Unity University
Faculty of Engineering

Department of Mining Engineering

GENERAL GEOLOGY (Geol 2081)

Chapter 5:

PHYSICAL GEOLOGY AND GEOMORPHOLOGY

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5. PHYSICAL GEOLOGY AND GEOMORPHOLOGY

5.1. Fundamental concepts

Uniformitarianism

Around 1785 English geologist James Hutton developed the concept of uniformitarianism. He suggested that the laws of nature do not change with time, and therefore processes that take place today are the same processes that shaped the earth millions and billions of years ago. Processes occurring today occurred in the same way and at the same rate in the past. Simply stated, what Hutton suggested was that the present is the key to the past. Today that principle forms the basis to our approach to deciphering the geologic history of the earth.

Original Horizontality (Steno)

The Principle of Original Horizontality was proposed by the Danish geological pioneer Nicholas Steno (1638-1686). This principle states that layers of sediment are originally deposited horizontally. The principle is important to the analysis of folded and tilted strata. From these observations is derived the conclusion that the Earth has not been static and that great forces have been at work over long periods of time, further leading to the conclusions of the science of plate tectonics; that movement and collisions of large plates of the Earth's crust is the cause of folded strata. As one of Steno's Laws, the Principle of Original Horizontality served well in the nascent days of geological science. However, it is now known that not all sedimentary layers are deposited purely horizontally. For instance, coarser grained sediments such as sand may be deposited at angles of up to 15 degrees, held up by the internal friction between grains which prevents them slumping to a lower angle without additional reworking or effort. This is known as the angle of repose, and a prime example is the surface of sand dunes. Similarly, sediments may drape over a pre-existing inclined surface: these sediments are usually deposited conformably to the pre-existing surface. Also sedimentary beds may pinch out along strike, implying that slight angles existed during their deposition. Thus the Principle of Original Horizontality is widely, but not universally, applicable in the study of sedimentology, stratigraphy and structural geology and one should always bear the above caveats in mind before accepting original horizontality as a fact.

Principle of Catastrophism

The principle of catastrophism is an assertion that catastrophic natural processes have been primarily responsible for the deposition of the various layers in the geologic column and all the rock formations that we observe. Until the 18th century, no other plausible explanation was considered. The biblical worldwide flood as well as other local floods was believed to be responsible for laying down the sedimentary rock layers we observe.
Someone noted the similarity between the life of a soldier and the deposition process. A solider has long periods of boredom with nothing "going on" with a few short periods of great trauma. Likewise the principle of catastrophism holds that normally very little deposition occurs during the long boring periods and almost all of the deposition occurs during the short traumatic catastrophic periods. The principle of catastrophism applies even more to the deposition of fossils. There is no possible way to fossilize an organism with slow deposition. The organism needs to be buried quickly to be fossilized. In the late 1700's and the early 1800's, James Hutton and Sir Charles Lyell convinced the scientific world that the present is the key to the past and this deposition always occurred exactly as we see it today. We know that this assumption is false based upon the recent tsunami and Mount St. Helens volcano eruption. We learned that rapid deposition and rapid canyon formation happens in a catastrophic fashion.

Developing a chronology

In geology, we use the following indirect methods to establish a relative age of events:

Principle of superposition

In a sequence of undeformed sedimentary rocks, the oldest beds are on the bottom and higher layers are successively younger.

Principle of fossil succession

Groups of plants and animals occur in the geologic record in a definite and determinable order. Geologists then can identify a particular period of geologic time based on its characteristic fossils.

Principle of crosscutting relationships

Igneous intrusions and faults are younger than the rocks they cut.

Principle of inclusion

A fragment of rock incorporated in another is older than the host rock.

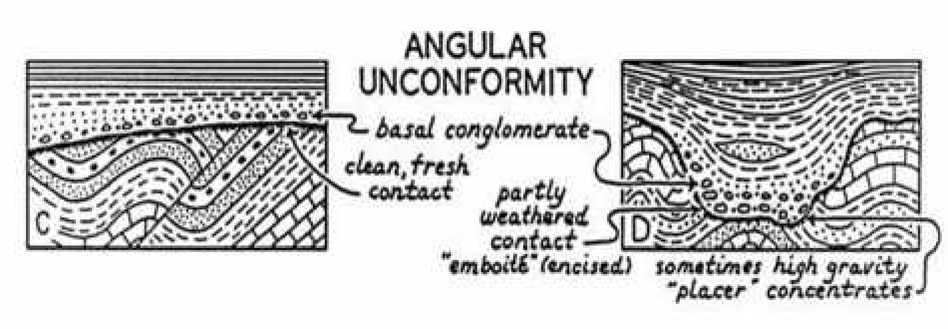
Notice that these methods of dating rock structures and formations don't imply any quantitative or absolute measure of time. Rather, these methods just place events in a sequential order. But ... sometimes time seems to be missing!

Unconformities – missing time

Sometimes we encounter situations that suggest that time is missing. A sequence of fossils may be missing; maybe younger horizontal beds are lie on inverted older beds. In geologic terms, this has been called as unconformities. Unconformities are discontinuities in the geologic time sequence. There are three types of unconformities; these are: (i) angular unconformity, (ii) nonconformity, and (iii) disconformity.

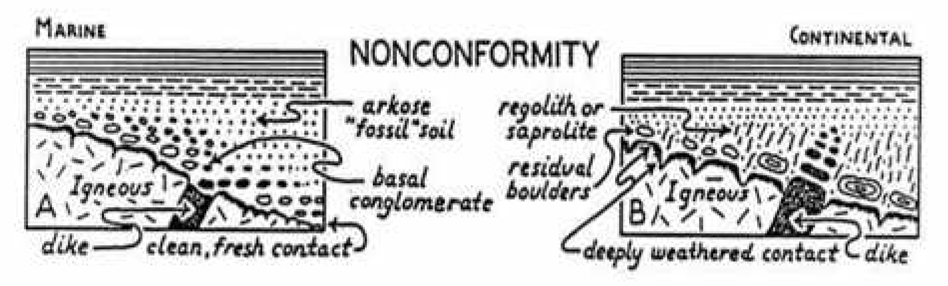
- **Angular unconformity**

Younger strata are deposited on uplifted, deformed, and partially eroded older strata.



