CHAPTER 2

Structural Geology

Structural geology describes the form, pattern, origin, and internal structure of rock and soil masses. Tectonics, a closely related field, deals with structural features on a larger regional, continental, or global scale. Figure 2-1, page 2-2, shows the major plates of the earth’s crust. These plates continually undergo movement as shown by the arrows. Figure 2-2, page 2-3, is a more detailed representation of plate tectonic theory. Molten material rises to the earth’s surface at midoceanic ridges, forcing the oceanic plates to diverge. These plates, in turn, collide with adjacent plates, which may or may not be of similar density. If the two colliding plates are of approximately equal density, the plates will crumple, forming mountain range along the convergent zone. If, on the other hand, one of the plates is more dense than the other, it will be subducted, or forced below, the lighter plate, creating an oceanic trench along the convergent zone. Active volcanism and seismic activity can be expected in the vicinity of plate boundaries. In addition, military engineers must also deal with geologic features that exist on a smaller scale than that of plate tectonics but which are directly related to the reformational processes resulting from the force and movements of plate tectonics.

The determination of geologic structure is often made by careful study of the stratigraphy and sedimentation characteristics of layered rocks. The primary structure or original form and arrangement of rock bodies in the earth’s crust is often altered by secondary structural features. These secondary features include folds, faults, joints, and schistosity. These features can be identified and mapped in the field through site investigation and from remote imagery.

Section I. Structural Features in Sedimentary Rocks

BEDDING PLANES

Structural features are most readily recognized in the sedimentary rocks. They are normally deposited in more or less regular horizontal layers that accumulate on top of each other in an orderly sequence. Individual deposits within the sequence are separated by planar contact surfaces called bedding planes (see Figure 1-7, page 1-9). Bedding planes are of great importance to military engineers. They are planes of structural weakness in sedimentary rocks, and masses of rock can move along them causing rock slides. Since over 75 percent of the earth’s surface is made up of sedimentary rocks, military engineers can expect to frequently encounter these rocks during construction.

Undisturbed sedimentary rocks may be relatively uniform, continuous, and predictable across a site. These types of rocks offer certain advantages to military engineers in completing horizontal and vertical construction missions. They are relatively stable rock bodies that allow for ease of rock excavation, as they will normally support steep rock
Figure 2-1. The major plates of the earth's crust.
faces. Sedimentary rocks are frequently oriented at angles to the earth’s “horizontal” surface; therefore, movements in the earth’s crust may tilt, fold, or break sedimentary layers. Structurally deformed rocks add complexity to the site geology and may adversely affect military construction projects by contributing to rock excavation and slope stability problems.

Vegetation and overlying soil conceal most rock bodies and their structural features. Outcrops are the part of a rock formation exposed at the earth’s surface. Such exposures, or outcrops, commonly occur along hilltops, steep slopes, streams, and existing road cuts where ground cover has been excavated or eroded away (see Figure 2-3). Expensive delays and/or failures may result when military engineers do not determine the subsurface conditions before committing resources to construction projects. Therefore, where outcrops are scarce, deliberate excavations may be required to determine the type and structure of subsurface materials. To determine the type of rock at an outcrop, the procedures discussed in Chapter 1 must be followed. To interpret the structure of the bedrock, the military engineer must measure and define the trend of the rock on the earth’s surface.

**FOLDS**

Rock strata react to vertical and horizontal forces by bending and crumpling. Folds are undulating expressions of these forces. They are the most common type of deformation. Folds are most noticeable in layered rocks but
rarely occur on a scale small enough to be observed in a single exposure. Their size varies considerably. Some folds are miles across, while others may be less than an inch. Folds are of significant importance to military engineers due to the change in attitude, or position, of bedding planes within the rock bodies (see Figure 2-4). These can lead to rock excavation problems and slope instability. Folds are common in sedimentary rocks in mountainous areas where their occurrence may be inferred from ridges of durable rock strata that are tilted at opposite angles in nearby rock outcrops. They may also be recognized by topographic and geologic map patterns and from aerial photographs. The presence of tilted rock layers within a region is usually evidence of folding.

Types

There are several basic types of folds. They are—
- Homoclinal.
- Monocline.
- Anticline.
- Syncline.
- Plunging.
- Dome.
- Basin.

A rock body that dips uniformly in one direction (at least locally) is called a homoclinal (see Figure 2-5a). A rock body that exhibits local steplike slopes in otherwise flat or gently inclined rock layers is called a monocline (see Figure 2-5b). Monoclines are common in plateau areas where beds may locally assume dips up to 90 degrees. The elevation of the beds on opposite sides of the fold may differ by hundreds or thousands of feet. Anticlines are upfolds, and synclines are downfolds (see Figure 2-5c and d, respectively). They are the most common of all fold types and are typically found together in a series of fold undulations. Differential weathering of the rocks composing synclines and anticlines tends to produce linear valleys and ridges. Folds that dip back into the ground at one or both ends are said to be plunging (see Figure 2-6). Plunging anticline and plunging syncline folds are common. Upfolds that plunge in all directions are called domes. Folds that are bowed toward their centers are called basins. Domes and basins normally exhibit roughly circular outcrop patterns on geologic maps.

Symmetry

Folds are further classified by their symmetry. Examples are—
- Asymmetrical (inclined).
- Symmetrical (vertical).
- Overturned (greatly inclined).
- Recumbent (horizontal).

