dune areas, such as those along the shorelines of the Great Lakes and the Atlantic Ocean, are unique natural areas with very fragile plant communities. Development is discouraged in these areas for this reason.

Airphoto Identification of Sand Dunes. *Topography*: Previously described. *Drainage*: Excellent internal drainage. *Erosion*: Frequent wind erosion when dunes are not stabilized by vegetation and wind velocities are sufficient to erode and transport sand grains. Some water erosion of steeper slopes. *Photo tone*: Sand without a vegetative cover photographs very light on panchromatic film. There is often a sharp contrast between

Figure 4.39 Exceptionally large transverse sand dunes. West central Nebraska, May 1973. 1:1,000,000. Landsat Band 7 (reflected infrared). (NASA image.)

sand dunes and surrounding materials due to a combination of soil moisture and vegetation type and vigor. *Vegetation and land use*: Active (migrating) dunes have essentially no vegetative cover. Stabilized dunes often have a grass or shrub cover. Agricultural crops are rare. Orchards

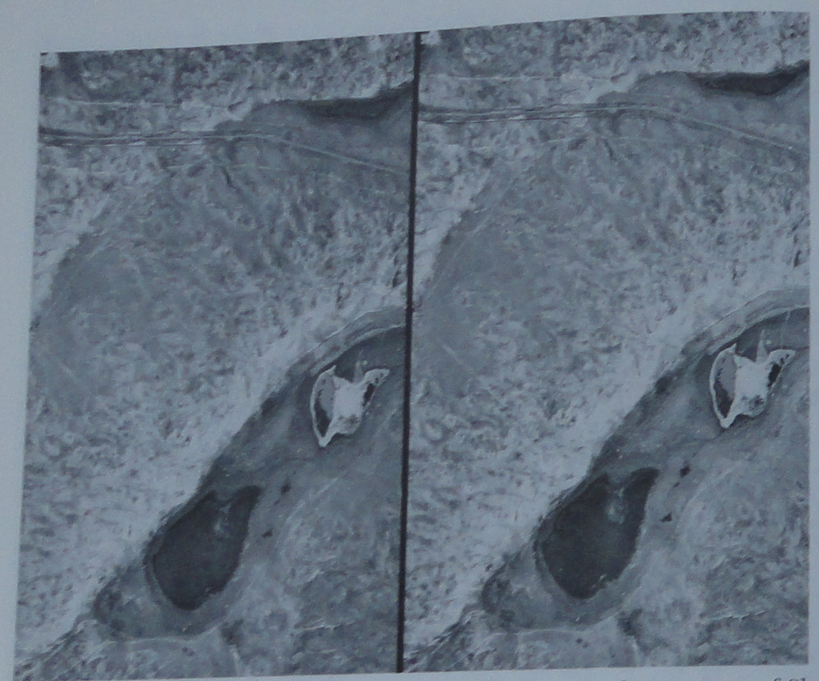


Figure 4.40 Exceptionally large transverse sand dunes. Southeast corner of Sheriden County, Nebraska, August 1954. 1:33,300. (USDA-ASCS photos. Stereogram.) *Note:* The location of the center of Figure 4.40 is 5.0 cm right and 6.5 cm down from the upper left corner of Figure 4.39.

and vineyards may be present. Stabilized dunes in humid areas may be used for grazing. *Other:* Stabilized sand dunes in a humid glaciated area are sometimes mistakenly identified as eskers (Section 4.10).

Figure 4.35 shows transverse sand dunes in an arid climate. The direction of the wind that formed these dunes was from upper left to lower right. The dunes are located in a valley between sandstone ridges.

Figure 4.36 shows barchan sand dunes in an arid climate formed by wind blowing from top to bottom (of the figure) across a smooth, gently sloping plain that descends to the Salton Sea. These dunes range in height from 3 to 10 m, with a horn-to-horn width of 50 to 250 m.

Figure 4.37 shows parabolic sand dunes in an arid climate formed by wind blowing from upper left to lower right.

Figure 4.38 shows longitudinal sand dunes in an arid climate formed by

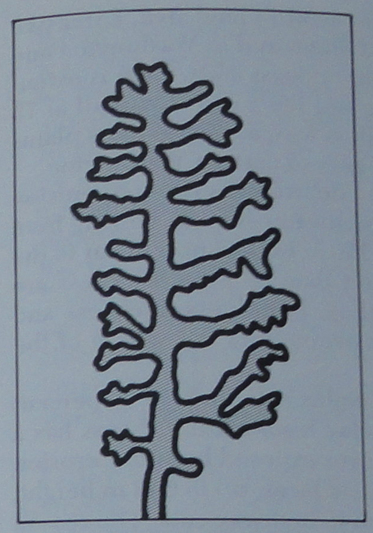


Figure 4.41 Outline of pinnate gully system typical of erosion of loess deposits (sketched from Figure 4.5*b*).

wind blowing from upper left to lower right. Note that when two longitudinal dunes merge into one, they join together downwind of the location of the two separate dunes (see also Figure 4.34).

Figures 4.39 and 4.40 show exceptionally large transverse sand dunes in the "Sand Hills" area of west-central Nebraska. The Sand Hills cover an area of more than 50,000 km², the largest continuous dune field in the Western Hemisphere. These dunes were formed by winds blowing from the upper left (northwest). In portions of west-central Nebraska, aeolian deposits change from transverse dunes to longitudinal dunes to loess as one proceeds downwind from the source. Figure 4.39 is a Landsat image (Chapter 10) covering an area 127 by 152 km. Here, the dunes can be seen as roughly parallel transverse ridges, often with wet soils or lakes between the dunes. Figure 4.40 is an airphoto stereopair covering an area 2.0 by 3.1 km. The dunes in the area of this illustration are typically 50 to 100 m high and 1500 m wide. The vegetative cover on the dunes is principally grass and the dunes are used for grazing of beef cattle.

Loess

Loess consists of unconsolidated, generally unstratified, silt-size windborne deposits that may contain minor amounts of fine sand and clay. Loess and

loess-like materials cover about one-tenth of the world's land area. Extensive loess deposits occur in the midwestern United States and in Washington and Idaho. Many of the best agricultural areas occur on loess soils. Corn is extensively cultivated on the loess plains of Illinois and Iowa with a rainfall of 75 to 100 cm/yr. Wheat is grown where the rainfall is less, as on the loess plains of Kansas and Nebraska and in the Palouse region of eastern Washington.

Loess generally consists of silt removed from desert areas by wind erosion or silt removed from sediments deposited by meltwater streams flowing from glaciers. In China, loess deposits greater than 150 m in thickness occur to the lee of deserts. In Illinois, loess deposits greater than 30 m in thickness are present to the lee of the Mississippi River Valley. Both loess thickness and loess particle size decrease with increasing distance from the source of the materials.

Loess typically has a yellow to buff color, contains at least 60 to 70 percent silt-sized particles and has a silt loam or silty clay loam texture. Loess has a tendency to cleave along vertical planes whenever exposed by water erosion or human activity. As a result, many stable vertical faces, up to 6 m in height, can be found in loess areas along gully sides and in highway cuts. The reason why loess remains stable in vertical cuts is not clearly understood but may be due to calcification of vertical root casts and other vertical cracks in the soil. Loess soils are typically well drained in their natural state, with a vertical permeability as much as 20 times greater than permeability in a horizontal direction. When loess is disturbed by human activity such as urban development or rural highway construction, the vertical drainage is impeded and poorly drained soils result. Loess is easily eroded by moving water and special care must be taken in the construction of drainage facilities, especially open ditches. Loess soils have a relatively low density (high air void space) compared with other soils. Loess has been called a "collapsible" material that may undergo excessive loss of strength or excessive settlement when subjected to an increase in moisture content, a heavy vertical load, vibrations, or a combination of these factors.

Great care must be taken in the development of loess areas. Potential problems can include: septic tank failure, excessive foundation settlement, severe water erosion, and frost damage. In addition, special consideration must be given to the unusual slope stability characteristics of loess.

Airphoto Identification of Loess. *Topography*: Thick undissected loess deposits typically have a gently undulating surface, with roughly parallel crests some 500 to 1000 m apart aligned transversely to the wind direction. Thin loess deposits form a mantle over the underlying rock and unconsolidated materials and the resulting ground surface tends to follow the contours of the underlying materials. However, there is a tendency for loess to smooth out the terrain, with thinner deposits found on ridges and thicker deposits in valleys. Very often, loess deposits are minutely dissected by stream and gully erosion. *Drainage and erosion*: In dissected loess areas, there is an intricately carved landscape formed by many streams and gullies. The overall drainage pattern is typically a modified dendritic pattern known as a pinnate (featherlike) drainage pattern, as illustrated in Figure 4.41. Gullies are U-shaped, with broad, flat bottoms and steep sides, often marked with small soil slips called "catsteps." *Photo tone*: Characteristically light because of good internal soil drainage. Often have tonal contrasts between gully bottoms, gully sides, and upland areas due to different vegetation types (e.g., trees versus grass). *Vegetation and land use*: Typically farmed, except on steeper slopes or in low rainfall areas.

Figure 4.5*b* illustrates a gully system in loess more than 5 m thick in central Nebraska, an area with about 60 cm/yr rainfall used for grazing. The soil is a well drained silt loam. Note the pinnate gully pattern and the broad-bottomed, steep-sided gullies with active erosion at their heads.

Figure 4.42 illustrates loess approximately 20 m thick just east of the Missouri River in Iowa. The loess is so strongly dissected that sharp-edged hills remain. This landscape is typical of thick dissected loess along the Mississippi and Missouri Rivers in the midwest United States. Distinct U-shaped gullies can be seen several places, especially in the central and lower portions of the stereogram.

4.10 GLACIAL LANDFORMS

Today, most of the water on the surface of the earth is in liquid form, in lakes and oceans. About two percent is in solid form, as glacial ice, at high latitudes and high elevations. About 10 percent of the earth's land surface is presently covered with glacial ice. During the past one million or more years, there have been repeated advances of glacial ice over about 30 percent of the earth's land surface. The major advances occurred during periods when the earth's climate was colder than at present. Glaciation occurred in both the form of *valley glaciation*, in which tongues of ice occupied mountain valleys, and as *continental glaciation*, as huge lobes of ice covering portions of several continents with an ice thickness up to 3 km. This size staggers the imagination and helps to explain the capability of a glacial advance to sculpt the terrain in its path. We discuss principally depositional landforms resulting from continental glaciation. Four distinct advances (or stages) have been identified in

Figure 4.42 Loess in a humid climate. Pottawattamie County, Iowa, September 1966. 1:22,200. (USDA-ASCS photos. Stereogram.)

the United States. The most recent ice advance was during the "Wisconsinan Stage" of glaciation that occurred during the period more than 70,000 to about 10,000 years ago.

As ice moves over the earth's surface, it abrades and plucks materials from the surface over which it moves. Some materials are carried within the ice and some are carried on the surface. Some materials are ground to a fine powder, while some are scarcely modified by glacial erosion and transportation. Some materials are sorted and rounded by flowing water.

Materials deposited by glaciation are called *glacial drift*. There are four principal kinds of glacial drift: (1) *till*, unsorted, unstratified material deposited directly from glacial ice with relatively little water-sorting action; (2) *ice-contact stratified drift*, material partly water-sorted and crudely stratified, deposited adjacent to melting ice; (3) *outwash*, sediment deposited away from

melting ice by meltwater streams; and (4) *glacio-lacustrine deposits*, sediments deposited in ephemeral glacial lakes. These *materials* are found in a variety of *landforms*, as categorized in Table 4.3.