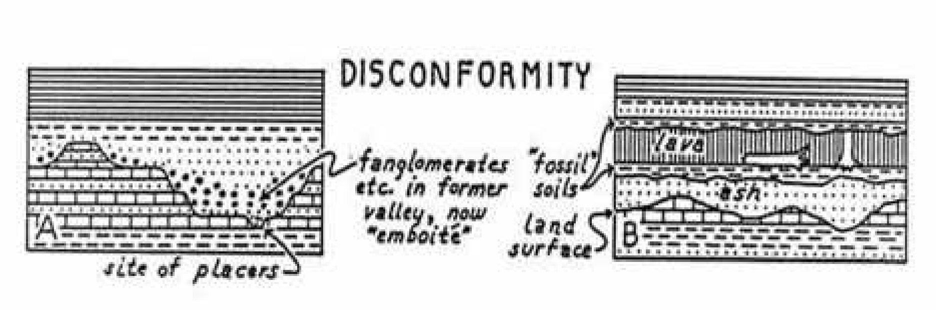
- **Nonconformity**

Plutonic igneous or metamorphic rocks are overlain by horizontally bedded sedimentary strata.



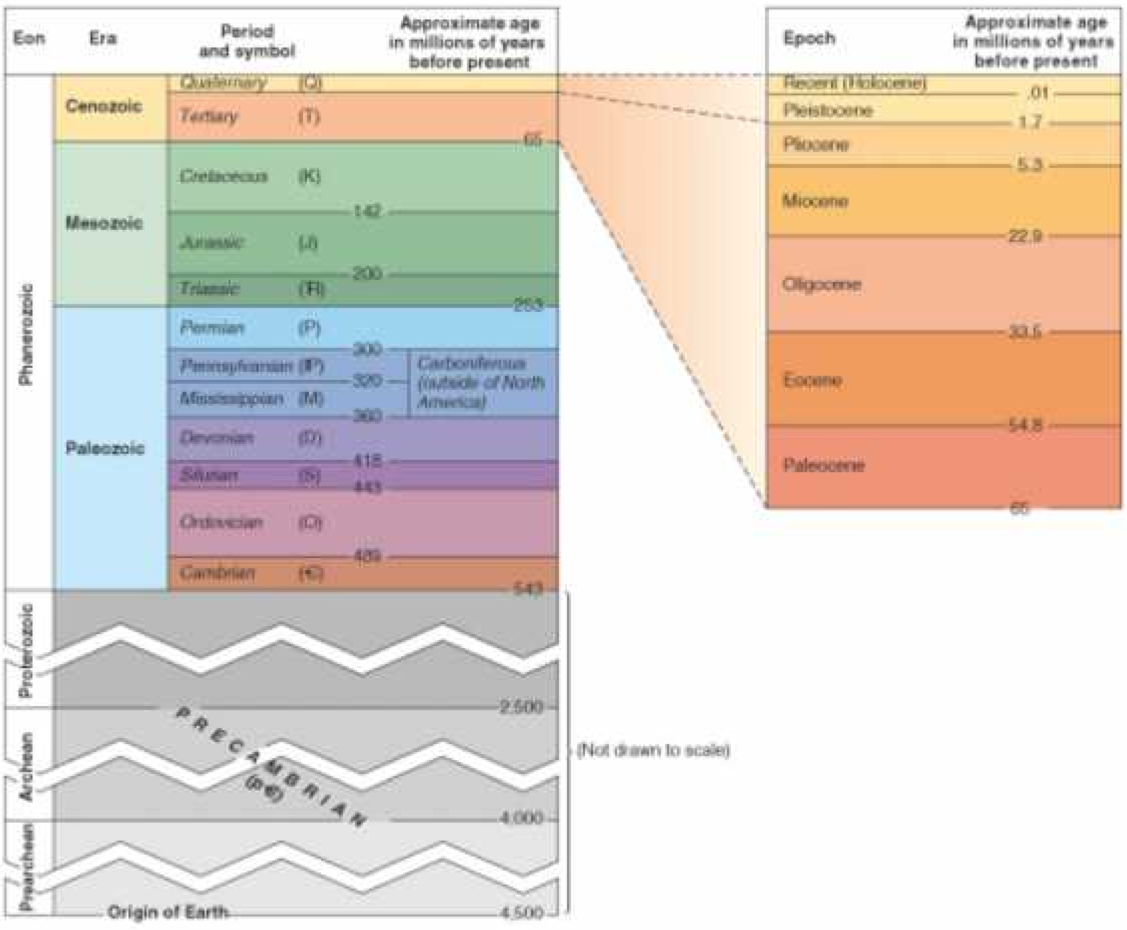
- **Disconformity**

Structurally, there is no difference between younger and older strata, but erosion has removed layers from the sequence.



Geologic Column

Using relative dating techniques geologists have, in effect, come up with a calendar that records the geologic history of the earth. The geologic column is subdivided into eons, which in turn are subdivided into eras, which are further subdivided into periods, then epochs. Each time unit is identified by its own geologic character.

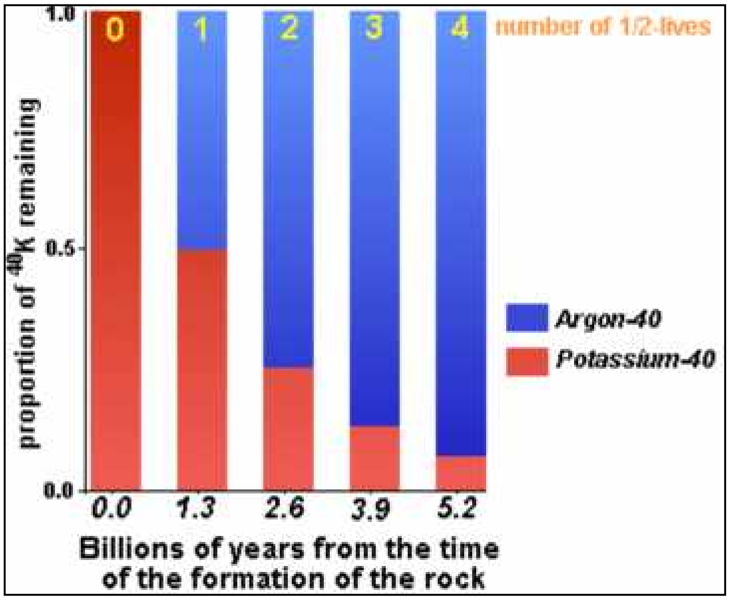


Absolute Time – applying specific units of time

Unlike relative age dating techniques which only allow us to put geologic events and formations in a chronological sequence, absolute dating techniques provide us with a numerical age. Various methods have been developed to determine absolute age:

Radiometric dating

Radioactive isotopes (parent isotopes) systematically, decay into another element (daughter isotope). The time it takes for half of the parent atoms to decay to form daughter atoms is referred to as the half-life of a radioactive isotope. By measuring the proportion of parent isotope to daughter isotope, and knowing the half-life, we are able to determine the absolute age of a rock or fossil fragment. Half-lives of unstable, radioactive isotopes varies from hours to hundreds of millions and even billions of years. Isotopes with long half-lives are best for geologic dating. During the last 50 years techniques have been developed to determine the *absolute* age of rocks on the basis of radioactive decay of elements such as uranium, potassium, strontium, carbon, and several others. For example, the rare isotope of potassium **40K** decays into the isotope of argon **40Ar**. We know that this decay takes place at a steady rate, a rate which has not changed over geological time, and is the same throughout the solar system. The decay of 40K has a **half-life** of 1.3 b.y., which means that in a rock which is 1.3 b.y. old, half of the original 40K will have decayed into 40Ar (see figure below). By accurately measuring the proportions of these isotopes it is possible to estimate the age of a rock. Generally speaking isotopic dating can only be applied to igneous rocks (rocks formed from magma) because they have been heated sufficiently to separate parent isotopes from daughter isotopes. In the case of 40K-40Ar, for example, an igneous rock will have no 40Ar at the time of its formation, and hence any 40Ar found in it can be assumed to be derived from the decay of 40K. By combining isotopic age information with paleontological information and geological relationship information it has been possible to attach absolute numbers to the geological time scale, and also to determine the absolute ages of most rocks.



Tree rings

In temperate climates trees develop a sequence of annual growth rings that provide a record of the conditions under which that tree grew. Information on microclimatic conditions, insect infestations and forest fires are reflected in the thickness and texture of the tree rings. By overlapping patterns of annual growth rings from numerous trees, living to dead, scientists can form records that may extend back thousands of years. Of course by now we appreciate the fact that a few thousand years is a very short time frame in relation to the history of the earth.

Varves

Glacial streams carry sediments, eroded by glaciers, to glacial lakes. In summer, thick layers of coarse-grained sediments are deposited, while in winter, thinner layers of fine-grained sediments are deposited. Year after year the sediments accumulate in this way. By counting these layers geologists can establish a record that goes back hundreds, even thousands of years. In the glaciated region around the Baltic Sea a 20,000 year record has been established. Shales in the Green River Formation of Wyoming contain a varved sequence thought to span a period of 5 million years!

Ice layers

Ice sheets in the polar regions of the globe represent amazing storehouses of information. Just like tree rings and varves, ice sheets preserve a record of conditions in the form of an annually accumulated sequence. Annual fluctuations in snowfall and snowmelt produce layers which preserve a sedimentological record of events that have occurred over the past 65,000 years. The history of volcanic eruptions, environmental contamination by human activity, and climate change is preserved in the ice layers.

By applying the principles of relative and absolute dating we can get a relatively accurate idea of the geologic history of an area.

5.2. Weathering

There are three major types of weathering, although most textbooks only distinguish two. The first type is **physical weathering** and is defined as the *mechanical breakup of rock*. The second type of weathering is called **chemical weathering**. This is the most important process in soil formation and involves *chemical changes during the breakup of rock*. The last of the weathering types (not always distinguished in texts) is **biological weathering**. This involves *the actions of plants and animals* and is really just a combination of physical and chemical weathering. The main thing to remember about these types of weathering is that they all reduce rock into sediment. Physical weathering does this with little loss in volume. Chemical weathering may result in a significant loss in volume.

Physical weathering

Physical weathering occurs everywhere, but is especially prevalent in areas of the Earth that are either very hot (e.g., deserts) or very cold (e.g., mountains). In hot areas, alternations between hot and cold conditions cause rock to expand and contract. It is felt by many geologists that this causes rocks to “sheet” off in a process called **exfoliation**. Another type of physical weathering is called **unloading**. Granite forms well below the surface of the Earth in areas of fairly high pressure. When exposed at the Earth’s surface, the rocks no longer feel the confining pressure and may tend to shatter because of the reduced pressure load. Unloading is really a problem in new mine shafts. Some granites (other rocks too, but granite is about the worst) will exploded in what is called a **rock burst**. This is just one of the hazards of being a miner. In cold climates, water is the major agent behind physical weathering. Liquid water expands when it freezes, so any water within cracks, fractures and joints exerts tremendous force when it freezes. Rocks can be literally split apart as the temperature drops. Mountains are particularly good areas to see the results of this **frost heaving**. The piles of rock that occur along the base of mountains (called scree or **talus**) were mostly derived from frost heave.

Physical weathering produces smaller bits of rock, but it doesn't actually change the composition of the rock. You would be able to recognize bits of granite or basalt or rhyolite. The most important thing it does is increase the relative **surface area** of the rock. The surface area is the *amount of contact area in an rock that is exposed to water*. Water is the principle agent behind chemical weathering so the more surface area, the more contact area for chemical weathering. Or to put it more succinctly, the higher the surface area, the faster chemical weathering occurs.

Chemical weathering reactions

There are three major reactions responsible for chemical weathering:
1**) Solution** (or **dissolution**)
2) **Oxidation**
3) **Hydrolysis**

Solution occurs when a mineral dissolves. The result is that you get ions in solution and nothing is left behind (example minerals: halite, calcite). Oxidation occurs when a mineral reacts with oxygen in the atmosphere or in water (example mineral: pyrite). Hydrolysis occurs when a mineral reacts with water (example minerals: orthoclase, pyrite, olivine).