The axial plane of a fold is the plane that bisects the fold as symmetrically as possible. The sides of the fold as divided by the axial plane are called the limbs. In some folds, the plane is vertical or near vertical, and the fold is said to be symmetrical. In others, the axial plane is inclined, indicating an asymmetrical fold. If the axial plane is greatly

Figure 2-4. Folding of sedimentary rock layers.
Figure 2-5. Common types of folds.

Figure 2-6. Topographic expression of plunging folds.
inclined so that the opposite limbs dip in the same direction, the fold is overturned. A recumbent fold has an axial plane that has been inclined to the point that it is horizontal. Figure 2-7 shows the components of an idealized fold. An axial line or fold axis is the intersection of the axial plane and a particular bed. The crest of a fold is the axis line along the highest point on an anticline. The trough denotes the line along the lowest part of the fold. It is a term associated with synclines.

CLEAVAGE AND SCHISTOSITY

Foliation is the general term describing the tendency of rocks to break along parallel surfaces. Cleavage and schistosity are foliation terms applied to metamorphic rocks. Metamorphic rocks have been altered by heat and/or pressure due to mountain building or other crustal movements. They may have a pronounced cleavage, such as the metamorphic rock slate that was at one time the sedimentary rock shale. Certain igneous rocks may be deformed into schists or igneouses with alignment of minerals to produce schistosity or gneissic foliation. The attitudes of planes of cleavages and schistosity can be mapped to help determine the structure of a rock mass. Their attitudes can complicate rock excavation and, if unfavorable, lead to slope stability problems.

FAULTS

Faults are fractures along which there is displacement of the rock parallel to the fracture plane; once-continuous rock bodies have been displaced by movement in the earth’s crust (see Figure 2-8). The magnitude of the displacement may be inches, feet, or even miles along the fault plane. Overall fault displacement often occurs along a series of small faults. A zone of crushed and broken rock may be produced as the walls are dragged past each other. This zone is called a “fault zone” (see Figure 2-9). It often contains crushed and altered rock, or “gouge,” and angular fragments of broken rock called “breccia.” Fault zones may consist of materials that have been altered (reduced in strength) by both fault movement and accelerated weathering by water introduced along the fault surface. Alteration of fault gouge to clay lowers the resistance of the faulted rock mass to sliding. Recognition of

Figure 2-7. Fold symmetry.
faults is extremely important to military engineers, as they represent potential weakness in the rock mass. Faults that cut very young sediments may be active and create seismic (earthquake) damage.

Recognition

Faults are commonly recognized on rock outcrop surfaces by the relative displacement of strata on opposite sides of the fault plane and the presence of gouge or breccia. Slickensides, which are polished and striated surfaces that result from movement along the fault plane, may develop on the broken rock faces in a direction parallel to the direction of movement. Faulting may cause a discontinuity of structure that maybe observed at rock outcrops where one rock layer suddenly ends against a completely different layer. This is often observed in road cuts, cliff faces, and stream beds. Although discontinuity of rock beds often indicates faulting, it may also be caused by igneous intrusions and unconformities in deposition. Faults that are not visibly identifiable can be inferred by sudden changes in the characteristics of rock strata in an outcrop or borehole, by missing or repeated strata in a stratigraphic sequence, or (on a larger scale) by the presence of long straight mountain fronts thrust up along the fault. Rock strata may show evidence of dragging along the fault. Drag is the folding of rock beds adjacent to the fault (see Figure 2-8 and Figure 2-10, page 2-8). Faults are identifiable on aerial photographs by long linear traces (lineations) on the ground surface and by the offset of linear features such as strata, streams, fences, and roads. Straight fault traces often indicate near-vertical fault planes since traces are not distorted by topographic contours.

Terminology

The strike and dip of a fault plane is measured in the same manner as it is for a layer of rock. (This procedure will be described later.) The fault plane intersection with the surface is called the fault line. The fault line is drawn on geologic maps. The block above the fault plane is called the hanging wall; the block below the fault plane is called the footwall. In the case of a vertical fault, there would be neither a hanging wall nor a footwall. The vertical displacement along a fault is called the throw. The horizontal displacement is the heave. The slope on the surface produced by movement along a fault is called the fault scarp. It may vary in

Figure 2-8. Faulting.

Figure 2-9. Fault zone.
Types

Faults are classified by the relative direction of movement of the rock on opposite sides of the fault. The major type of movement determines their name. These types are—

- Normal (gravity).
- Reverse (thrust).
- Strike-slip.

Normal faults are faults along which the hanging wall has been displaced downward relative to the footwall (see Figure 2-12a). They are common where the earth’s surface is under tensional stress so that the rock bodies are pulled apart. Normal faults are also called gravity faults and usually are characterized by high-angle (near-vertical) fault planes. In a reverse fault, the hanging wall has been displaced upward relative to the footwall (see Figure 2-11b). Reverse faults are frequently associated with compressional forces that accompany folding. Low-angle (near-horizontal) reverse faults are called overthrust faults. Thrust faulting is common in many mountainous regions, and overthrusting rock sheets may be displaced many kilometers over the underlying rocks (see Figure 2-10). Strike-slip faults are characterized by one block being displaced laterally with respect to the other; there is little or no vertical displacement (see Figure 2-12c). Many faults exhibit both vertical and lateral displacement. Some faults show rotational movement, with one block rotated in the fault plane relative to the opposite block. A block that is downthrown between two faults to form a depression is called a “graben” (see Figure 2-13a). An upthrown block between two faults produces a “horst” (see Figure 2-13b). Horsts and grabens are common in the Basin and Range Province located in the western continental United States. The grabens comprise the valleys or basins between horst mountains.