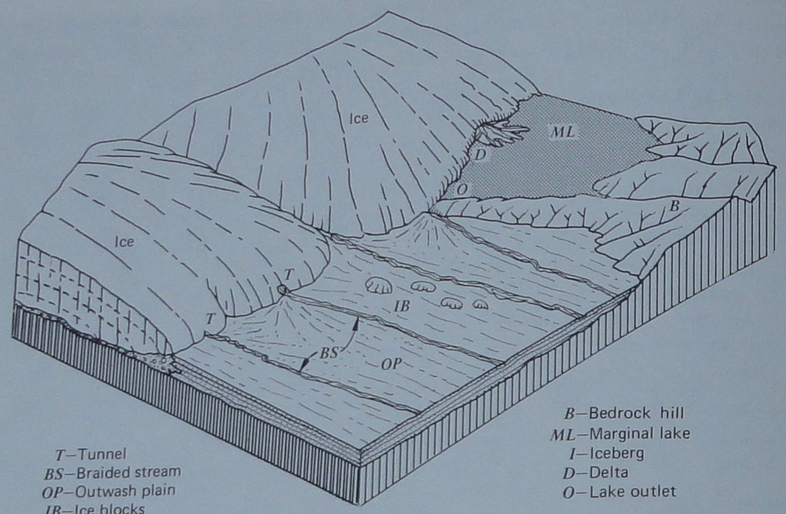
Table 4.3 Landforms Resulting from Continental Glaciation

Till Landforms
End Moraine
Terminal moraine
Recessional moraine
Interlobate moraine
Ground moraine
Ablation ground moraine
Basal ground moraine
Drumlin
Ice-contact Stratified Drift Landforms
Esker
Kame
Outwash Landforms
Outwash plain
Valley train
Outwash terrace
Glacio-lacustrine Landforms
Lakebed
Beach ridge
Delta

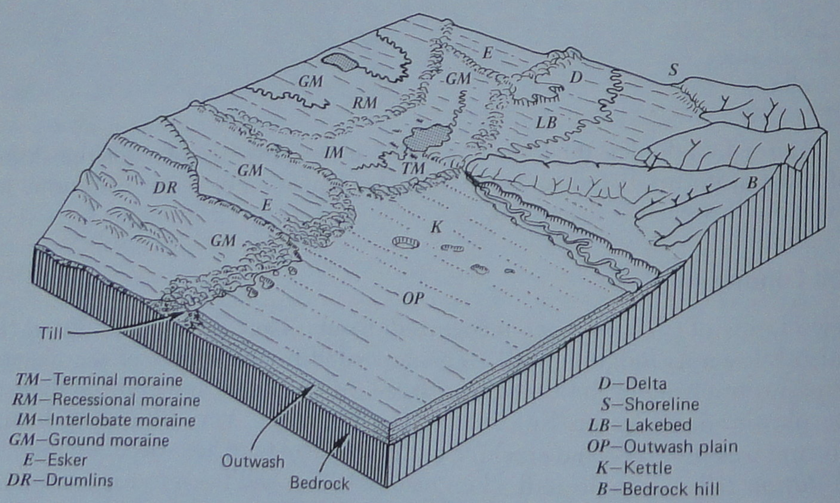
Figure 4.43 depicts the formation and resulting physiographic relationships of the landforms listed in Table 4.3. The formation of these landforms is explained as each is discussed.

Till Landforms

Two forms of till have been recognized: basal till and ablation till. *Basal till* (also known as lodgement till) was deposited from the base of the glacier. Pressure melting of the flowing ice freed drift particles and allowed them to be plastered, under pressure, under the glacial ice. Very little particle size sorting was involved and crushing and abrasion of particles was often intense. *Ablation till* was deposited when materials that had been transported on or near the surface of the ice accumulated on the ground as the ice melted. Many of the finer particles (silt and clay) carried on the ice were washed away during the process of melting.



(a) With the ice front stabilized and the ice in a wasting, stagnant condition, various depositional features are built by meltwaters.



(b) After the ice has wasted completely away, a variety of new landforms made under the ice is exposed to view.

Figure 4.43 Schematic diagram showing glacial landforms resulting from continental glaciation. (Original drawn by A. N. Strahler [17].)

Till textures can vary greatly, depending on the nature of the rock and/or soil material eroded by the glacial ice. In southeastern Wisconsin, for example, till of the portion of the Green Bay Lobe that eroded sandstone and dolomite typically has a texture of sandy loam or gravelly loam, whereas till of the portion of the Lake Michigan Lobe that eroded shale and lake clays has a texture of silty clay loam and clay loam. With till derived from the same rock and/or soil material, ablation till would tend to have a coarser texture than basal till because of the mode of formation.

End moraines are ridgelike deposits of till, with varying proportions of ice-contact stratified drift inclusions, that have accumulated along the margins of glacial ice. As illustrated in Figure 4.43, end moraines associated with the farthest extent of an advance of a lobe of glacial ice are called *terminal moraines*, those associated with temporary periods of a stationary ice front behind the terminal moraine are called *recessional moraines*, and those formed between two lobes of glacial ice are called *interlobate moraines*.

At the time of end moraine formation, there is an equilibrium between the rate of advance of the glacial ice and the rate of melting of the ice, causing a period when the ice front is stationary. At this time, materials carried within or on the ice are deposited by ablation at the ice front. When the rate of melting exceeds the rate of ice flow toward the margins, the ice front retreats and a thinner deposit of till is spread across the terrain forming ground moraine areas. A few small end moraines may be formed by the bulldozing action of the advancing ice. Glacial ice tends to override such moraines when their height exceeds 10 meters. Thus, most end moraines have been formed principally by ablation. Interlobate moraines typically contain more ice-contact stratified drift than terminal or recessional moraines.

Numerous irregularly shaped depressions called *kettles* are found in end moraines. They were formed by the melting of buried blocks of ice after sedimentation had ceased at the site of the kettles. Kettles are also found in association with eskers, kames, and outwash.

End moraines can be found throughout the glaciated portions of the world. A small moraine may have a length of only a few kilometers, a width of less than ½ km, and a height of less than 15 m. A large moraine may have a length over 150 km, a width of 10 km or more, and a height up to about 150 m.

End moraines often have a wide variation in soil and drainage conditions. Sand and gravel are found in localized stratified drift deposits, often as lenses surrounded by till. Very poorly drained fine-textured and organic soils are often found in kettle holes.

End moraine areas are typically better suited to low density residential development than to intensive urban development because of the variable terrain and soil conditions. The characteristics of end moraine areas are often well suited to the development of golf courses, campgrounds, and other recreational uses.

Figure 4.44 End moraine in a humid climate. Clay County, Minnesota, November 1959. 1:30,000. (USDA-ASCS photos. Stereogram.)

Airphoto Identification of End Moraines. *Topography*: Hummocky and variable, a disordered arrangement of hillocks and depressions. Lack of continuity among hillock-top elevations and a lack of continuity among depression-bottom elevations. Viewed over a large area, end moraines form gently curving or lobe-shaped belts of hummocky ablation till (Figure 4.43). *Drainage and erosion*: A deranged drainage pattern; aimlessly directed short streams, ponds, and marshes at widely differing elevations. When present, gullies can indicate soil texture. *Photo tone*: A striking mottled pattern, with light and dark areas being related to topography and surface soil texture and moisture content. This mottled pattern is especially evident when photographs are taken in the spring (little or no crop cover) 1 to 2 days after a rainfall. The mottled pattern may be difficult to discern in mid-summer photographs when crops are mature. *Vegetation and land use*: Variable, depending on slope, soil, and moisture conditions. Typically farmed on slopes less than 12 percent. End moraine crests and other portions with slopes over 12 percent usually wooded. Excessively well-drained pockets of stratified drift typically wooded.

Figure 4.44 shows an end moraine in a humid climate. Note the hummocky topography, variable hilltop and pond elevation, lack of an integrated surface drainage pattern, and mottled photo tone. The soil parent material is well drained to somewhat excessively drained sandy loam till with pockets of stratified drift. The weathered soil profile is thin on hilltops and steep slopes. Very poorly drained mineral and organic soils are found in many depressions (kettle holes). The depth of till over bedrock is approximately 60 to 100 m.

Ablation ground moraine areas consist of ablation till that was deposited under conditions of a retreating ice front, as previously described. The physical characteristics—as well as the appearance on aerial photographs—of ablation ground moraine are similar to end moraine, except that: (1) the ablation till of ablation ground moraine areas forms a general ground cover instead of occurring as ridgelike lobes; (2) the topographic relief is generally less in ablation ground moraine areas; (3) the thickness of ablation till over basal till or bedrock is generally less in ablation ground moraine areas; and (4) the ablation till cover of ablation ground moraine areas may be discontinuous.

Basal ground moraine areas consist of basal till that was deposited at the base of glacial ice, as previously described. Great thicknesses of basal till can be built up as the ice continues to ride over the already deposited basal till, plastering on more and more material. Large areas of northern Indiana have a basal till cover 15 to 100 m in thickness built up from several ice advances. In the case of ablation till, only the materials existing in or on the ice at the time of melting can be deposited. Thus, the thickness of ablation till in ablation ground moraine areas is likely to be less than that of basal till in basal ground moraine areas. However, deposits of ablation till as thick as 40 m have been reported in ablation ground moraine areas.

Large basal ground moraine areas that consist of thick basal till are typically rather flat plains with local relief of only a few meters. Sometimes the terrain may have a series of elongated rises whose crests are aligned with the direction of ice movement, forming a grooved terrain of "mini-drumlins." Although the topography is favorable, basal ground moraine areas may or may not be well suited to urban development, depending on the soil and drainage conditions.

Airphoto Identification of Basal Ground Moraine Areas. This discussion refers principally to basal ground moraine areas of Wisconsinan age. Older basal ground moraine areas characteristically have greater relief and a more completely formed surface drainage system than de-

Figure 4.45 Basal ground moraine in a humid climate. Madison County, Indiana, May 1961. 1:20,000. (USDA-ASCS photos. Stereogram.)

scribed here. *Topography*: Broad, gently rolling plains with a swell-and-swale terrain that contain many shallow depressions with no natural drainage outlet. *Drainage and erosion*: The surface drainage pattern is not well developed because of the flat terrain and young age of the landform. A discontinuous and disordered network of broad, gently curving (fine-textured type) gullies roughly connects into an incipient dendritic pattern. Most of the surface precipitation drains into the ground rather than running off through surface drainage channels, unless farmers have constructed artificial drainage channels. *Photo tone*: A striking mottled pattern of light and dark tones, especially well seen in spring airphotos taken 1 to 2 days after a rainfall. *Vegetation and land use*: In most cases, the land has been cleared of native growth and is cultivated.

Figure 4.45 shows a typical basal ground moraine area in central Indiana. The striking mottled pattern results from different soil moisture conditions on the rises and depressions. The typical elevation difference between adjacent rises and depressions is ½ to 1 m. The total elevation difference in the area shown in this figure is about 3 m. The soils on the rises are somewhat poorly drained and have a silt loam surface soil texture. The soils in the depressions are very poorly drained and have a silty clay loam surface soil texture. The weathered soil profile is about one meter in thickness. The underlying till parent material is a loam to clay loam till under both the rises and depressions. The soils in the depressions are so poorly drained that tile drains or surface ditches are required to remove excess water so that the area can be farmed. The depth of till over bedrock in this area is at least 30 m.