1) Dissolution

$NaCl \xrightarrow{H_2O} Na^+ + Cl^-$
(Halite)
$CaCO3 \xrightarrow{H_2O} Ca^{2+} + HCO3^-$
(Calcite)

2) Oxidation

$FeS_2 \xrightarrow{O_2} Fe_2O_3 + SO_2$
(Pyrite) (Hematite)

3) Hydrolysis
$FeS_2 + H_2O + O_2 \longrightarrow FeOOH + 2H_2SO_4$
(Pyrite) (Limonite) (Sulfuric acid)

$KAlSi_3O_8 + H_2O + CO_2 \longrightarrow Al_2Si_2O_5(OH)_4$
(K-feldspar) (Kaolinite)

Mineral stability

Igneous rocks are composed of minerals that form from molten rock. Minerals that form at high temperature and/or high pressure do so because they are stable under those conditions. Olivine is very stable at 1800 °C, but at temperatures significantly less than that, like that at the surface of the Earth, olivine is unstable. Add water in the form of rain fall, and the mineral becomes very reactive. Olivine-rich rocks such as dunite, peridotite or basalt porphyry do not survive long at the surface of the Earth. Bowen's Reaction Series can also be considered a stability series. Those minerals that form first from a melt (e.g., olivine, pyroxene, Ca-plagioclase), are at the low stability end of the series while those that form last (e.g., quartz, muscovite), are at the high stability end of the series. Quartz is the most stable of the common minerals. For the purposes of mineral stability, we will add four other minerals/mineraloids to our modified Bowen's Reaction Series. Kaolinite (a **clay** mineral) is more stable than muscovite. Limonite, hematite and bauxite are all more stable than quartz.

Factors that Influence Weathering

- **Rock Type & Structure**
  - Different rocks are composed of different minerals, and each mineral has a different susceptibility to weathering. For example granite consisting mostly of quartz is already composed of a mineral that is very stable on the Earth's surface, and will not weather much in comparison to limestone, composed entirely of calcite, which will eventually dissolve completely in a wet climate.
  - Bedding planes, joints, and fractures, all provide pathways for the entry of water. A rock with lots of these features will weather more rapidly than a massive rock containing no bedding planes, joints, or fractures.
  - If there are large contrasts in the susceptibility to weathering within a large body of rock, the more susceptible parts of the rock will weather faster than the more resistant portions of the rock. This will result in ***differential weathering.***
- **Slope -** On steep slopes weathering products may be quickly washed away by rains. On gentle slopes the weathering products accumulate. On gentle slopes water may stay in contact with rock for longer periods of time, and thus result in higher weathering rates.
- **Climate-** High amounts of water and higher temperatures generally cause chemical reactions to run faster. Thus warm humid climates generally have more highly weathered rock, and rates of weathering are higher than in cold dry climates. Example:

limestones in a dry desert climate are very resistant to weathering, but limestones in tropical climate weather very rapidly.

- **Animals-** burrowing organisms like rodents, earthworms, & ants, bring material to the surface were it can be exposed to the agents of weathering.

Soils

Soil consists of rock and sediment that has been modified by physical and chemical interaction with organic material and rainwater, over time, to produce a substrate that can support the growth of plants. Soils are an important natural resource. They represent the interface between the lithosphere and the biosphere - as soils provide nutrients for plants. Soils consist of weathered rock plus organic material that comes from decaying plants and animals. The same factors that control weathering control soil formation with the exception, that soils also requires the input of organic material as some form of Carbon.

When a soil develops on rock, a soil profile develops as shown below (Fig. 5.1). These different layers are not the same as beds formed by sedimentation; instead each of the horizons forms and grows in place by weathering and the addition of organic material from decaying plants and plant roots.

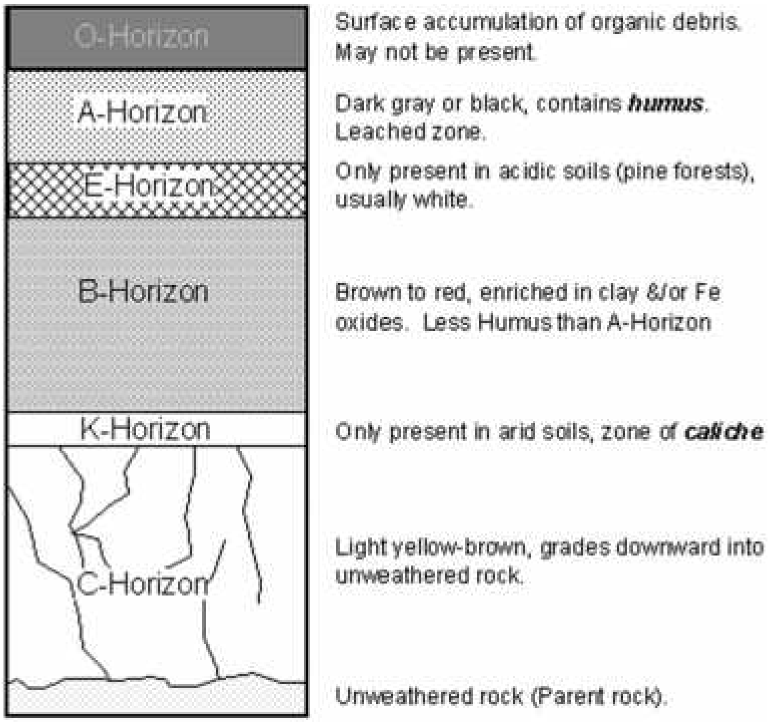


Figure 1.1. Soil profile.

Although you will not be expected to know all of the soil terminology, the following terms are important.

Caliche - Calcium Carbonate (Calcite) that forms in arid soils in the K-horizon by chemical precipitation of calcite. The Ca and Carbonate ions are dissolved from the upper soil horizons and precipitated at the K-horizon. In arid climates the amount of water passing through the soil horizons is not enough to completely dissolve this caliche, and as result the thickness of the layer may increase with time.

Laterites - In humid tropical climates intense weathering involving leaching occurs, leaving behind a soil rich in Fe and Al oxides, and giving the soil a deep red color. This extremely leached soil is called a laterite.

Soil Erosion

In most climates it takes between 80 and 400 years to form about one centimeter of topsoil (an organic and nutrient rich soil suitable for agriculture). Thus soil that is eroded by poor farming practices is essentially lost and cannot be replaced in a reasonable amount of time. This could become a critical factor in controlling world population.