JOINTS

Rock masses that fracture in such a way that there is little or no displacement parallel to the fractured surface are said to be jointed, and the fractures are called joints (see Figure 2-14, page 2-10). Joints influence the way the rock mass behaves when subjected to the
stresses of construction. Joints characteristically form planar surfaces. They may have any attitude; some are vertical, others are horizontal, and many are inclined at various angles. Strike and dip are used to measure the attitude of joints. Some joints may occur as curved surfaces. Joints vary greatly in magnitude, from a few feet to thousands of feet long. They commonly occur in more or less parallel fractures called joint sets. Joint systems are two or more related joint sets or any group of joints with a characteristic pattern, such as a radiating or concentric pattern.

**Formation**

Joints in rock masses may result from a number of processes, including deformation, expansion, and contraction. In sedimentary rocks, deformation during lithification or folding may cause the formation of joints. Igneous rocks may contain joints formed as lava cooled and contracted. In dense, extrusive igneous rocks, like basalt, a form of prismatic fracturing known as columnar jointing often develops as the rock cools rapidly and shrinks. Jointing may also occur when overlying rock is removed by erosion, causing a rock mass to expand. This is known as exfoliation. The outer layers of the rock peel, similar to the way that an onion does.

**Significance**

Because of their almost universal presence, joints are of considerable engineering importance, especially in excavation operations. It is desirable for joints to be spaced close enough to minimize secondary plugging and blasting requirements without impairing the stability of excavation slopes or increasing

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**Figure 2-12. Types of faults.**

(a) Normal Fault  
(b) Reverse Fault  
(c) Strike-Slip Fault

**Figure 2-13. Graben and horst faulting.**

(a) Graben  
(b) Horst
the overbreakage in tunnels. The spacing of the joints can control the size of the material removed and can also affect drilling and blasting. The ideal condition is seldom encountered. In quarry operations, jointing can lead to several problems. Joints oriented approximately at right angles to the working face present the most unfavorable condition. Joints oriented approximately parallel to the working face greatly facilitate blasting operations and ensure a fairly even and smooth break, parallel to the face (see Figure 2-14). Joints offer channels for groundwater circulation. In excavations below the groundwater table, they may greatly increase water problems. They also may exert an important influence on weathering.

**STRIKE AND DIP**

The orientation of planar features is determined by the attitude of the rock. The attitude is described in terms of the strike and dip of the planar feature. The most common planar feature encountered is a sedimentary bed. Strike is defined as the trend of the line of intersection formed between a horizontal plane and the bedding plane being measured (see Figure 2-14). The strike line direction is given as a compass bearing that is always in reference to true north. Typical strikes would thereby fall between north 0 to 90 degrees east or north 0 to 90 degrees west. They are never expressed as being to the southeast or southwest. Azimuths may be readily converted to bearings (for example, an azimuth of 350 degrees would be converted to a bearing of north 10 degrees west).

The dip is the inclination of the bedding plane. It is the acute angle between the bedding plane and a horizontal plane (see Figure 2-14). It is a vertical angle measured at right angles from the strike line. The dip direction is defined as the quadrant of the compass the bed is dipping into (northeast, northwest, southeast, or southwest). By convention, the dip angle is given in degrees followed by the
dip direction quadrant (for example, 30 degrees northeast).

The strike and dip measurements are taken in the field on rock outcrops with a standard Brunton compass. The Brunton compass is graduated in degrees and has a bull’s-eye level for determining the horizontal plane when measuring the strike direction. The strike is determined by aligning the compass along the strike direction and reading the value directly from the compass. Included with the Brunton compass is a clinometer to measure the dip angle. This angle is measured by placing the edge of the compass on the dipping surface at right angles to the strike direction and reading the acute angle indicated by the clinometer (see Figure 2-17, page 2-12).

Strike and dip symbols are used on geologic maps and overlays to convey structural orientation. Basic symbols include those for inclined, vertical, and horizontal beds (see Figure 2-18, page 2-12). For inclined beds, the direction of strike is designated as a long line that is oriented in reference to the map grid lines in exactly the same compass direction as it was measured. The direction of the dip is represented by a short line that is always drawn perpendicular to the strike line and in the direction of the dip. The angle of the dip is written next to the symbol (see Figure 2-18a, page 2-12). For vertical beds, the direction of the strike is designated as it is for inclined beds. The direction of the dip is a short line crossing the strike line at a right angle extending on both sides of the strike line (see Figure 2-18b, page 2-12). For horizontal beds, the direction of strike is represented by crossed lines which indicate that the rock strikes in every direction. The dip is represented by a circle encompassing the crossed lines. The circle implies that there is no dip direction and the dip angle is zero (see Figure 2-18c, page 2-12). These basic symbols are commonly used to convey attitudes of sedimentary rocks (see Figure 2-19, page 2-13). Similar symbols are used to convey attitudes of other types of planar features, such as folds, faults, foliation, and jointing in other rock bodies.