Drumlins are composed of compact till molded into smooth, oval-shaped hills resembling an inverted spoon. They are shaped by the weight of the overriding glacial ice and have their long axes parallel to the direction of glacial ice movement. Drumlins are excellent examples of natural streamlining. Most well-formed drumlins have a length at least several times their width. The drumlin end facing the direction from which the ice came is decidedly steeper than the down-ice end. The high point on a drumlin is typically 2/5 of the length back from the nose. From this high point, the drumlin tapers gently toward the tail where it blends smoothly into the surrounding terrain. Drumlin sides are typically steeper than the nose, locally attaining slopes up to about 35 percent. Drumlins typically have a height of 10 to 50 m, a width of 200 to 600 m, and a length of 1 to 3 km. However, proportions ranging from nearly circular to a length/width ratio of 50:1 can be found. Single isolated drumlins are rare. Usually drumlins occur in large groups in areas of thick till in a belt 15 to 30 km wide located at least several kilometers up-ice from the end moraine of the stage of glaciation during which they were formed. They may be surrounded by and altered by recessional moraines.

Large groups of drumlins occur in New York (about 10,000) and Wisconsin (about 5000). Both Bunker Hill and Breed's Hill, which played historic roles in the Revolutionary War, are drumlins.

Drumlins can be found with a variety of till textures. Because of topographic limitations, high density urban development is not desirable in drumlin areas.

Airphoto Identification of Drumlins. *Topography*: Streamlined, ice-molded shape, with typical dimensions as previously described. In drumlin belts, adjacent drumlins may be separated from each other only indistinctly and shapes may vary widely. *Drainage*: Essentially no drainage pattern develops on drumlins because of their small size. Very poorly drained, marshy areas may occur in the depressions between drumlins. *Erosion*: Because of the steep side slopes, erosion may be sheet erosion rather than rill and gully erosion. *Photo tone, vegetation,*

and land use: The photo tone on drumlins often contrasts with the tone on the adjacent lowland because of differences in vegetation (e.g., trees on drumlin versus crops on lowland; different crops on drumlin versus lowland; crops on drumlin versus marsh vegetation on lowland) or soil moisture (e.g., well drained soils on drumlin versus poorly drained soils on lowland). The long dimensions of cultivated fields tend to be aligned with the drumlin axes.

Figure 4.46 shows drumlins in a humid climate. These drumlins are 25 to 30 m high, 300 to 500 m wide, and about 1.5 km long. The direction of ice movement was from top to bottom in Figure 4.46*a* and right to left in Figure 4.46*b*. The broad depressions between drumlins that have a faintly mottled, drab gray tone on the photos are occupied by very poorly drained silty clay loam soils.

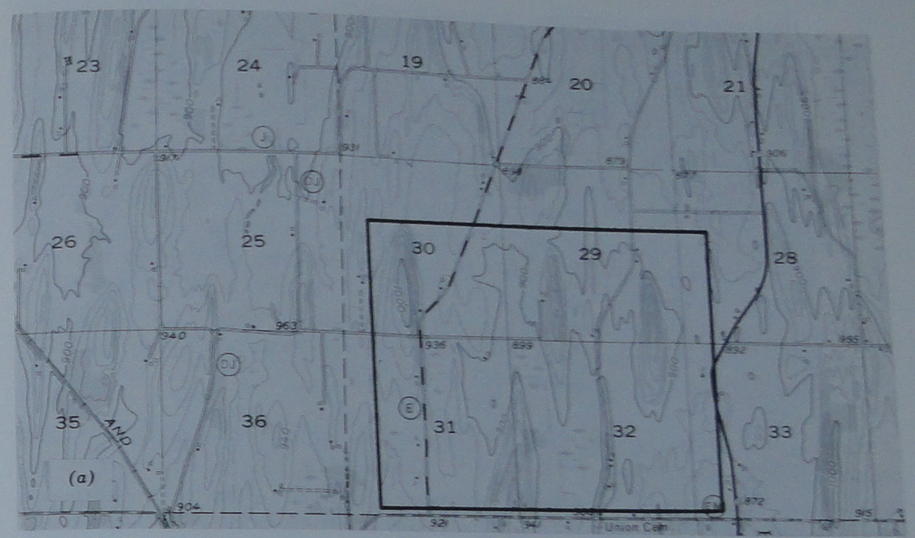
Ice-Contact Stratified Drift Landforms

Ice-contact stratified drift consists of materials partly water-sorted and crudely stratified, deposited adjacent to melting ice. Deposition can take place upon, against, or underneath the wasting terminal zone of the glacier and is likely to be sporadic and irregular. Ice is likely to melt from beneath accumulating ice-contact sediments, or from a supporting position beside them, causing sagging, collapse, or slump. The principal landforms resulting from this process are eskers and kames.

Eskers are long, sinuous ridges of ice-contact stratified drift deposited from streams flowing on, within or under the glacial ice. Eskers are typically 5 to 20 m high (maximum over 50 m), 50 to 100 m wide (maximum over 250 m) and 100 m to several km long (maximum over 250 km with short gaps). Side slopes are typically 30 to 45 percent (60 percent maximum). Eskers are often aligned with their length along the direction of ice movement. Some eskers are relatively straight while others have wide curves resembling stream meanders. At times they may branch, forming a series of esker ridges in a dendritic pattern. Eskers may connect "downstream" with fans or deltas. They may form a braided pattern or grade into kames. Eskers can have a wide range in crest elevation and may cross drumlins or bedrock hills.

Eskers are composed principally of stratified sand and gravel with parent material textures of gravelly sand and very gravelly sand. Soils developed on eskers are usually excessively well drained because of the elevated topographic position and coarse-textured parent material.

Eskers are excellent sources of sand and gravel for construction projects. In fact, many eskers near urban areas have been almost entirely removed for construction materials. On the other hand, eskers can provide excellent lo-



(North to top)

(North to right)

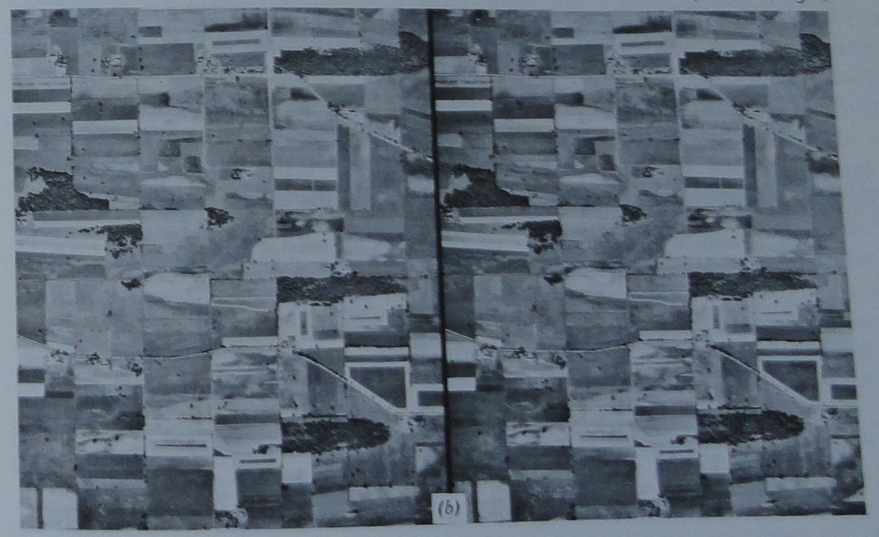


Figure 4.46 Drumlins in a humid climate. Dodge County, Wisconsin. (*a*) Topographic map, 20 ft. (6.1 m) contour interval, 1955. 1:62,500. (U.S. Geological Survey.) (*b*) Aerial photographs, June 1956. 1:43,500. (USDA-ASCS photos. Stereogram.) The outlined portion of the topographic map shows the area covered by the stereogram.

cations for hiking trails due to their linear nature and often-forested vegetation.

Airphoto Identification of Eskers. *Topography*: Size and shape previously described. *Drainage and erosion*: Little surface drainage or gullying due to small size and coarse-textured materials. *Photo tone, vegetation, and land use*: The photo tone on eskers typically contrasts with the tone on the adjacent landform (usually ground moraine) because of differences in vegetation (e.g., trees on esker versus crops on ground moraine; grass on esker versus row crops on ground moraine). Sand and gravel pits common (portions of esker may have been removed), especially near roads that cut eskers.

Figure 4.47 shows a portion of an esker in a ground moraine area in a humid climate. This esker is 10 m high, 100 m wide, and 27 km long (with small gaps). The esker soils are excessively well drained stratified sand and gravel. The ground moraine soils are well to moderately well drained sandy loam to loam till. About ⅓ down from the top of the figure, there is an area of very poorly drained mineral and organic soils on both sides of the esker.

Kames are mound-like hills or ridges of ice-contact stratified drift that may occur individually or in groups. Some kames are formed by deposition in crevasses and other openings within or on the surface of stagnant or nearly stagnant glacial ice that later melted away, leaving isolated or semi-isolated mounds of ice-contact stratified drift that we call *individual kames*. Another type of kame results from deposition of fan-like deposits built outward from the ice, or inward against the ice, or between two lobes of ice, which later melted and collapsed, forming large irregular mounds of ice-contact stratified drift called *kame complexes*. Kame complexes grade into kame terraces, ablation till, and eskers, and also form integral parts of some end moraines. Most kame complexes are found in association with kettles and with them record stagnant, disintegrating ice.

Individual kames are typically 15 to 25 m high and up to 150 m wide. Kame complexes cover a much larger area and often blend into eskers or end moraines. The characteristics of interlobate moraines are closer to our description of kame complexes than end moraines because they contain so much ice-contact stratified drift.

Kames are composed principally of stratified sand and gravel and tend to be somewhat finer-textured than eskers. Typical kame parent material textures are sand, gravelly sand, and very gravelly sand. Soil drainage is excessive due to the elevated topographic position and coarse-textured parent material.

Figure 4.47 Esker in a humid climate. Oconto County, Wisconsin, May 1958. 1:20,000. (USDA-ASCS photos. Stereogram.)

Kames are very good sources of sand and gravel for construction projects. They can also provide excellent locations for recreational development such as hiking trails and picnic areas because of their varied topography.

Airphoto Identification of Kames. *Topography*: Individual kames are isolated, conical to irregularly shaped mounds with steep side slopes. Kame complexes have a hummocky topography, with variable hilltop and depression-bottom elevations, that has been described as resembling crumpled aluminum foil. *Drainage and erosion*: Drainage is mostly internal with few gullies. Most depressions in kame complexes are dry rather than containing ponds or marshes. When gullies are present, they are the V-shaped (sand and gravel) type. *Photo tone*: Generally light-toned. *Vegetation and land use*: Typically grass or tree covered. May be used for grazing but seldom planted in row crops. Vegetation

often contrasts with that on adjacent landform (e.g., grass or trees on kames versus row crops on end moraine). Sand and gravel pits often seen in kame areas. *Other*: Since kame complexes intergrade with end moraines, especially interlobate moraines, airphoto identification of kame complexes versus end moraines can become difficult. The following criteria can be used to differentiate between kame complexes and end moraines: (1) Kame complexes have steeper side slopes and sharper ridges than end moraines. (2) Kame complexes have dry depressions while end moraines often have ponds and marshes in depressions. (3) Kame complexes tend to have a uniform light tone while end moraines have a mottled tone pattern. (4) Kame complexes usually have a grass or tree cover while end moraines usually have a row crop cover (except that end moraines are often tree-covered at their crests where they may contain significant amounts of stratified drift).