5.3. Geomorphologic processes

Geomorphology is the study of landforms and the processes that shape them. Geomorphologists seek to understand why landscapes look the way they do. To understand landform history and dynamics, and predict future changes through a combination of field observation, physical experiment, and numerical modeling. Geomorphology is practiced within geology, geodesy, geography, archaeology, and civil and environmental engineering. Early studies in geomorphology are the foundation for pedology, one of two main branches of soil science. Landforms evolve in response to a combination of natural and anthropogenic processes. The landscape is built up through tectonic uplift and volcanism. Denudation occurs by erosion and mass wasting, which produces sediment that is transported and deposited elsewhere within the landscape or off the coast. Landscapes are also lowered by subsidence, either due to tectonics or physical changes in underlying sedimentary deposits. These processes are each influenced differently by climate, ecology, and human activity. Practical applications of geomorphology include measuring the effects of climate change, hazard assessments including landslide prediction and mitigation, river control and restoration, and coastal protection.

Modern geomorphology focuses on the quantitative analysis of interconnected processes, such as the contribution of solar energy, the rates of steps of the hydrologic cycle, plate movement rates from computing the age and expected fate of landforms and the weathering and erosion of the land. The use of more precise measurement technique has also enabled processes like erosion to be observed directly, rather than merely surmised from other evidence. Computer simulation is also valuable for testing that a particular model yields results with properties similar to real terrain. Primary surface processes responsible for most topographic features include wind, waves, weathering, mass wasting, ground water, surface water, glaciers, tectonism, and volcanism.

Fluvial

Rivers and streams are not only conduits of water, but also of sediment. The water, as it flows over the channel bed, is able to mobilize sediment and transport it downstream, either as bed load, suspended load or dissolved load. The rate of sediment transport depends on the availability of sediment itself and on the river's discharge. As rivers flow across the landscape, they generally increase in size, merging with other rivers. The network of rivers thus formed is a drainage system and is often dendritic, but may adopt other patterns depending on the regional topography and underlying geology.

Hill slope

Soil, regolith, and rock move down slope under the force of gravity via creep, slides, and flows, topple, and fall. Such mass wasting occurs on both terrestrial and submarine slopes, and has been observed on Earth, Mars, and Venus.

Glacial

Glaciers, while geographically restricted, are effective agents of landscape change. The gradual movement of ice down a valley causes abrasion and plucking of the underlying rock. Abrasion produces fine sediment, termed glacial flour. The debris transported by the glacier, when the glacier recedes, is termed a moraine. Glacial erosion is responsible for U-shaped valleys, as opposed to the V-shaped valleys of fluvial origin.

Weathering

This results from chemical dissolution of rock and from the mechanical wearing of rock by plant roots, ice expansion, and the abrasive action of sediment. Weathering provides the source of the sediment transported by fluvial, glacial, aeolian, or biotic processes.

Taxonomy

Different geomorphological processes dominate at different spatial and temporal scales. To help categorize landscape scales some geomorphologists use the following taxonomy:
1st -Continent, ocean basin, climatic zone (~10,000,000 km^2)
2nd - Shield, e.g. Baltic shield, or mountain range (~1,000,000 km^2)
3rd – Isolated sea, Sahel (~100,000 km^2)
4th - Massif, e.g. Massif Central or Group of related landforms, e.g., Weald (~10,000 km^2)
5th - River valley, Cotswold (~1,000 km^2)
6th – Individual mountain or volcano, small valleys (~100 km^2)
7th – Hill slopes, stream channels, estuary (~10 km^2)
8th -gully, bar channel (~1 km^2)
9th - Meter-sized feature

Mass Movements

Mass movements (also called mass-wasting) are the down-slope movement of ***Regolith*** (loose uncemented mixture of soil and rock particles that covers the Earth's surface) by the force of gravity without the aid of a transporting medium such as water, ice, or wind. Mass movements are part of a continuum of erosional processes between weathering and stream transport. Mass movement causes regolith and rock to move down-slope where sooner or later the loose particles will be picked up by another transporting agent and eventually moved to a site of deposition such as an ocean basin or lake bed. Mass movement processes are occurring continuously on all slopes; some act very slowly, others occur very suddenly, often with disastrous results.

Gravity is the main force responsible for mass movements. Gravity is a force that acts everywhere on the Earth's surface, pulling everything in a direction toward the center of the Earth. On a flat surface, parallel to the Earth's surface, the force of gravity acts downward. So long as the material remains on the flat surface it will not move under the force of gravity. Of course if the material forming the flat surface becomes weak or fails then the unsupported supports mass will move downward. Slope, the force of gravity can be resolved into two components: a component acting perpendicular to the slope, and a component acting parallel to the slope. The perpendicular component of gravity, g_p, helps to hold the object in place on the slope. The component of gravity acting parallel to the slope, g_s, causes a shear stress parallel to the slope and helps to move the object in the down-slope direction. On a steeper slope, the shear stress component of gravity, $g_{s,}$ increases, and the perpendicular component of gravity, g_p, decreases.

Another force resisting movement down the slope is grouped under the term ***shear strength*** and includes frictional resistance and cohesion among the particles that make up the object. When the sheer stress becomes greater than the combination of forces holding the object on the slope, the object will move down-slope. Thus, down-slope movement is favored by steeper slope angles (increasing the shear stress) and anything that reduces the shear strength (such as lowering the cohesion among the particles or lowering the frictional resistance. For unconsolidated material, the angle that forms a stable slope is called the ***angle of repose***.

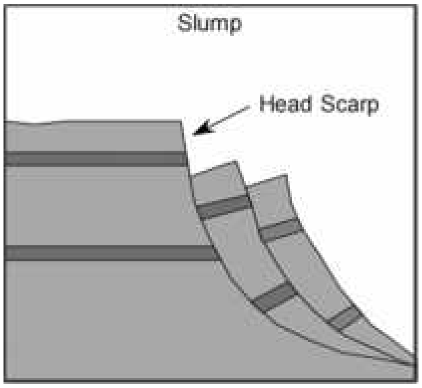
Although water is not always directly involved as the transporting medium in mass movement processes, it does play an important role. Addition of water from rainfall or snow melt adds weight to the slope. Water can seep into the soil or rock and replace the air in the pore space or fractures. Since water is heavier than air, this increases the weight of the soil. If the material becomes saturated with water, vibrations could cause liquifaction to occur, just like often happens during earthquakes. Water can reduce the friction along a sliding surface. Water has the ability to change the angle of repose (the slope angle which is the stable angle for the slope). Think about building a sand castle on the beach. If the sand is totally dry, it is impossible to build a pile of sand with a steep face like a castle wall. If the sand is somewhat wet, however, one can build a vertical wall. If the sand is too wet, then it flows like a fluid and cannot remain in position as a wall. Dry unconsolidated grains will form a pile with a slope angle determined by the ***angle of repose***. The angle of repose is the steepest angle at which a pile of unconsolidated grains remains stable, and is controlled by the frictional contact between the grains. In general, for dry materials the angle of repose increases with increasing grain size, but usually lies between about 30 and 45 ^{o}. Coarser grained and angular particles have a steeper angle of repose than fine grained and rounded particles.