**Section II. Geologic Maps**

**TYPES**

Geologic maps show the distribution of geologic features and materials at the earth’s surface. Most are prepared over topographic base maps using aerial photography and field survey data. From a knowledge of geologic processes, the user of a geologic map can draw many inferences as to the geologic relationships beneath the surface and also much of the geologic history of an area. In engineering practice, geologic maps are important guides to the location of construction...
Figure 2-17. Measuring strike and dip with a Brunton compass.

(a) Strike: N 25 E
Dip: 49 SE
(Inclined Bed)

(b) Strike: N 25 E
Dip: 90 SE or 90 NW
(Vertical Bed)

(c) Strike: None
Dip: 0
(Horizontal Bed)

Figure 2-18. Strike and dip symbols.
materials and the evaluation of foundation, excavation, and ground water conditions.

The following geologic maps are used for military planning and operations:
- Bedrock or aerial maps.
- Surficial maps.
- Special purpose maps.

**Bedrock or Aerial Maps**
These maps show the distribution of rock units as they would appear at the earth’s surface if all unconsolidated materials were removed. Symbols on such maps usually show the age of the rock unit as well as major structural details, such as faults, fold axes, and the attitudes of planar rock units or features. Thick deposits of alluvium (material deposited by running water) may also be shown.

**Surficial Maps**
These maps show the distribution of unconsolidated surface materials and exposed bedrock. Surface materials are usually differentiated according to their physical and/or chemical characteristics. To increase their usefulness as an engineering tool, most surficial maps show the distribution of materials at some shallow mapping depth (often one meter) so that minor residual soils and deposits do not mask the essential features of engineering concern.

**Special Purpose Maps**
These maps show selected aspects of the geology of a region to more effectively present information of special geologic, military, or engineering interest. Special purpose maps are often prepared to show the distribution of—
- Engineering hazards.
- Construction materials.
- Foundation conditions.
- Excavation conditions.
- Groundwater conditions.
- Trafficability conditions.
- Agricultural soils.
- Surface-water conditions.

Very detailed, large-scale geologic maps may show individual rock bodies, but the smallest unit normally mapped is the formation. A formation is a reasonably extensive, distinctive series of rocks deposited during a particular portion of geologic time (see Table 2-1, page 2-15). A formation may consist of a single rock type or a continuous series of related rocks. Generally, formations are
named after the locality where they were first defined. Formations may be grouped by age, structure, or lithology for mapping purposes.

SYMBOLS
Symbols are used to identify various features on a geologic map. Some of those features are:
- Formations (see Figure 2-21, page 2-18).
- Contacts (see Figure 2-21, page 2-18).
- Attitudes (see Figure 2-21, page 2-18).
- Fault lines and fold axes (see Figure 2-21, page 2-18).
- Cross sections (see Figure 2-23, page 2-19).

Formations
Letters, colors, or symbolic patterns are used to distinguish formations or rock units on a geologic map. These designators should be defined in a legend on the map. Letter symbols usually consist of a capital letter indicating the period of deposition of the formation with subsequent letters (usually lower case) that stand for the formal name of the unit, (see Table 2-1). Maps prepared by the US Geological Survey and many other agencies use tints of yellow and orange for Cenozoic rocks, tints of green for Mesozoic rocks, tints of blue and purple for Paleozoic rocks, and tints of red for Precambrian rocks, Symbolic patterns for various rock types are given in Figure 2-20, page 2-17.

Contacts
A thin, solid line shows contacts or boundaries between rock units if the boundaries are accurately located. A dashed line is used for an approximate location and a dotted line if the contact is covered or concealed. Questionable or gradational contacts are shown by a dashed or dotted line with question marks.

Attitudes
Strike and dip symbols describe planes of stratification, faulting, and jointing. These symbols consist of a strike line long enough so that its bearing can be determined from the map, a dip mark to indicate the dip direction of the plane being represented, and a number to show the value (in degrees) of the dip angle. The number is omitted on representations of both horizontal and vertical beds, because the values of the dips are automatically acknowledged to be 0 and 90 degrees, respectively. Figure 2-22, page 2-19, shows the placement of strike and dip symbols on a geologic map with respect to the location and orientation of a sedimentary rockbed.

Fault Lines and Fold Axes
Heavy black lines, which may be solid, dashed, or dotted (as described for contacts), show fault lines and fold axes. The direction of movement along faults is shown by arrows or by the use of symbols to indicate up thrown and down thrown sides. The arrows accompanying fold axes indicate the dip direction of the limbs and/or the plunge direction of the fold.

Cross Sections
Cross sections show the distribution of geologic features and materials in a vertical plane along a line on a map. Cross sections are prepared in much the same way as topographic profiles using map, field, and borehole data. Geologic sections accompany many geologic maps to clarify subsurface relationships. Like geologic maps, geologic sections are often highly interpretive, especially where data is limited and structures are complex or concealed by overburden. Maps and sections use similar symbols and conventions. Because of the wealth of data that can be shown, geologic maps and sections are the two most important means of recording and communicating geologic information.