Figure 4.48 shows a large kame complex located on a portion of an interlobate moraine that extends for more than 200 km in eastern Wisconsin. This kame complex is 45 m high and has side slopes of 25 to 40 percent. Note the dry depressions and the even light tone on this excessively well drained kame complex. The kame complex is composed of stratified sand and gravel with some cobblestones. It is too steep and dry for cultivation and is used for perennial pasture. An esker runs from left to right across the bottom of the figure. At the top of the figure is a very poorly drained area of mineral and organic soils that appears as a mottled, darker-toned area with a stream meandering from right to left. This area is subject to ponding after heavy rains and can be farmed only if tile drains or ditches are used to drain excessive water.

Outwash Landforms

Outwash sediments are stratified drift deposited by streams flowing away from glacial ice. Outwash consists mainly of layers of sand and gravel that have come to rest on the beds of meltwater streams as they flow away from the glacier. The silt and clay particles are carried in suspension downstream from the outwash plain and are eventually deposited in glacial lakes, on stream flood plains, or in the ocean. Outwash sediments typically form a series of fans that spread out downstream from the ice and often coalesce. The individual apexes of the fans can often be recognized. The streams that distribute and deposit the outwash sediments take on a braided pattern as they flow down the fans and the remnants of braiding are clearly visible on present-day aerial photographs (the braided distributary channels of a present-day alluvial fan are shown in Figure 4.56). Numerous chunks of ice may be carried in the streams and form kettle holes upon melting.

Figure 4.48 Kame complex and esker in a humid climate. Walworth County, Wisconsin, October 1956. 1:20,000. (USDA-ASCS photos. Stereogram.)

Outwash sediments which form broad, nearly level plains are called *outwash plains*. Those confined to a valley are called *valley trains*. Outwash sediments with numerous kettle holes are called *pitted outwash*. Outwash plains and valley trains are often eroded by streams leaving *outwash terraces*.

Outwash deposits are almost ideally suited to urban development, except for excessively pitted areas. The nearly level terrain poses no limitations to development. The granular materials provide excellent foundation supporting strength and drainage conditions are favorable to development. In some valley train areas, the water table may be near the ground surface causing foundation problems. Where septic tanks are employed for the disposal of domestic sewage, there is a potential danger of drinking water contamination due to the porous nature of the outwash materials. The nearly level terrain

allows for intensive subdivision development. Lower density subdivisions can be placed on nearby end moraines, along with low density recreational development.

Airphoto Identification of Outwash Sediments. *Topography*: Nearly level surface sloping away from the source of the materials. Former distributary channels remain as a braided series of small depressions (less than ½ m deep). Numerous kettles in the case of pitted outwash. Outwash plains appear as a series of coalescing fans on a photo mosaic. Valley trains are confined by valley walls. Outwash terraces form steep escarpments above streams. *Drainage and erosion*: Internal drainage is rapid and there are few surface streams or drainage ditches. The former distributary channels are a relic, not a present-day drainage pattern. *Photo tone*: Overall light photo tone with former distributary channels appearing darker and giving a distinct "braided" or "wormlike" mottled tone. *Vegetation and land use*: Typically farmed in areas with sufficient rainfall, unless excessively pitted.

Figure 4.49 shows a portion of a large outwash plain just beyond the terminal moraine of Wisconsinan age glaciation in southern Wisconsin. The area generally to the left of the road that runs vertically in the figure is an outwash plain with a 0.25 percent slope from bottom to top in this figure. The area generally to the right of the road is the outermost extent of the terminal moraine. The glacial melt water that formed this outwash plain flowed from bottom to top in this figure (note the braided pattern of the former distributary channels). The outwash material is 20 m thick over bedrock and contains 60 to 70 percent gravel, 25 to 35 percent sand, and 1 to 5 percent silt and clay. There is a 1 to 1.5 m loess cover over the outwash so that the soil is classified well drained rather than excessively drained, as might be expected with stratified sand and gravel. As a result, this loess-covered outwash plain is one of the finest agricultural areas in the state.

Figure 4.50 shows an outwash terrace about 30 m above the Chippewa River in Wisconsin. Note the well-developed braided pattern of former distributary channels and the V-shaped (sand and gravel type) gullies along the terrace face above the river. The outwash material is stratified sand with some gravel and contains 5 to 15 percent fine gravel, 80 to 90 percent sand, and 1 to 5 percent silt and clay. These sandy soils are somewhat excessively drained and subject to wind erosion. Note that the terrace face above the river appears to have a slope of at least 60 degrees. The natural angle of repose of this material is around 30 degrees. Taking stereo exaggeration into account and applying Table 4.2, we find that the angle should appear to be about 60 degrees on the stereogram to most observers.

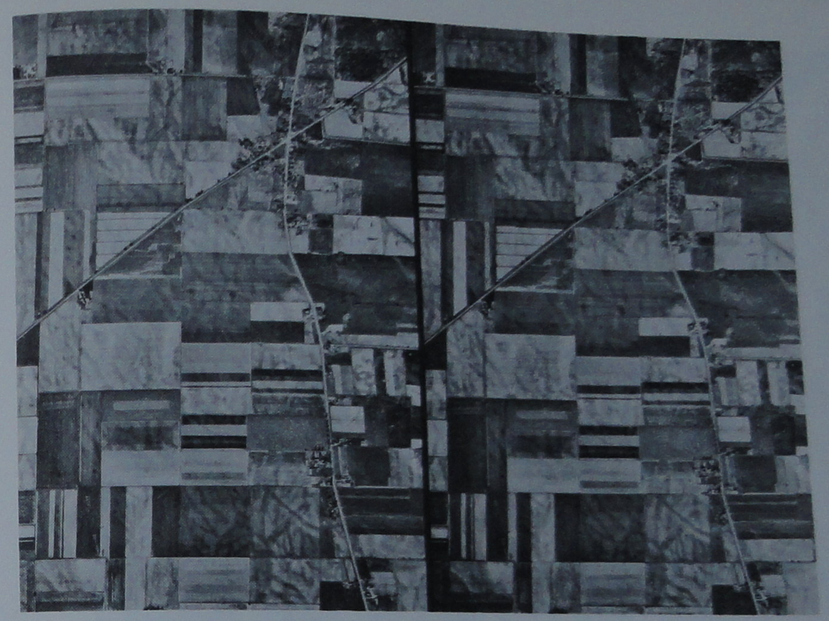


Figure 4.49 Outwash plain in a humid climate. Rock County, Wisconsin, May 1956. 1:40,000. (USDA-ASCS photos. Stereogram.)

Glacio-Lacustrine Landforms

As illustrated in Figure 4.43, ephemeral glacial lakes can be formed at the margin of glacial ice. Sediments deposited in the relatively quiet lake waters are called *glacial lakebed* deposits. Materials reworked into distinct linear ridges at the lake shoreline(s) are called *beach ridges*. Where streams enter the lake, *deltas* may be formed (Section 4.11). In areas of sandy near-shore lakebed deposits, the wind may later rework the dry materials into sand dunes.

Numerous glacial lakebeds of widely varying size can be found in glaciated areas. Perhaps the largest region of glacial lakebed deposits is the area of the glacial Great Lakes where glacial lakes existed along an ice front more than 2000 km long from the upper St. Lawrence to Saskatchewan. One of the lakes, glacial Lake Agassiz, left deposits over an area of 500,000 km². In contrast, the glacial lakebed and beach ridge shown in Figure 7.15 occupied an area of only 8 km².

Glacial lakebed deposits consist principally of the finer-textured products of glacial erosion (silt and clay). Near the lake shorelines, some sandy areas

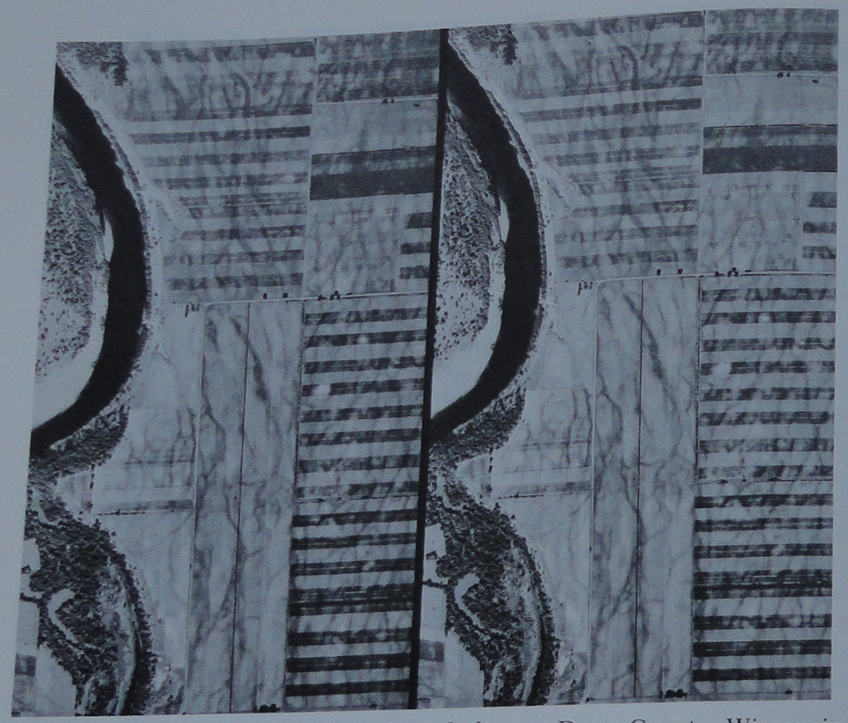


Figure 4.50 Outwash terrace in a humid climate. Dunn County, Wisconsin, July 1958. 1:26,700. (USDA-ASCS photos. Stereogram.)

can be found where waves have sorted the sediments, washing finer-textured materials out to deeper waters and spreading a veneer of sandy material in shallow water areas. Deep-water deposits are typically alternating layers (varves) of silty clay and clay. It has been hypothesized that each pair of layers represents one year's deposition, with silty clay deposited during the summer and clay deposited during the calmer winter conditions when the water surface is frozen. The thickness of these varves varies, but is rarely in excess of 5 cm. Lakebed soils typically have a seasonally high groundwater level and are somewhat poorly to poorly drained.

Although glacial lakebed topography is favorable for urban development, soil and drainage conditions pose severe limitations to building and road construction and to septic tank use. Glacial lakebed areas are commonly in agricultural use. Where outlets are available, tile drains and ditches are provided to improve drainage for agricultural purposes.