We will use a common classification of mass movements, which divides the processes into two broad categories and further subdivides these categories.

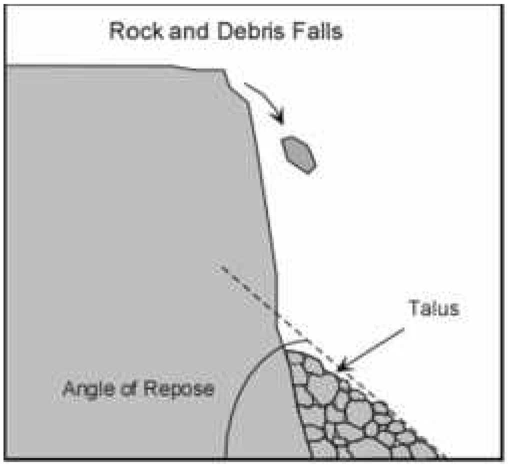
1. ***Slope Failures*** - a sudden failure of the slope resulting in transport of debris downhill by sliding, rolling, falling, or slumping.
2. ***Sediment Flows*** - material flows down hill mixed with water or air.

Slope Failures

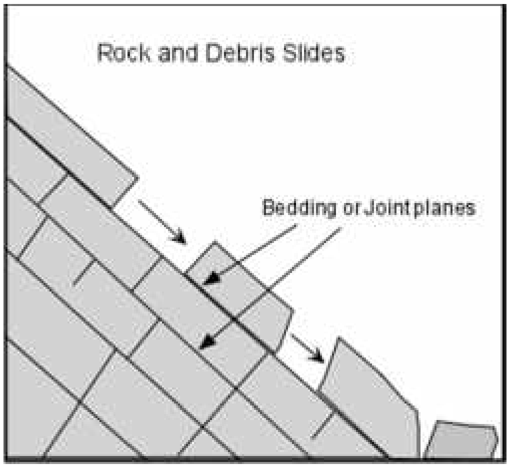
***Slumps* -** types of slides wherein downward rotation of rock or regolith occurs along a curved surface. The upper surface of each slump block remains relatively undisturbed, as do the individual blocks. Slumps leave arcuate scars or depressions on the hill slope. Heavy rains or earthquakes usually trigger slumps.



Rock Falls and Debris Falls - Rock falls occur when a piece of rock on a steep slope becomes dislodged and falls down the slope. Debris falls are similar, except they involve a mixture of soil, regolith, and rocks. A rock fall may be a single rock, or a mass of rocks, and the falling rocks can dislodge other rocks as they collide with the cliff. At the base of most cliffs is an accumulation of fallen material termed ***talus***. The slope of the talus is controlled by the angle of repose for the size of the material. Since talus results from the accumulation of large rocks or masses of debris the angle of repose is usually greater than it would be for sand.



Rock Slides and Debris Slides - Rock slides and debris slides result when rocks or debris slide down a pre-existing surface, such as a bedding plane or joint surface. Piles of talus are common at the base of a rock slide or debris slide.



Sediment Flows

Sediment flows occur when sufficient force is applied to rocks and regolith that they begin to flow down slope. A sediment flow is a mixture of rock, regolith with some water. They can be broken into two types depending on the amount of water present.

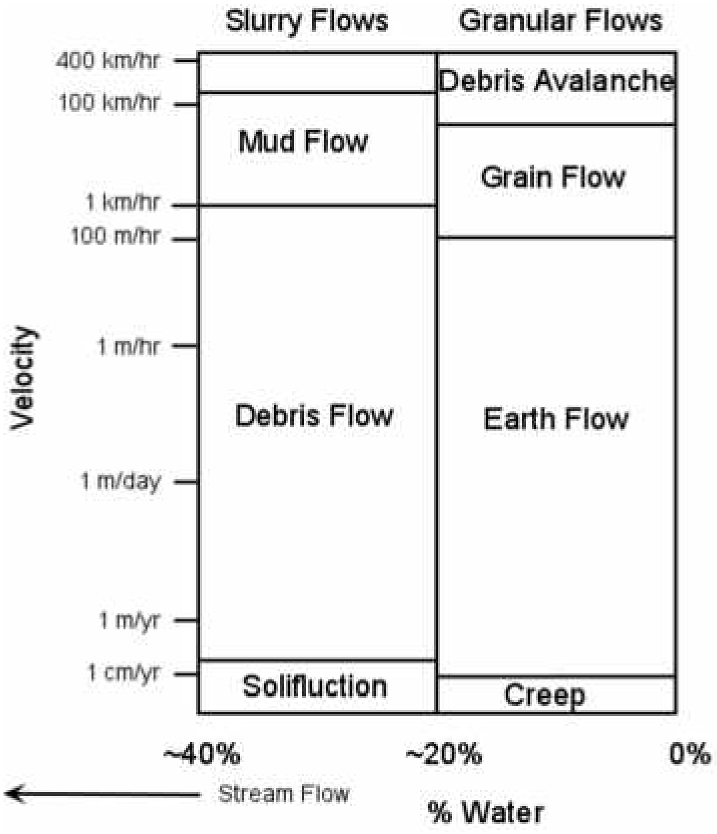
1. ***Slurry Flows***- are sediment flows that contain between about 20 and 40% water. As the water content increases above about 40% slurry flows grade into streams.
2. ***Granular Flows*** - are sediment flows that contain between 20 and 0% water. Note that granular flows are possible with little or no water. Fluid-like behavior is given these flows by mixing with air.

Each of these classes of sediment flows can be further subdivided on the basis of the velocity at which flowage occurs.