OUTCROP PATTERNS
An outcrop is that part of a rock formation that is exposed at the earth’s surface. Outcrops are located where there is no existing soil cover or where the soil has been removed, leaving the rock beneath it exposed. Outcrops may indicate both the type and the structure of the local bedrock. Major types of structural features can be easily recognized on geologic maps because of the distinctive patterns they produce. Figures 2-24 through 2-31, pages 2-20 through 2-21, show basic examples of common structural patterns.
<table>
<thead>
<tr>
<th>Era</th>
<th>Period or System</th>
<th>Symbol</th>
<th>Epoch or Series</th>
<th>Important Physical Events and Flora and Fauna</th>
<th>Million Years Ago</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cenozoic</td>
<td>Quaternary</td>
<td>Q</td>
<td>Recent</td>
<td>Glaciers melted; milder climates; many mammals disappeared.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Neogene</td>
<td></td>
<td>Pleistocene</td>
<td>Glaciation; fluctuating cold to mild climates; most invertebrate living species; dominance of large mammals; man.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tertiary</td>
<td>T</td>
<td>Pliocene</td>
<td>Continued uplift and mountain building; climate cooler; mammals reach peak in size and abundance.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paleogene</td>
<td></td>
<td>Miocene</td>
<td>Uplifts of Sierras and Rockies; moderate climates; rise of grazing mammals.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Oligocene</td>
<td>Lands generally low; rise of Alps and Himalayas began; volcanoes in Rockies area; first saber-toothed cats.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Eocene</td>
<td>Mountains eroded; many lakes in western North America; climates mild to very tropical; all modern mammals present (first horses).</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Paleocene</td>
<td>Mountains high; climates mild to cool; primitive mammals; modern birds; new invertebrates.</td>
<td></td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Cretaceous</td>
<td>K</td>
<td>Lands low and extensive; mild climates; last widespread oceans; flowering plants expand rapidly; giant reptiles become extinct; modern insects; ammonites die out; foraminifera; period closed with Laramide Revolution (Sierra uplifted).</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jurassic</td>
<td>J</td>
<td>Continents low; large areas of Europe covered by seas; climates mild; mountains from Alaska to Mexico rise; eruptions and intrusions in the northwest; dinosaurs; marine reptiles; ammonites and belemnites abundant; ginkgoes; conifers; cycads.</td>
<td>135</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Triassic</td>
<td>TR</td>
<td>Continents mountains; large areas arid; eruptions in eastern North America and New Zealand; first dinosaurs and marine reptiles; first hexacorals, last conodonts.</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Permian</td>
<td>P</td>
<td>First mammal-like reptiles, other reptiles diversified; many marine invertebrates become extinct; last trilobites; period ended with Appalachian Revolution.</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>Paleozoic</td>
<td>Carboniferous</td>
<td>IP</td>
<td>Lands low; covered by shallow seas or extensive coal swamps; climates warm; amphibians and reptiles reach large size; large insects; scorpions; cockroaches; fusulinid foraminifera abundant.</td>
<td>270</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mississippian</td>
<td>M</td>
<td>Widespread seas retreated as result of mountain building in eastern United States, Texas, Colorado; climates warm; crinoids dominate; amphibians, sharks and bony fishes spread; insects develop wings.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Devonian</td>
<td>D</td>
<td>North America low and flat, but mountains and volcanoes present in eastern United States and Canada; Europe mountainous with arid basins; fishes dominant; first amphibians; many brachiopods, corals, bryozoans and blastoids; first ammonites.</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silurian</td>
<td>S</td>
<td>Continents relatively flat; mountains building in Europe; climates mild; much salt deposited; eurypterids and corals abundant; first air breathers; lycopod plants.</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ordovician</td>
<td>O</td>
<td>Continents low with shallow seas; mountains rose at close in Europe and North America; abundant graptolites, trilobites, nautiloids, cystoids; first ostracods and conodonts; seaweeds and algae; climates uniformly mild.</td>
<td>440</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cambrian</td>
<td>E</td>
<td>Extensive seas in major synclines on all continents; climates mild; marine invertebrates and algae abundant; trilobites dominant; all animal phyla probably existed.</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Precambrian</td>
<td>Proterozoic</td>
<td>PC</td>
<td>Shallow seas in geosynclines; climates warm and moist to dry and cold; glaciation in eastern Canada; bacteria; marine algae; worm burrows; sponge spicules; probably most phyla lived but left no record; few fossils; iron area of Lake Superior formed.</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Algonkian)</td>
<td></td>
<td>Extensive mountain building with intrusions and eruptions; iron deposits formed; earliest known life; blue-green algae; fungi; graphite and carbonaceous shales in Australia and Canada; carbon in Rhodesian rock.</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Archaeozoic</td>
<td></td>
<td>Formation of the Earth's crust; no rocks have been found, therefore cannot be dated by any known method.</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Primitive Life)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Azoic (Without Life)</td>
<td>PC</td>
<td></td>
<td></td>
<td>6000</td>
</tr>
</tbody>
</table>
Each illustration contains a block diagram showing a particular structural feature along with its topographic expression. The outcrop pattern of each rock unit shown on the block diagram is projected to a horizontal plane, resulting in the production of a geologic map that is also shown. This allows the reader to readily relate the structure shown on the block diagram to the map pattern. Structural details can be added to basic maps using the symbols in Figure 2-21, page 2-18.

The illustrations include some of the following structural features:
- Horizontal strata.
- Inclined strata.
- Domes.
- Basins.
- Plunging folds.
- Faults.
- Intrusive rocks.
- Surficial deposits.