Airphoto Identification of Glacial Lakebed. *Topography*: Very flat with undulations less than ½ m high. *Drainage*: A general lack of surface drainage despite the very poor internal drainage. This is because of the flat topography, lack of a drainage outlet, and high groundwater table. Streams originating beyond the margin of the lakebed may meander across the lakebed (as in the case of the Red River of the North shown in Figure 4.51), but there is seldom much of a surface drainage network connected with these streams. Artificial drainage is common in agricultural areas; buried tile drains and a network of open ditches may be seen on airphotos. *Erosion*: Few gullies due to flat topography and lack of an integrated surface drainage network. Some fine-textured type gullies may be seen draining into large streams, especially if the streams are entrenched. *Photo tone*: Darker tone than surrounding better-

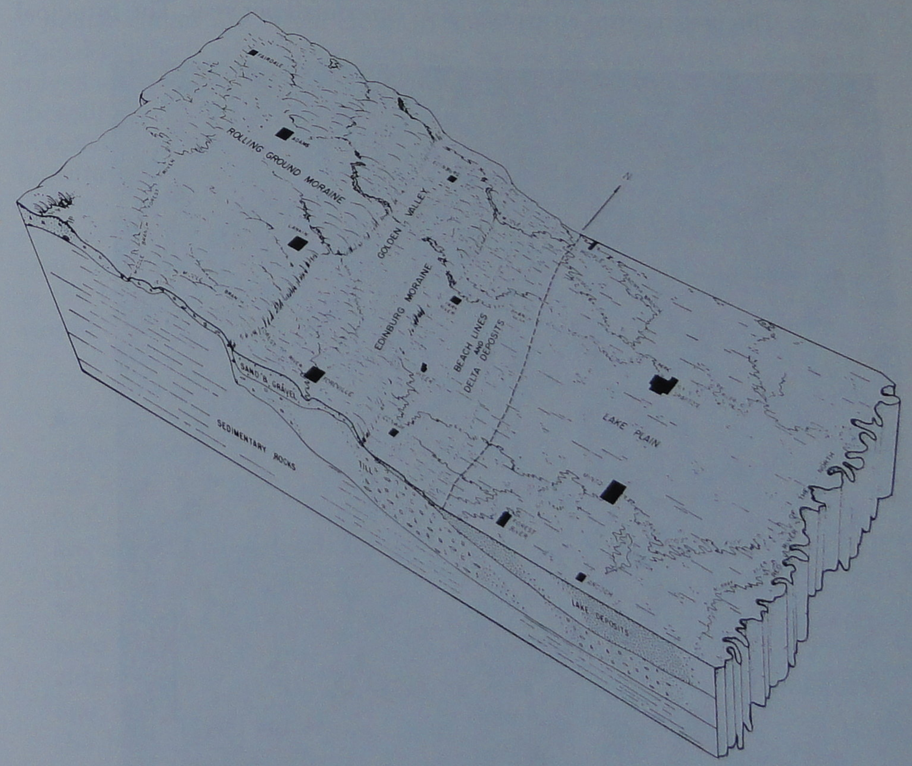


Figure 4.51 Schematic diagram illustrating the relationships among lakebed, shoreline, and till deposits in Walsh County, North Dakota. (From USDA-SCS [21].)

Figure 4.50 Outwash terrace in a humid climate. Dunn County, Wisconsin, July 1958. 1:26,700. (USDA-ASCS photos. Stereogram.)

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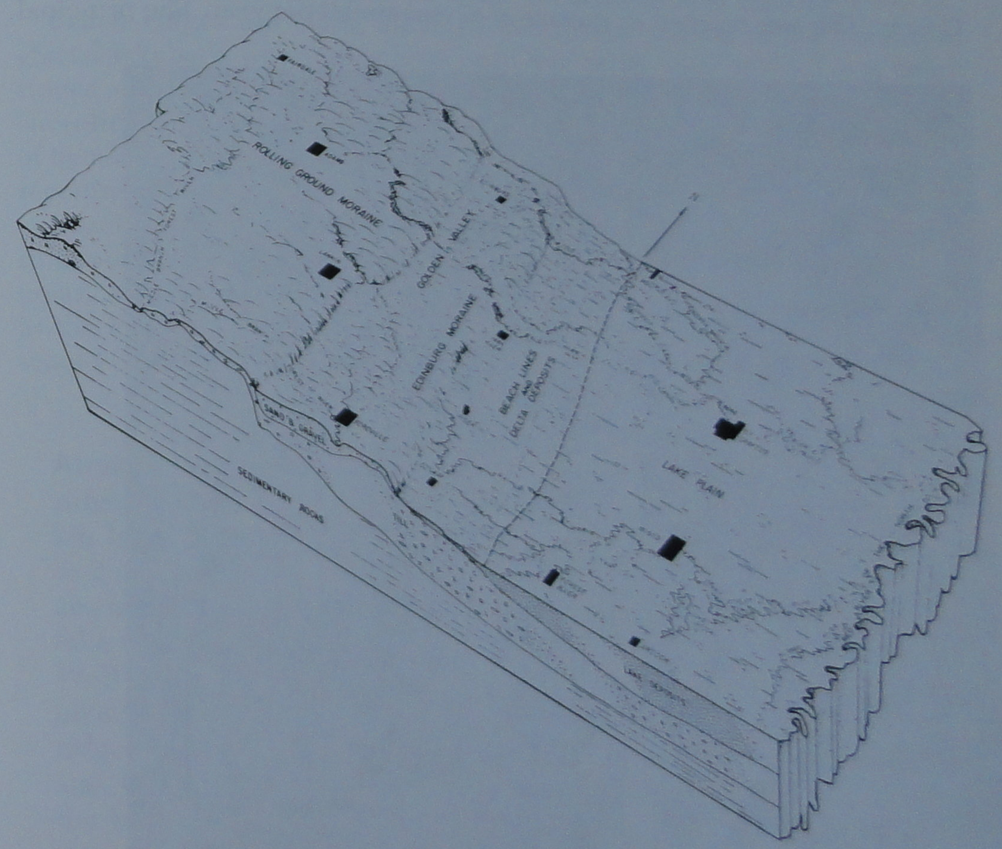

Figure 4.51 Schematic diagram illustrating the relationships among lakebed, shoreline, and till deposits in Walsh County, North Dakota. (From USDA-SCS [21].)

drained materials. Often a striking mottled tone of uneven linears, with the lighter-toned areas slightly higher and drier and the darker-toned areas slightly lower and wetter. *Vegetation and land use*: Typically farmed where climate is satisfactory.

Figure 4.51 illustrates the relationships among lakebed, shoreline, and till deposits in Walsh County, North Dakota. The initial glaciation of this area produced a continuous cover of till over sedimentary bedrock. The till cover is thinner in the ground moraine area covering the higher elevations of bedrock and thicker on the end moraine. The waters of glacial Lake Agassiz covered about 60 percent of this county (including most of the Edinburg Moraine) to depths ranging to at least 135 m. As lake waters receded, at least 10 beach ridges were formed, with at least four of them concentrated in the portion of the figures labelled "beach lines and delta deposits."

Figure 4.52 shows a glacial lakebed in the southeast corner of Walsh County. This area receives an average of 47 cm rainfall per year. The principal

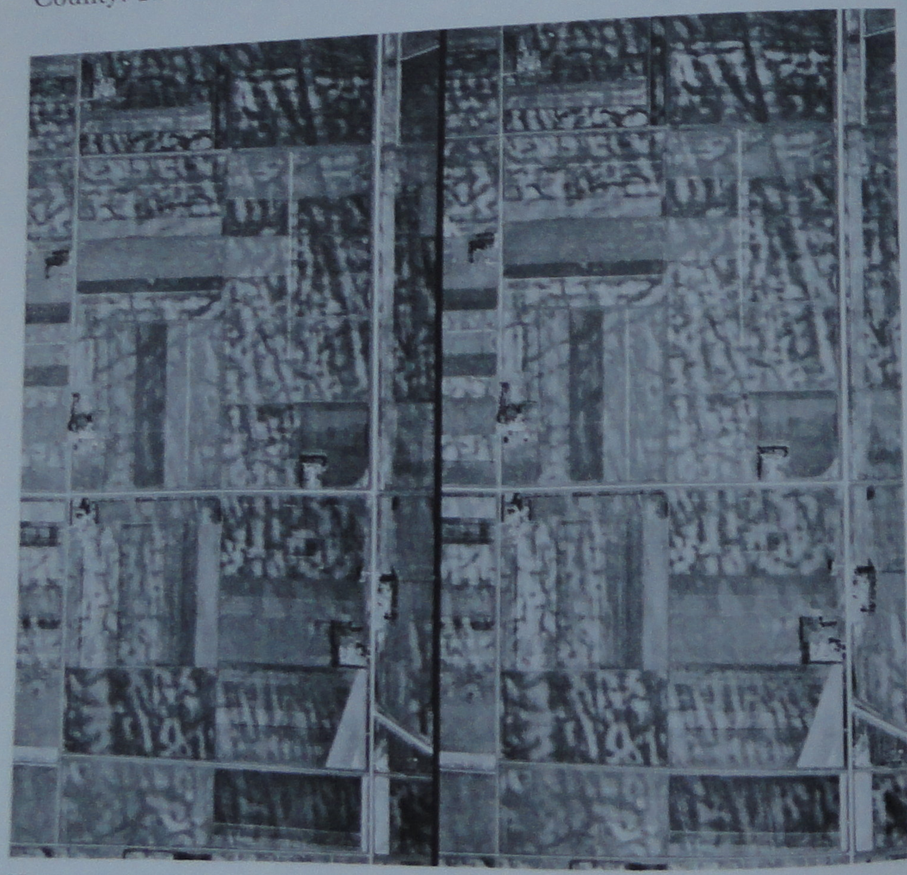

Figure 4.52 Glacial lakebed. Walsh County, North Dakota, July 1962. 1:36,400. (USDA-ASCS photos. Stereogram.)

crop is hay. Note the striking mottled tone of uneven linears. The origin of these linears is not well understood. The following hypotheses have been given: (1) the linear ridges formed when the lake was shallow by the squeezing of soft lake sediment up into the cracks of thick lake ice; (2) the lineations resulted when wind-driven ice blocks moved over the lake and dragged on the soft sediments of the nearly flat lake floor; (3) the lineations are shoreline features; (4) the lineations are an unusual form of permafrost patterned ground or fracture fillings formed in lake ice; (5) the lineations result from the cracking of clay soils upon drying; and (6) lineations are reflections of bedrock jointing. The most recent (1972) USDA-SCS soil survey [21] recognizes the existence of an irregular pattern of ridges, only 15 to 30 cm high that are separated by slightly concave areas, but both the lower and higher areas are included in the same soil map unit. The lakebed soils in this figure are very poorly drained with 75 cm of silty clay over varved lacustrine clay and have a seasonal water table within 90 to 150 cm of the ground surface.

Beach ridges are often, although not always, present at the margins of glacial lakebeds where they have been formed by wave action. Large beach ridges are likely to be associated with rising water levels and the advance of shorelines upon the land, because of continuous reworking and concentration of beach sediment. A series of small ridges is more commonly associated with receding shorelines.

Beach ridge soils are typically excessively drained sand and gravel. Beach ridges are often important sources of construction materials in glacial lakebed areas. Also, beach ridges provide suitable foundation strength and can serve as the location for transportation routes where construction on lakebed soils would cause severe problems.

Airphoto Identification of Beach Ridges. *Topography*: Individual ridges can be as large as 5 to 10 m high, 200 to 1000 m wide, and many km long. A series of small ridges left by receding waters is typically 1 to 2 m high, less than 100 m wide, and of variable length. Beach ridges are asymmetrical in cross section with a smooth, steep slope facing the lake and an irregular, gentle slope away from it. *Drainage and erosion*: Well drained internally due to coarse-textured soil. Few gullies. In the case of large individual ridges, the upslope area adjacent to the beach ridge may be wet as the beach ridge acts as a small dam blocking drainage. Occasional streams may cross the ridge. Some water flows through the base of the ridge and may leave a wet area immediately in front of the ridge. In the case of a series of ridges, the areas between ridges are often very wet with a ground water table at or near the surface. *Photo tone, vegetation, and land use*: Often contrast with less well-drained soils to either side of the beach ridge.

Figure 4.53 shows an individual beach ridge in Niagara County, New York, 13 km south of the present shoreline of Lake Ontario. Most of Niagara County was once covered by a glacial lake. At one stage in the successive lowering of the lake levels to the present level of Lake Ontario, about 12,000 years ago, glacial "Lake Iroquois" had its shoreline at the location of this figure. The resulting beach ridge is 5 to 6 m high, 300 to 600 m wide, and many kilometers long. Note that a major highway and several houses are located on the beach ridge whereas there are no houses and only minor roads on either side of the ridge. The beach ridge soils are excessively drained sand and gravel containing 20 to 45 percent gravel, 45 to 65 percent sand, and 0 to 25 percent silt and clay. These soils are warm and dry in the early spring and provide very good growing conditions for early fruit and vegetable crops.