- ***Slurry Flows (high amounts of water)***
    - ***Solifluction -*** flowage at rates measured on the order of centimeters per year of regolith containing water. Solifluction produces distinctive lobes on hill slopes. These occur in areas where the soil remains frozen and is then is thawed for a short time to become saturated with water.
    - ***Debris Flows-*** these occur at higher velocities than solifluction, and often result from heavy rains causing saturation of the soil and regolith with water. They sometimes start with slumps and then flow down hill forming lobes with an irregular surface consisting of ridges and furrows.
    - ***Mudflows***- a highly fluid, high velocity mixture of sediment and water that has a consistency of wet concrete. These usually result from heavy rains in areas where there is an abundance of unconsolidated sediment that can be picked up by streams. Thus, after a heavy rain streams can turn into

mudflows as they pick up more and more loose sediment. Mudflows can travel for long distances over gently sloping stream beds. Because of their high velocity and long distance of travel they are potentially very dangerous. Mudflows on volcanoes are called ***lahars***.

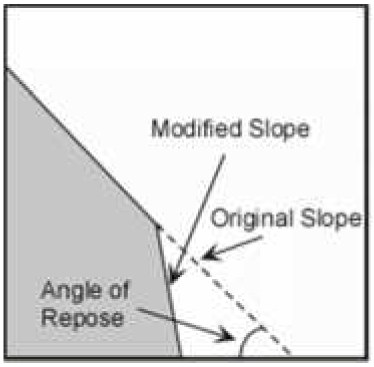
- ***Granular Flows (low amounts of water)***
    - ***Creep-*** the very slow, usually continuous movement of regolith down slope. Creep occurs on almost all slopes, but the rates vary. Evidence for creep is often seen in bent trees, offsets in roads and fences, and inclined utility poles (see figure 16.2c in your text).
    - ***Earthflows -*** are usually associated with heavy rains and move at velocities between several cm/yr and 100s of m/day. They usually remain active for long periods of time. They generally tend to be narrow tongue-like features that begin at a scarp or small cliff
    - ***Grain Flows -*** usually form in relatively dry material, such as a sand dune, on a steep slope. A small disturbance sends the dry unconsolidated grains moving rapidly down slope.
    - ***Debris Avalanches -*** These are very high velocity flows of large volume mixtures of rock and regolith that result from complete collapse of a mountainous slope. They move down slope and then can travel for considerable distances along relatively gentle slopes. They are often triggered by earthquakes and volcanic eruptions. Snow avalanches are similar, but usually involve only snow.

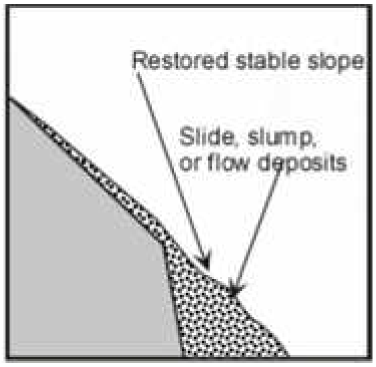


Triggering Events

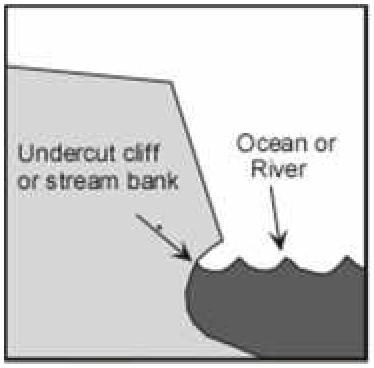
A mass movement can occur any time a slope becomes unstable. Sometimes, as in the case of creep or solifluction, the slope is unstable all of the time and the process is continuous. But other times, triggering events can occur that cause a sudden instability to occur. Here we discuss major triggering events, but it should be noted that it if a slope is very close to instability, only a minor event may be necessary to cause a failure and disaster.

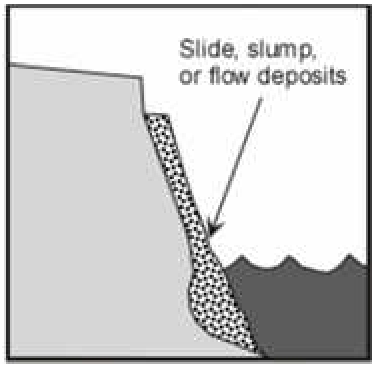
- **Shocks and vibrations -** A sudden shock, such as an earthquake may trigger slope instability. Minor shocks like heavy trucks rambling down the road, trees blowing in the wind, or human made explosions can also trigger mass movement events.
- **Slope Modification -** Modification of a slope either by humans or by natural causes can result in changing the slope angle so that it is no longer at the angle of repose. A mass movement can then restore the slope to its angle of repose.





- **Undercutting -** streams eroding their banks or surf action along a coast can undercut a slope making it unstable.





- **Changes in Hydrologic Characteristics -** heavy rains can saturate regolith reducing grain to grain contact and reducing the angle of repose, thus triggering a mass movement. Heavy rains can also saturate rock and increase its weight. Changes in the groundwater system can increase or decrease fluid pressure in rock and also triggers mass movements.

- **Changes in slope strength -** Weathering creates weaker material, and thus leads to slope failure. Vegetation holds soil in place and slows the influx of water. Trees put down roots that hold the ground together and strengthen the slope. Removal of tress and vegetation either by humans or by a forest fire, often results in slope failures in the next rainy season.
- **Volcanic Eruptions -** produce shocks like explosions and earthquakes. They can also cause snow to melt or discharges from crater lakes, rapidly releasing large amounts of water that can be mixed with regolith to reduce grain to grain contact and result in debris flows, mudflows, and landslides.

Assessing Mass Movement Hazards

Mass movements can be extremely hazardous and result in extensive loss of life and property. But, in most cases, areas that are prone to such hazards can be recognized with some geologic knowledge, slopes can be stabilized or avoided, and warning systems can be put in place that can reduce vulnerability. Because there is usually evidence in the form of distinctive deposits and geologic structures left by recent mass movements, it is possible to construct maps of all areas prone to possible landslide hazards (see Fig. 5.2). Planners can use such hazards maps to make decisions about land use policies in such areas or, steps can be taken to stabilize slopes to attempt to prevent a disaster or minimize its effects. Short-term prediction of mass-wasting events is somewhat more problematical. For earthquake triggered events, the same problems that are inherent in earthquake prediction are present. Slope destabilization and undercutting triggered events require constant monitoring. Mass movement hazards from volcanic eruptions can be predicted with the same degree of certainty that volcanic eruptions can be predicted, but again, the threat has to be realized and warnings need to be heeded. Hydrologic conditions such as heavy precipitation can be forecast with some certainty, and warnings can be issued to areas that might be susceptible to mass movement processes caused by such conditions.