Figure 2-20. Symbolic patterns for rock types.
Contacts

- Accurately Located
- Approximately Located
- Covered or Concealed

Strike and Dip Symbols

<table>
<thead>
<tr>
<th>Inclined</th>
<th>Vertical</th>
<th>Horizontal</th>
<th>Overturned</th>
</tr>
</thead>
<tbody>
<tr>
<td>For Strata:</td>
<td><img src="image" alt="Inclined Symbol" /></td>
<td><img src="image" alt="Vertical Symbol" /></td>
<td><img src="image" alt="Horizontal Symbol" /></td>
</tr>
<tr>
<td>For Joints:</td>
<td><img src="image" alt="Inclined Symbol" /></td>
<td><img src="image" alt="Vertical Symbol" /></td>
<td><img src="image" alt="Horizontal Symbol" /></td>
</tr>
<tr>
<td>For Foliation:</td>
<td><img src="image" alt="Inclined Symbol" /></td>
<td><img src="image" alt="Vertical Symbol" /></td>
<td><img src="image" alt="Horizontal Symbol" /></td>
</tr>
</tbody>
</table>

Axes of Folds

- Anticline
- Syncline showing plunge of axes.
- Overturned anticline and syncline showing dip of limbs.

Fault Traces

- Fault showing dip of fault plane.
- Fault showing relative movement (U, upthrown side, D, downthrown side).
- Thrust fault (Ts or hachures on upper plate).

Figure 2-21. Geologic map symbols.
Horizontal Strata

Dendritic (branching or treelike) drainage patterns typically develop on horizontal strata and cut canyons or valleys in which progressively older rock units are exposed at depth (see Figure 2-24, page 2-20). The result is that the map patterns of horizontal strata parallel stream valleys, producing dendritic pattern on the geologic map. Although all maps do not show topographic contour lines, the contacts of horizontal rock units parallel the contours. Escarpments and gentle slopes generally develop on resistant and nonresistant beds, respectively, producing variations in the width of the map outcrop pattern. The upper and lower contacts are close together on steep cliffs; on gentle slopes of the same formation, the contacts are further apart. The map width of the outcrops of horizontal beds does not indicate the thickness of the strata. Gently dipping beds develop the same basic outcrop pattern as horizontal beds.
Figure 2-24. Outcrop patterns of horizontal strata.

Figure 2-25. Outcrop patterns of inclined strata.

Figure 2-26. Outcrop patterns of an eroded dome.

Figure 2-27. Outcrop patterns of an eroded basin.

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Figure 2-28. Outcrop patterns of plunging folds.

Figure 2-29. Outcrop patterns produced by faulting.

Figure 2-30. Outcrop patterns of intrusive rocks.

Figure 2-31. Outcrop patterns of surficial deposits.

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However, the contacts of gently dipping strata, if traced far enough up a valley, cross topographic contours and form a large V-shaped pattern that points in the direction the beds dip, assuming that the beds do not, dip in the direction of the stream gradient, but at a smaller angle.

Inclined Strata

When a sequence of rocks is tilted and cut off by erosion, the outcrop pattern appears as bands that, on a regional basis, are roughly parallel. Where dipping strata cross a valley, they produce a V-shaped outcrop pattern that points in the direction of dip, except in cases where the beds dip in the direction of the stream gradient at smaller angles than the gradient. The size of the V is inversely proportional to the degree of dip.

- Low-angle dip (large V) (see front part of Figure 2-25, page 2-20).
- High-angle dip (small V).
- Vertical dip (no V) (see back part of Figure 2-25, page 2-20).

Other relationships that are basic to the interpretation of geologic maps are also shown in Figure 2-25, page 2-20. For example, they show that older beds dip toward younger beds unless the sequence has been overturned (as by folding or faulting). Maps also show that outcrop width depends on the thickness of the beds, the dip of the beds (low dip, maximum width), and the slope of the topography (steep slope, minimum width).

Domes

Eroded dome-shaped structures form a roughly circular outcrop pattern with beds dipping away from a central area in which the oldest rocks outcrop (see Figure 2-26, page 2-20). These structures range from small features only a few meters across to great Upwarps covering areas of hundreds or thousands of square kilometers.

Drainage patterns are helpful in interpreting a domal structure. Radial drainage patterns tend to form on domes. Streams cutting across the resistant beds permit one to apply the “rule of Vs” as explained above to interpret the direction of dip.

Basins

Eroded structural basins form an outcrop pattern very similar to that of an eroded dome (see Figure 2-27, page 2-20). However, two major features serve to distinguish them: younger rocks outcrop in the center of a basin and, if the structure has been dissected by stream erosion, the outcrop Vs normally point toward the center of a basin, whereas they usually point away from the center of a dome.

Plunging Folds

Folding is found in complex mountain ranges and sometimes in lowlands and plateaus. When folds erode, the oldest rocks outcrop in the center of the anticlines (or upfolds) and the youngest rocks outcrop in the center of the synclines (or downfolds). The axes of folded beds are horizontal in some folds, but they are usually inclined. In this case, the fold is said to plunge. Plunging folds form a characteristic zigzag outcrop pattern when eroded (see Figure 2-28, page 2-21). A plunging anticline forms a V-shaped pattern with the apex (or nose) of the V pointing in the direction of the plunge. Plunging synclines form a similar pattern, but the limbs of the fold open in the direction of the plunge.

Faults

Fault patterns on geologic maps are distinctive in that they abruptly offset structures and terminate contacts (see Figure 2-29, page 2-21). They are expressed on the geologic map by heavy lines in order to be readily distinguished. Some common types are:

- Normal.
- Reverse.
- Thrust.