Figure 4.53 Beach ridge in a humid climate. Niagara County, New York, August 1958. 1:20,000. (USDA-ASCS photos. Stereogram.)

To the left of the beach ridge are poorly drained to very poorly drained lakebed soils (very fine sand, silt, and clay), deposited during a higher lake level, which are not suited to growing fruit (note the complete lack of orchards to the left of the beach ridge). The dark-toned area just at the right-hand edge of the beach ridge is a poorly drained to very poorly drained area of fine sand where ground water seeping under the beach ridge emerges. The far right-hand portion of the figure is somewhat poorly drained, loamy-textured, shallow-water lakebed deposits over till. Some fruit is grown on these soils, but they are not as well suited for this purpose as the beach ridge soils.

Figure 4.54 shows a series of more than a dozen small beach ridges along Lake Michigan. These ridges are less than 2 m high, sandy, and mostly tree covered (pines, spruce, and fir). The interridge depressions have a ground-water table at or near the surface most of the year and have principally marsh vegetation (sedges and grasses). Soils in the interridge areas are highly or-

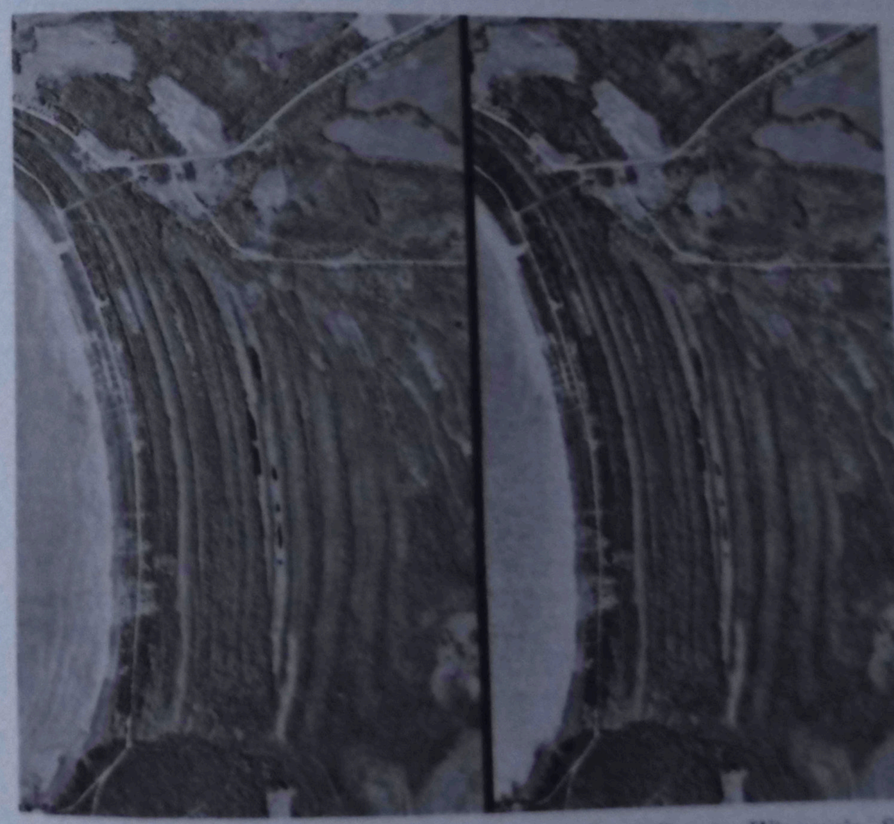

Figure 4.54 Beach ridges in a humid climate. Door County, Wisconsin, September 1961. 1:25,000. (USDA-ASCS photos. Stereogram.)

ganic (mostly peat). Toward the right-hand portion of the figure, where the deposits are older, many shrubs and trees (tamarack, ash, and willow) are growing on the wet organic soils. The flat-topped hill in the upper right-hand portion of the figure, which rises 20 m above the surrounding terrain, is horizontally bedded dolomite with a thin veneer (less than one m thick) of well drained sandy loam till.

4.11 FLUVIAL LANDFORMS

Fluvial landforms are created by the erosion, transportation, and deposition of unconsolidated materials by the action of flowing water. The principal fluvial landforms to be described are alluvial fans, flood plains, and deltas.

The ability of flowing water to erode and transport soil and rock particles depends on water velocity and particle size, as shown in Figure 4.55. It requires a greater velocity to erode particles than it does to keep them moving (transportation). As velocities fall below a certain value, deposition takes place. The larger particles are bounced and rolled along the stream bed (*bed load*). The smaller particles are picked up and carried forward in suspension (*suspended load*). Certain particles, especially sand-sized particles, may travel by suspension or as a bed load at different times, depending on the stream velocity. Small particles require a considerable velocity to erode them, but, once moving, can be transported in suspension over a wide range of stream velocities. The greatest erosion and transportation of sediments takes place during floods. The increase in velocity and volume of water results in an increase in both the size and volume of materials that can be transported.

The term *stream competence* refers to the maximum size particles a stream can transport at a given velocity. *Stream capacity* refers to the maximum amount of materials the stream can transport and is related to stream volume. A small, rapid stream can move relatively large particles, and while its competence is great, the amount of material that can be moved (capacity) is small. A large, slow-moving stream may carry in suspension a great quantity of small particles and have a small competence but a large capacity.

As shown in Figure 4.55, deposition takes place selectively by particle size as the stream velocity decreases. Rapidly flowing mountain streams often deposit sand and gravel as *alluvial fans* at the base of the mountains as the stream velocities decrease and the streams are no longer competent to transport such large size particles. Streams flowing on *flood plains* will deposit much material both along their channels and by overbank flooding. As streams enter lakes or oceans, *deltas* are often formed as a result of the rapid decrease in stream velocity. The description of each of these landforms follows.

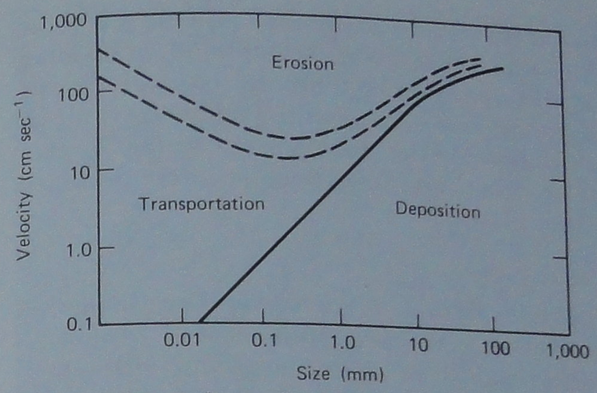

Figure 4.55 Relationships among erosion, transportation, and deposition as a function of stream velocity and particle size. (Modified from Twidale [19].)

Alluvial Fans

Alluvial fans occur at the base of steep slopes where streams discharge into an area having a more subdued relief. The fans are built of coarse-textured materials eroded from the higher elevations and transported downslope. As stream velocities decrease upon flowing from the upland area, the streams are no longer competent to transport the larger sized particles and deposition occurs. Stream channels are relatively fixed at their canyon mouth but are free to wander downslope, forming a braided pattern. As this process proceeds over a long period of time, the fan builds upward and outward with the stream swinging over perhaps 90 degrees right and left until a surprisingly symmetrical and uniform alluvial fan has been formed.

Alluvial fans are best developed in arid areas at the base of high mountain ranges. Approximately 30 percent of the land area of the southwest United States is covered by alluvial fans that can be up to 15 km long and several hundred meters thick. In humid areas alluvial fans are smaller, typically only a few hundred meters long. Slopes on alluvial fans are in the 2 to 15 percent range, with steeper slopes at the head of the fan and gentler slopes near the base.

Alluvial fan materials are principally sand and gravel, with some silt. Alluvial fans are often the only source of water in arid areas. The surface water percolates into the ground and the porous soil mass acts as an underground storage reservoir. Shallow wells are best located near the base of the fans where the depth to water is least and there may be some pressure head.

Alluvial fan soils provide good foundation conditions for highways and buildings. The sloping terrain provides good view sites for subdivision de-

velopment and the location below mountain valleys may provide a cooling breeze at night. However, the shifting stream channels and frequent flooding that can occur on alluvial fans present serious limitations to development. Major sections of the Alaska Highway have been rerouted following destruction of the original road crossing alluvial fans. Subdivisions in the Denver area and several southern California locations have been severely damaged by shifting alluvial fan distributary channels.

Airphoto Identification of Alluvial Fans. *Topography*: Fan-shaped, with a slope of 2 to 15 percent away from apex. *Drainage and erosion*: Excellent internal drainage. Limited surface drainage system with few gullies. Numerous distributary (constructional) channels. *Photo tone*: Generally light; distributary channels may be darker. *Vegetation and land use*: General lack of vegetation along distributary channels; may be heavier vegetation at base of fan due to ground water seepage. Humid areas often cultivated; natural vegetation on fan may contrast with adjacent landforms.

Figure 4.56 shows coalescing alluvial fans along the western edge of Death Valley. The slope of the alluvial surface is 12 percent in the mountain valley, 10 percent at the apex of the fan, and 8 percent at the base of the fan. Numerous distributary channels are clearly visible on the photograph. Note the darker tone and presence of vegetation near the base of the fan (resulting from higher soil moisture content) and the topographic and tonal contrast between the base of the fan and the adjacent light-toned valley floor.

Flood Plains

Flood plains are depositional landforms created by the processes of stream meandering and overbank flooding. Stream meandering is the result of a stream's adjustment to its environment in order to carry its load most efficiently. Meandering streams tend to follow certain mathematical rules with regard to meander wavelength, meander amplitude, stream flow volume, stream flow velocity, channel width, channel depth, flood plain slope, and river gradient.

Because water velocities are highest there, river banks normally erode on the outside and downstream side of each curve, though during high flow periods the river tends to follow a straighter course and erode on the inside of the curves. The inside of each curve is normally a place of deposition of gravel and sand called a *point bar deposit*. As the radius of river meanders becomes larger, a point is reached where meanders are cut off and an abandoned meander called an *oxbow* remains. When oxbows are filled with standing water, they are called *oxbow lakes*. Meanders tend to migrate downslope, which also results in shifting channel patterns.

Figure 4.56 Alluvial fans in an arid climate. Inyo County, California, (Death Valley), October 1952. 1:75,000. (USGS photos. Stereogram.)

Streams on a flood plain often overflow their banks and, as they do, some alluvial material is deposited just outside the normal stream channel as a *natural levee*. Natural levees are too small to be noticed on many streams. However, large rivers such as the Mississippi often have prominent levees. Artificial levees are sometimes constructed atop natural levees to protect flood plains from subsequent flooding. If a river restrained by an artificial levee cannot overflow its banks and deposit its sediment load on the floodplain, it tends to deposit materials in its own channel. This new sediment tends to raise the level of the riverbed. To prevent the next flood from overflowing, the artificial levee must be constructed even higher. Artificial levee construction on one stretch of a river may lead to increased flooding on other stretches of the river. Overbank flooding results when streams overflow their levees

and slow-moving waters cover much of the flood plain. Deposits from these slow-moving waters are called *slack water deposits* (also called *backswamp deposits*).

Flood plain terrain has an overall level relief with minor irregularities and a gentle downstream gradient. The texture of flood plain materials varies greatly because they have slowly accumulated over years of shifting stream courses and overbank flooding. Point bar deposits consist principally of gravel and sand. Natural levees contain principally sand and silt. Oxbows often contain standing water or very poorly drained organic soils. Slack water deposits are usually poorly drained silts and clays. The depth to bedrock is variable, depending on the nature of the buried terrain. Wider flood plains generally have greater depths to bedrock. Using airphoto interpretation, the present surface soils can be effectively estimated, but it must be realized that materials will vary with depth because a variety of flood plain features can lie buried beneath the present land surface.

Development on flood plains must proceed with extreme caution. Annual losses of life and property on flood plains are staggering. In addition to the danger of flooding, serious foundation limitations are imposed by the extremely variable soils and high groundwater table. If development is to take place on flood plains, it must be preceded by a careful study of the soils present, the internal soil drainage and groundwater conditions, and the frequency and severity of flooding that can be expected. Flood plains are better suited to agricultural or parkland uses that can withstand periodic flooding with comparatively low losses.

Mapping of flood plains for developmental planning and flood insurance purposes has received major emphasis in the United States. In this process, the *floodway* (area covered by a flood) is delineated for floods occurring with a given probability. The determination of the limits of a given flood often incorporates flood plain terrain evaluation, topographic mapping through photogrammetric techniques, and hydrologic modeling.

Airphoto Identification of Flood Plains. *Topography*: Generally level with small downstream gradient. Natural levees slightly higher position. Slack water deposits in lowest position. *Drainage and erosion*: A principal stream flows on its flood plain. On wide flood plains, secondary streams may be present near the outer edges of the flood plain (yazoo streams) and flow a considerable distance before connecting with the principal stream. Because groundwater tables are high and the terrain level, and because of periodic flooding on the flood plain, there is seldom an integrated drainage pattern connected with the principal stream.

Photo tone: A complex pattern of tones is present, reflecting the variety of soil and moisture conditions. Point bar deposits have a light tone that may alternate with darker-toned depressions between point bars. Natural levees are lighter-toned than surrounding slack water deposits. Slack water deposits are darker-toned, often with distinct artificial drainage features. Oxbows have a uniform gray tone if filled with standing water, or a darker tone if occupied by organic soils. *Vegetation and land use*: Often agricultural use, especially drained slack water deposits. Natural marsh or swamp vegetation in organic oxbow deposits. Point bar deposits that flood annually may be barren; those that flood only occasionally may be farmed.

Figure 4.57 is a photo-mosaic (note photo numbers at upper right of each frame) showing a portion of the flood plain of the White River. The shifting channels of the river can be clearly seen (note numerous oxbows). Figure 4.58 shows a portion of the area covered in Figure 4.57 (photo QQ-IV-74). The present course of the stream meanders across the top of Figure 4.58. The trees immediately below the river are growing on a small natural levee. Numerous arc-shaped point bar deposits can be seen in the upper right of the figure below the river. These are small, well-drained, sandy rises with a nearly white photo tone. In the lower center of the figure are two well-developed oxbows. These contain standing water for part of the year, but are gradually becoming filled with organic material. In the lower left of the figure are poorly drained slack water deposits with a clay loam texture. Note the striped pattern caused by numerous ditches constructed to drain these soils to allow cultivation.

Deltas

Deltas form where streams discharge into bodies of quiet water (lakes and oceans). The stream velocity rapidly decreases and deposition of sediment takes place.

Most deltas have shifting multiple distributary channels (analogous to alluvial fans) and form fan shapes, as in the case of the Nile Delta. Such deltas are called *arcuate deltas*. Streams carrying a large load of silt and clay tend to flow within a few relatively stable distributary channels confined by natural levees (analogous to river flood plains) and to form branching deltas, as in the case of the Mississippi Delta. Such deltas are called *birdfoot deltas*.

Arcuate delta soils typically contain a great deal of sand with some gravel. Arcuate deltas deposited in former glacial lakes are often used as sources of sand and gravel for construction activities. Arcuate deltas protruding into present-day lakes often make excellent sites for recreational development.

Figure 4.57 Flood plain in a humid climate. Knox and Gibson Counties, Indiana, August 1958. 1:76,000. (USDA-ASCS photo mosaic.)

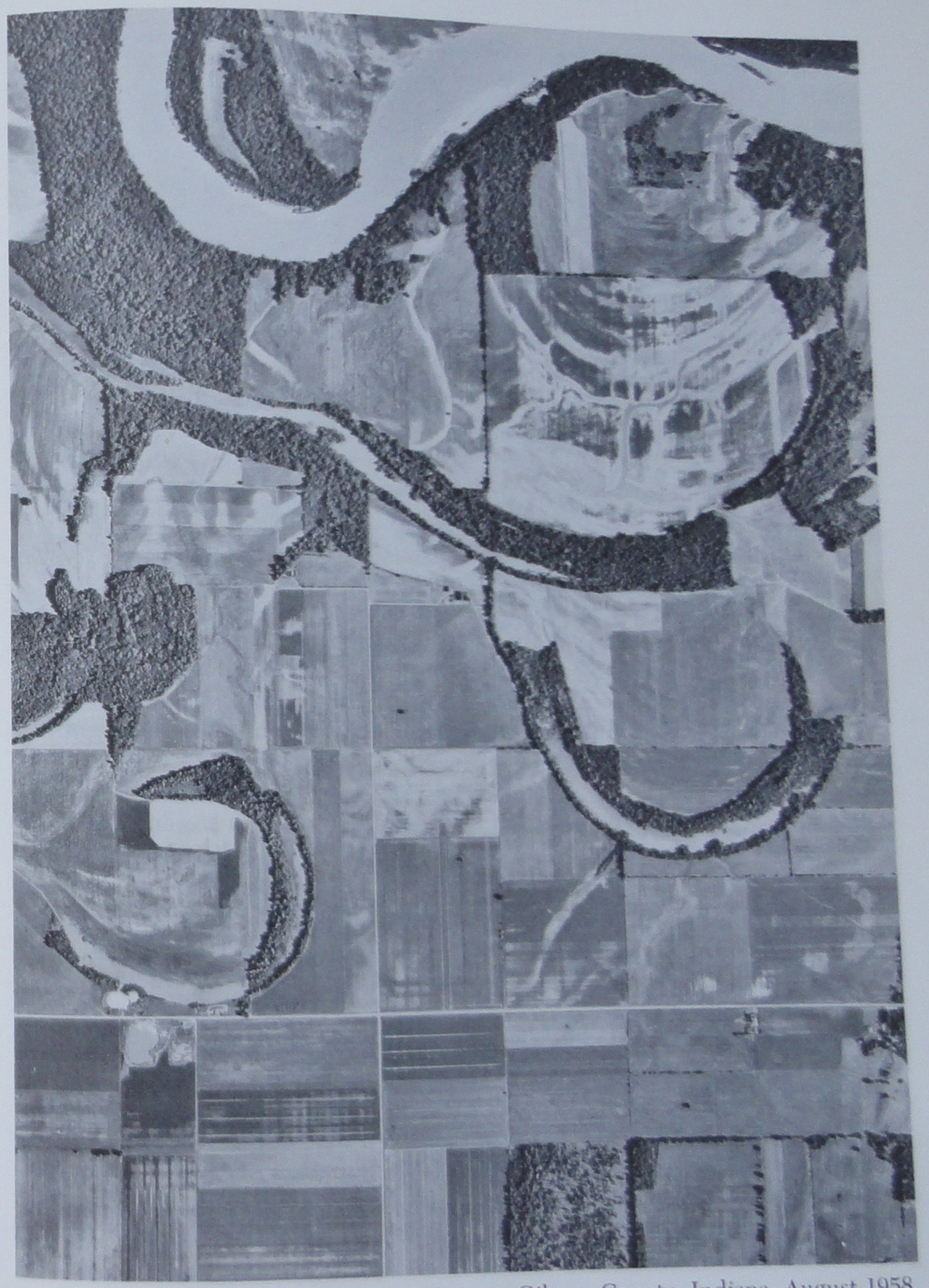

Figure 4.58 Flood plain in a humid climate. Gibson County, Indiana, August 1958. 1:22,200. (USDA-ASCS photo.)

Topography is favorable for active sports, lake access is convenient, sloping sandy beaches may be present, and occasional flooding from distributary channels can be tolerated. Power plants often compete with recreational uses for space on arcuate deltas as site conditions are also favorable for power plant location, as long as potential flooding is taken into account in site design.

Birdfoot delta site conditions present limitations to development because soil and drainage are extremely variable, as in the case of river flood plains, and the delta is subject to overbank flooding. The use of birdfoot deltas for agriculture is important on a worldwide scale.

Airphoto Identification of Deltas. *Topography*: Nearly level surface bounded by upland areas and water. Overall arcuate or birdfoot shape. *Drainage and erosion*: Distributary streams present. Arcuate deltas have one or more main channels arranged in a fan-shaped radial pattern. Also, former distributary channels (typically braided) are present. Birdfoot deltas have one major channel plus several large branches extending in random directions. Birdfoot deltas may have numerous ponds and low wet areas. Gullies seldom present. *Photo tone*: Variable, depending on soil and moisture conditions. Arcuate deltas tend to be light-toned, with a braided pattern revealing former distributary channels. Birdfoot deltas resemble river flood plains, with natural levees, slack water deposits, and so on. *Vegetation and land use*: Variable, depending on climate and depth to water table. Some deltas used extensively for agriculture; others undisturbed marshland.

Figure 4.59 shows a small arcuate delta formed where a stream flows into a deep lake. Note the recreational development on this delta.

Figure 4.60 contains two Landsat images (see Chapter 10) showing the extensive birdfoot delta of the Mississippi River. Figure 4.60*a* shows the river flowing within its banks and pouring vast quantities of silt into the Gulf of Mexico. Figure 4.60*b* shows the many distributary channels of the delta, each confined by a natural levee.

Figure 4.61 shows a small birdfoot delta formed where a stream flows into a shallow lake. Note that the natural levee of the stream carries well into the lake, forming the birdfoot delta. Numerous cottages are located on the natural levee to the left of the stream. To both sides of the levees are very poorly drained organic soils plus some standing water with aquatic vegetation. In these early July photographs, there is a great deal of sun glitter (specular reflection) on the left photograph, making stereoviewing somewhat distracting.

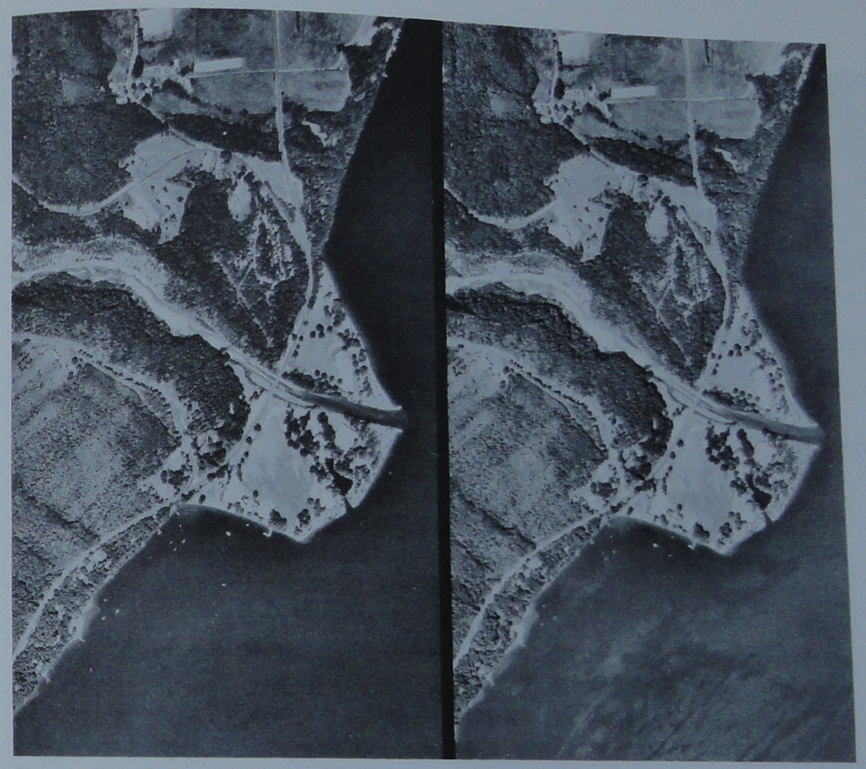

Figure 4.59 Arcuate delta in a humid climate. Tompkins County, New York, July 1964. 1:20,000. (USDA-ASCS photos. Stereogram.)