Normal and Reverse (see A and B, respectively, in Figure 2-29, page 2-21). Both normal and reverse fault planes generally dip at a high angle, so outcrop patterns are relatively straight. Older rocks are usually exposed on the upthrown block. It is thus possible to determine the relative movement on most
high-angle faults from map relations alone. Linear streams, offsets, linear scarps, straight valleys, linear-trending springs or ponds, and omitted or repeated strata are common indications of faulting (see paragraph on recognition of faults, page 2-7).

**Thrust** (see C in Figure 2-29, page 2-21). Thrust faults are reverse faults that dip at low angles (less than 15 degrees) and have stratigraphic displacements, commonly measured in kilometers (see Figure 2-10, page 2-8). The trace of the thrust commonly forms Vs where it intersects the valleys. The Vs point in the direction of the fault plane dip, except in cases where the fault plane dips in the direction of the stream gradient, but a smaller angle. Erosion may form windows (fensters) through the thrust sheet so that underlying rocks are exposed or produce isolation remnants (klippen) above the underlying rocks. Hachure symbols are used to designate the overthrust block that usually contains the oldest rocks.

**Intrusions**

Larger igneous intrusions, such as batholiths and stocks, are typically discordant and appear on geologic maps as elliptical or roughly circular areas that cut across the contacts of surrounding formations (see Figure 2-30, page 2-21). Smaller discordant intrusions, such as dikes, are usually tabular and appear on geologic maps as straight, usually short, bands. However, some dikes are lenticular and appear as such on the map. Concordant intrusions, such as sills and laccoliths, have contacts that parallel those of the surrounding formations (see Figure 1-5, page 1-7).

The relative age of igneous bodies can be recognized from crosscutting relationships. The younger intrusions cut the older ones. With this in mind, it is clear from the relationships in Figure 2-30, page 2-21, that the elliptical stock is the oldest intrusion, the northeast trending dike the next oldest, and the northwest trending dike the youngest. The age of the small discontinuous dikes near the western part of the map is younger than that of the stock, but the age relation with the other dikes is not indicated.

**Surficial Deposits**

Surficial deposits are recent accumulations of various types of sediment or volcanic debris on the surface of the landscape (see Figure 2-31, page 2-21). The primary types are—
- Windblown sand and loess.
- Stream channel and floodplain deposits.
- Landslide deposits.
- Glacial deposits.
- Present beaches and other shoreline sediments.

**Section III. Engineering Considerations**

**ROCK DISTRIBUTION**

Geologic structure controls the distribution of rock bodies and features along and beneath the earth’s surface. The presence and orientation of such features as bedding, folding, faulting, and unconformities must be determined before construction begins. Otherwise, foundation, excavation, and groundwater conditions cannot be properly evaluated.

**ROCK FRAGMENTATION**

Rocks tend to fracture along existing zones of weakness. The presence and spacing of bedding, foliation, and joint planes can control the size and shape of rock fragments produced in quarries and other excavations. Operational and production costs may be prohibitive if rock fragments are too large, too small, too slabby, or too irregular for aggregate requirements. Advantageous joint or bedding spacings can significantly reduce excavation and aggregate production costs.

Many weak, thinly bedded, or highly fractured rocks can be excavated without blasting by using ripping devices drawn by heavy crawler tractors. When ripping is used to break up and loosen rock for removal, the work should proceed in the direction of the dip. This prevents the ripping devices from riding up the dip surfaces and out of the rock mass (see Figure 2-32, page 2-24).
Most rock must be drilled and blasted for removal. Where joints or bedding planes incline across the axis of the drill hole, drill bits tend to follow these planes, causing the holes to be misaligned; or, more often, the bits to bind, stick, or break off in the holes (see Figure 2-33). Open fractures and layers of weak rock greatly reduce blasting effectiveness by allowing the force of the blast to escape before the surrounding rock has been properly fragmented. Such situations require special drilling and blasting techniques that generally lower the efficiency of quarrying operations.

**ROCK SLIDES AND SLUMPS**

Massive rock slides may occur where unconfined rock masses overlie inclined bedding, foliation, fault, or joint surfaces (see Figure 2-34). The risk of such slides is generally greatest over smooth, continuous, water- or clay-lubricated surfaces that dip steeply toward natural or man-made excavations. The following general observations may assist in evaluating hazards (see Figure 2-35):

- Most rocks are stable above surfaces that dip less than about 18 degrees toward an excavation. Excavation slopes with horizontal to vertical ratios of 1:2 (1 foot horizontal to 2 feet vertical) are usually feasible in such cases unless weak rocks underlie the excavation sidewalls.
- Some rocks may slide on surfaces that dip between about 18 degrees and 35 degrees toward an excavation, particularly if the surfaces are wet, clayey, smooth, and continuous. Side slopes of 1:1 or flatter may be required to stabilize such surfaces. It may be necessary to remove the hazardous rock entirely. Where excessive excavations must be avoided for economic, environmental, or other reasons, artificial supports or drainage works may be employed to stabilize the rock.
- Unless rock surfaces are discontinuous or very rough and uneven,
most unconfined rocks will slide over surfaces steeper than about 35 degrees. Excavation side slopes should be cut back to the dipping surface or slightly beyond to assure stability against sliding.

- Rocks along planes of weakness that dip almost vertically toward or away from excavation sidewalls should be cut on horizontal to vertical ratios of 1:4 or 1:2 to prevent toppling failures. This is particularly important if the rocks are weak or the planes of weakness are closely spaced.