4.12 ORGANIC SOILS

Organic deposits are widely distributed throughout the world. They form wherever production of organic matter exceeds its mineralization, usually under conditions of almost continuous water saturation that limits the circulation of oxygen through the soil, slows the decomposition of organic matter, and permits its accumulation. The principal organic soils are muck and peat. *Muck* is dark-colored organic soil material that is partially decomposed. *Peat* is organic soil material that is relatively undecomposed with recognizable plant fragments. Peat becomes muck upon further decomposition.

Muck and peat occur in wet, low areas of the landscape in association with numerous landforms, especially in glaciated areas and on flood plains (the presence of organic soils was mentioned in several figure descriptions). The conversion of living vegetation to peat and muck is a dynamic process re-

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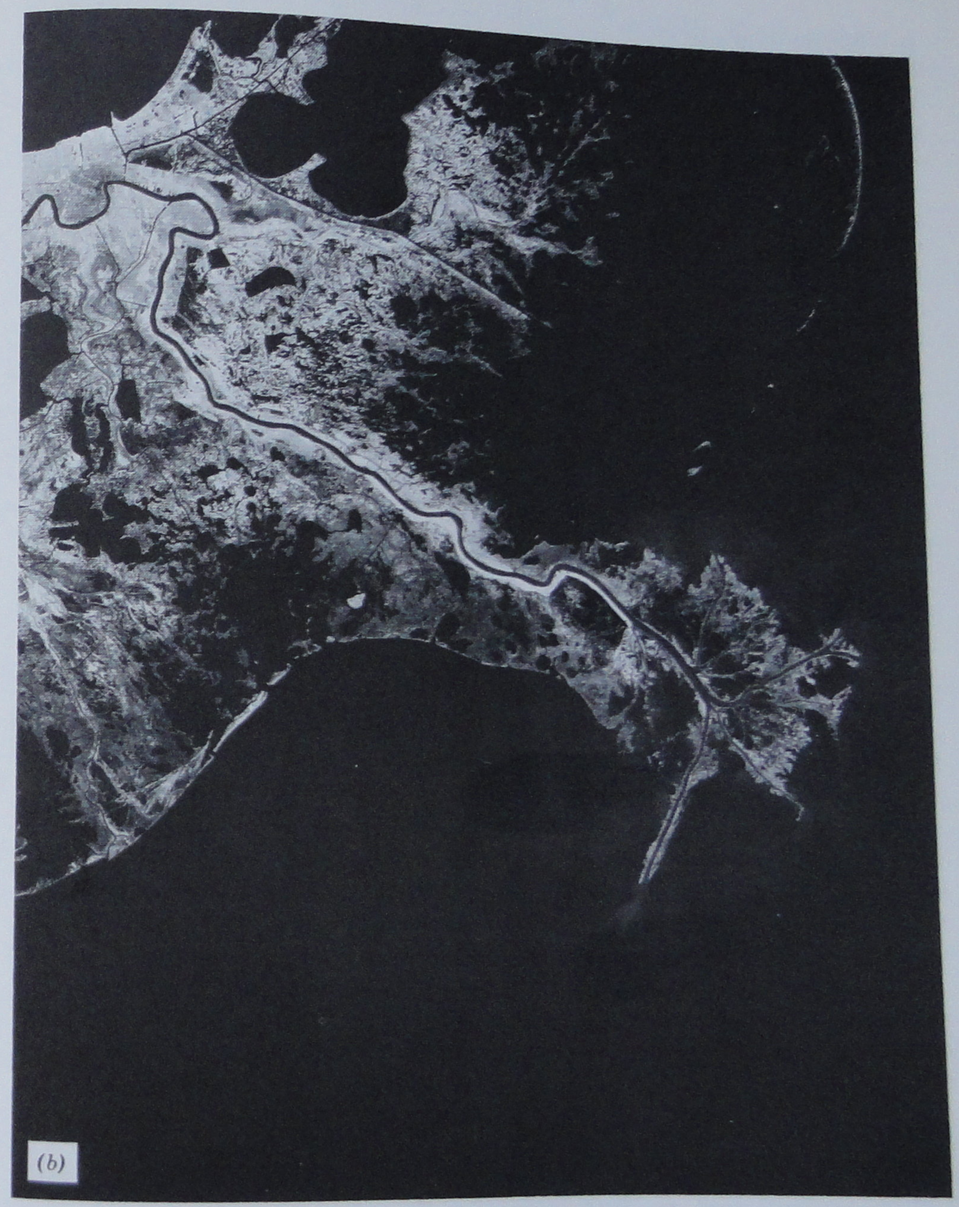

Figure 4.60 Birdfoot delta, Mississippi River and Gulf of Mexico below New Orleans. (*a*) Landsat Band 5 (red). (*b*) Landsat Band 7 (reflected infrared). January 16, 1973. 1:1,100,000. (NASA images.)

sulting in organic deposits of variable age, size, thickness, number of layers of materials, and stage of decomposition. Airphoto interpretation can be effectively utilized to delineate the extent and general nature of organic deposits, but field soil borings are required for information about the total thickness of the deposits and their composition at depth.

Peat soils can be described as *sedimentary peat*, *fibrous peat*, or *woody peat*, depending on the nature of the plant fragments. Organic soil formation typically begins in shallow lakes or ponds with aquatic vegetation (water lilies, duckweed, algae). The annual addition of decaying plants results in a soft, oozy, structureless *sedimentary peat*. As organic material builds up on the pond bottom and water depths decrease, marsh vegetation (cattails, sedges, grasses) encroaches on the pond, decreasing the open water surface and the amount of aquatic vegetation. The peat resulting from the decomposition of marsh vegetation is a *fibrous peat* with a firm but porous interwoven network of stems, roots, and leaf fragments. The final stage of native vegetation that typically establishes itself upon a layer of fibrous peat is a swamp forest (tamarack, alder, willow). Decomposition of leaves, needles, bark, twigs, and cones produces *woody peat*.

Mineral soils typically have 1.5 to 2.5 grams of solid material per cubic centimeter of soil volume (g/cc). Organic soils typically have only 0.5 g/cc solid material and have been found with densities as low as 0.1 g/cc. The volume not occupied by solid particles is occupied by water plus a small amount of air if the soils are not saturated. Mineral soils usually have a ratio of water to solids of 5 to 20 percent on a weight basis. Organic soils typically have a ratio of 100 to 500 percent, which means that there is more water than solid material in muck and peat deposits.

Muck and peat present extremely poor foundations for construction activities and should be avoided in urban and suburban development. Highways crossing muck and peat are susceptible to both soil failure and excessive settlement, unless elaborate (and expensive) design and construction procedures are utilized.

Muck and peat in suitable climates are often drained and farmed for crops such as potatos, peppermint, celery, onions, and sod for lawns. In such cases, care must be taken not to overdrain the organic soils as they are susceptible to an irreversible hardening that restricts water movement and root penetration. In addition, dry muck and peat present a fire hazard. Fires on these materials are difficult to control and may burn for months, polluting the air and destroying the organic material. Many wetland areas with organic soils provide an important, productive wildlife habitat for both resident species and migrating birds. When such areas are drained and farmed (or dredged for other uses), important wildlife habitats are often destroyed permanently. Organic soil areas in their natural state adjacent to inland lakes often serve to trap silt and nutrients which may otherwise contribute to the eutrophication of lakes. If such areas are drained and farmed, lake water quality usually worsens.

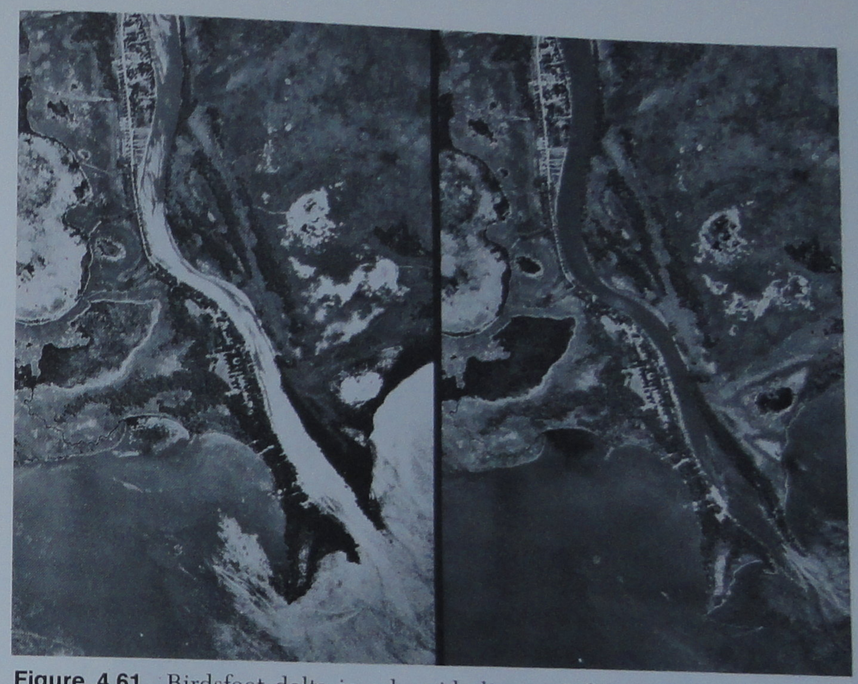

Figure 4.61 Birdsfoot delta in a humid climate. Jefferson County, Wisconsin. July 1957. 1:28,600. (USDA-ASCS photos. Stereogram.)

Airphoto Identification of Organic Soils. Organic soils are found in topographic depressions in areas such as end moraine and ground moraine, flood plains (especially oxbows), depressions between sand dunes, depressions between beach ridges, limestone sinkholes, and kettle holes. *Topography*: Very flat; often sharp contrast with surrounding material. *Drainage and erosion*: Typically very poorly drained with water table at or near the ground surface for much of the year. Few gullies. Artificial drainage if drained for farming. *Photo tone; vegetation, and land use*: Bare (unvegetated) soil has a very dark tone. Native grass, sedge and shrub vegetation has a drab gray, mottled appearance. Drained agricultural areas have a distinctive pattern (Figure 4.62) of artificial drainage ditches and intensively farmed areas.

Figure 4.62 Organic soils in a humid climate. Jefferson County, Wisconsin, July 1957. 1:36,400. (USDA-ASCS photos. Stereogram.)

Figure 4.62 shows organic soils in Jefferson County, Wisconsin, a county with nearly 20 percent of its land area occupied by organic soils. Organic soils occupy the left and bottom portions of the figure. The upper right portion is principally glacial till (note the well-formed drumlin at extreme upper right). A large area of organic soils has been drained and farmed, as indicated by the elaborate system of drainage ditches and intensive cultivation. The remainder of the organic soil area is in native vegetation, principally marsh grass, with some trees and shrubs. The organic soils here are fibrous peat, 2 to 5 m thick, in a former glacial lakebed. They contain 80 to 95 percent organic matter and 5 to 20 percent mineral matter.

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