**WEAK ROCKS**

Weak rocks, such as shales, may shear or crush under the weight of overlying rock and allow excavation sidewalls to slump or cave in. Such failures can be prevented by installing artificial supports or by using flattened or terraced side slopes to reduce the load on the potential failure zone.

**FAULT ZONES**

Fault zones are often filled with crushed and broken rock material. When these materials are water-soaked, they may weaken and cause the fault zone to become unstable. Such zones are extremely hazardous when encountered in tunneling and deep excavations because they frequently slump or cave in. Artificial supports are usually required to stabilize such materials.

**GROUNDWATER**

Water entering the ground percolates downward, through open fractures and permeable rocks, until it reaches a subsurface zone below which all void spaces are filled.

<table>
<thead>
<tr>
<th>If dip is toward road (degrees)</th>
<th>0-18</th>
<th>18-35</th>
<th>35-75</th>
<th>75-90</th>
<th>Or dipping away from the road</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope ratio should be (horizontal; vertical)</td>
<td>1:2</td>
<td>1:1</td>
<td>Cut to dip angle</td>
<td>1:4 or 1:2</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2-34.** Rock slide on inclined bedding plane.

**Figure 2-35.** Rules of thumb for inclined sedimentary rock cuts.
with water. Where such ground water is intersected in an excavation, such as a road cut or tunnel, drainage problems may occur; rock slides triggered by the weakening and/or lubricating of the rock mass may result. In addition, water trapped under hydrostatic pressure in fault zones, joints, and permeable rock bodies can cause sudden flooding problems when released during excavation. Permeable rock zones may also permit water to escape from canals and reservoirs. However, if properly evaluated, the structural conditions that produce ground water problems can also provide potential supplies of groundwater or subsurface drainage for engineering projects.

**ROAD CUT ALIGNMENT**

The most advantageous alignment for road cuts is generally at right angles (perpendicular) to the strike of the major planes of weakness in the rock (usually the bedding). This allows the rock surfaces to dip along the cut rather than into it (see Figure 2-36a and 2-36b). Where roads must be aligned parallel to the strike of the major planes of weakness, the most stable alignment is one in which the major planes of weakness dip away from the excavation; however, some overhang should be expected (see Figure 2-36c).

**QUARRY FACES**

Quarries should normally be developed in the direction of strike so that the quarry face itself is perpendicular to strike (see Figure 2-37a page 2-28). This particular orientation is especially important where rocks are steeply inclined, because it allows for the optimization of drilling and blasting efforts by creating a vertical or near-vertical rock face after each blast. If necessary, quarries maybe worked perpendicular to the strike direction in instances where the rocks are not steeply inclined, but drilling and blasting will prove to be more difficult. In addition, if the rocks dip away from the excavation, overhang and oversized rocks can be expected (see Figure 2-37b page 2-28). If the rocks dip toward the excavation, problems with slope instability and toeing may result (see Figure 2-37c page 2-28). In massive igneous rock bodies and horizontal sedimentary rock layers, the direction of quarrying should be chosen based on the most prominent joint set or other discontinuity.

**ROCK DEFORMATION**

Rocks may behave as elastic, plastic, or viscous solids under stress. Heavy loads, such as dams, massive fills, tall buildings, or bridge piers, may cause underlying rocks to compress, shear, or squeeze laterally. Particular problems exist where rocks of different strength underlie a site. For example, where weak shale and stronger limestone support different parts of the same structure, the structure may tile or crack due to uneven settlement.

The removal of confining stresses during excavation may cause rocks to expand or squeeze into the excavated area. Such problems seldom cause more than an increase in excavation or maintenance costs for roads, airfields, and railroads; however, they may cause serious damage to dams, buildings, canals, and tunnels where deformation cannot be tolerated. Weak clays and shales (especially compaction shales) are the most common cause of such problems. Other rocks can also cause trouble if they are weathered or if they have been under great stress. To neutralize the effects of rock flow or rebound, the following may be required:

- Additional excavation.
- Artificial supports or hold-downs.
- Compensating loads.
- Adjustment periods before construction.

**EARTHQUAKES (FAULT MOVEMENTS)**

Movement along active faults produces powerful ground vibrations and rock displacements that can seriously disrupt engineering works. Unless proven otherwise by geological or historical evidence, all faults that disrupt recent geologic deposits should be considered active. Many areas suffer earthquakes as a result of deep-seated faults that do not appear at the earth’s surface. Consequently, seismic hazards must be thoroughly investigated before any major
(a) Map view, illustrating strike and dip symbols. The best road alignment, based on the structural geology, is NW-SE, perpendicular to the strike.

(b) Through cut in the hill, illustrating rock dipping along the road. This is the most naturally stable road alignment.

(c) Cross section of same hill with side hill cuts oriented parallel to strike direction, illustrating unstable orientation where rock beds dip toward the road and a more stable orientation where the rock beds dip away from the road.

Figure 2-36. Road cut alignment.
structure is undertaken. Power lines, dams, canals, tunnels, bridges, and pipelines across active faults must be designed to accommodate earth movements without failure. Vertical structures must be designed to accommodate the lateral movements and vibrations associated with earthquakes where seismic hazards exist. Expect increased seismic risk in marginal areas of continental plates (see Figure 2-1, page 2-2).

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Figure 2-37. Quarry in the direction of strike.