Some warning signs can be recognized by observations of things around you:

- Springs, seeps, or saturated ground in areas that have not typically been wet before.
- New cracks or unusual bulges in the ground, street pavements or sidewalks.

- Soil moving away from foundations.
- Ancillary structures such as decks and patios tilting and/or moving relative to the main house.
- Tilting or cracking of concrete floors and foundations.
- Broken water lines and other underground utilities.
- Leaning telephone poles, trees, retaining walls or fences
- Offset fence lines.
- Sunken or down-dropped road beds.
- Rapid increase in creek water levels, possibly accompanied by increased turbidity (soil content).
- Sudden decrease in creek water levels though rain is still falling or just recently stopped.
- Sticking doors and windows, and visible open spaces indicating jambs and frames out of plumb.
- A faint rumbling sound that increases in volume is noticeable as the landslide nears.
- Unusual sounds, such as trees cracking or boulders knocking together, might indicate moving debris.

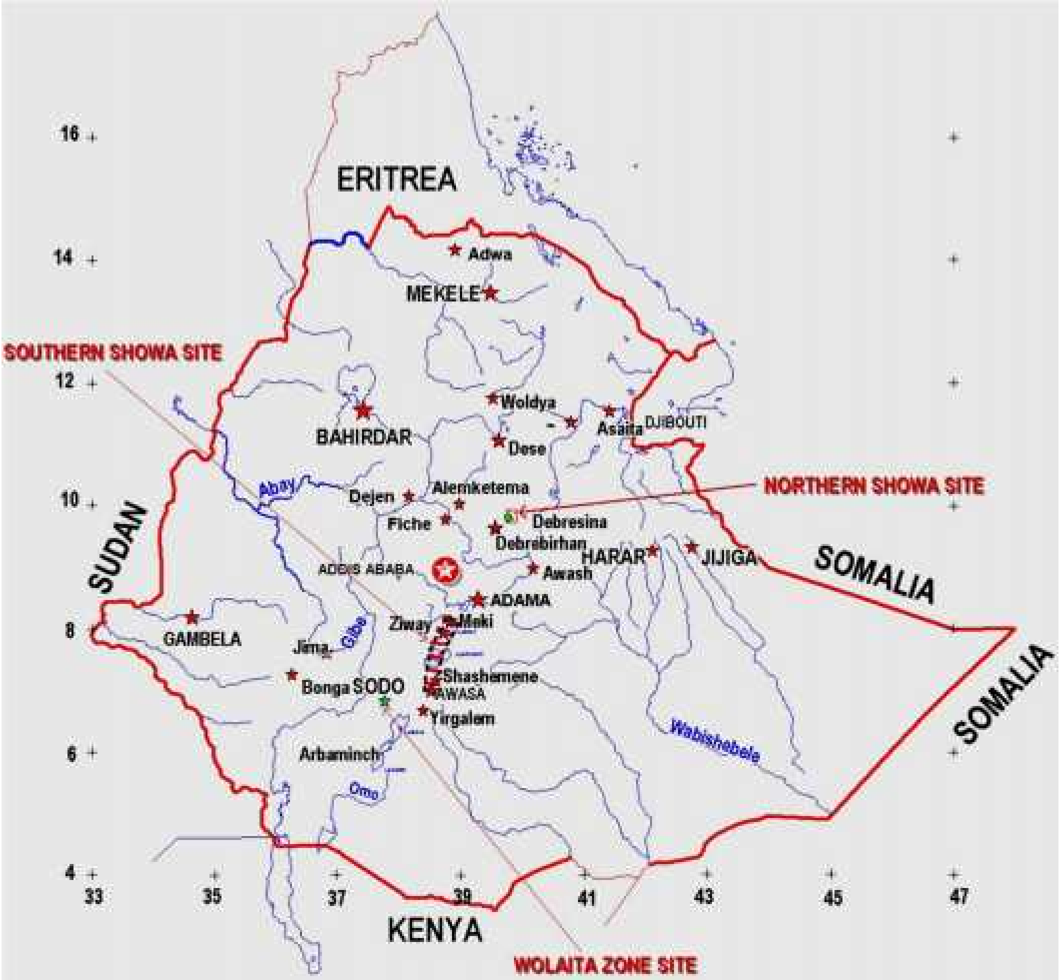


Figure 5.2. Map showing areas prone to possible landslide hazards in Ethiopia.

Prevention and Mitigation

All slopes are susceptible to mass movement hazards if a triggering event occurs. Thus, all slopes should be assessed for potential landslide hazards. Mass movements can sometimes be avoided by employing engineering techniques to make the slope more stable. Among them are:

- Steep slopes can be covered or sprayed with concrete covered or with a wire mesh to prevent rock falls.
- Retaining walls could be built to stabilize a slope.
- If the slope is made of highly fractured rock, rock bolts may be emplaced to hold the slope together and prevent failure.
- Drainage pipes could be inserted into the slope to more easily allow water to get out and avoid increases in fluid pressure, the possibility of liquefaction, or increased weight due to the addition of water.
- Oversteepened slopes could be graded to reduce the slope to the natural angle of repose.
- In mountain valleys subject to mudflows, plans could be made to rapidly lower levels of water in human-made reservoirs to catch and trap the mudflows.
- Trees or other vegetation could be planted on bare slopes to help hold soil.

Some slopes, however, cannot be stabilized, or only stabilized at great expense. In these cases, humans should avoid these areas or use them for purposes that will not increase susceptibility of lives or property to mass movement hazards.

Drainage system

In geomorphology, a drainage system is the pattern formed by the streams, rivers, and lakes in a particular drainage basin. They are governed by the topography of the land, whether a particular region is dominated by hard or soft rocks, and the gradient of the land.

Geomorphologists and hydrologists often view streams as being part of drainage basins. A drainage basin is the topographic region from which a stream receives runoff, through flow, and groundwater flow. Drainage basins are divided from each other by topographic barriers called a watershed. A watershed represents all of the stream tributaries that flow to some location along the stream channel. The number, size, and shape of the drainage basins found in an area vary and the larger the topographic map, the more information on the drainage basin is available (Fig. 5.3).

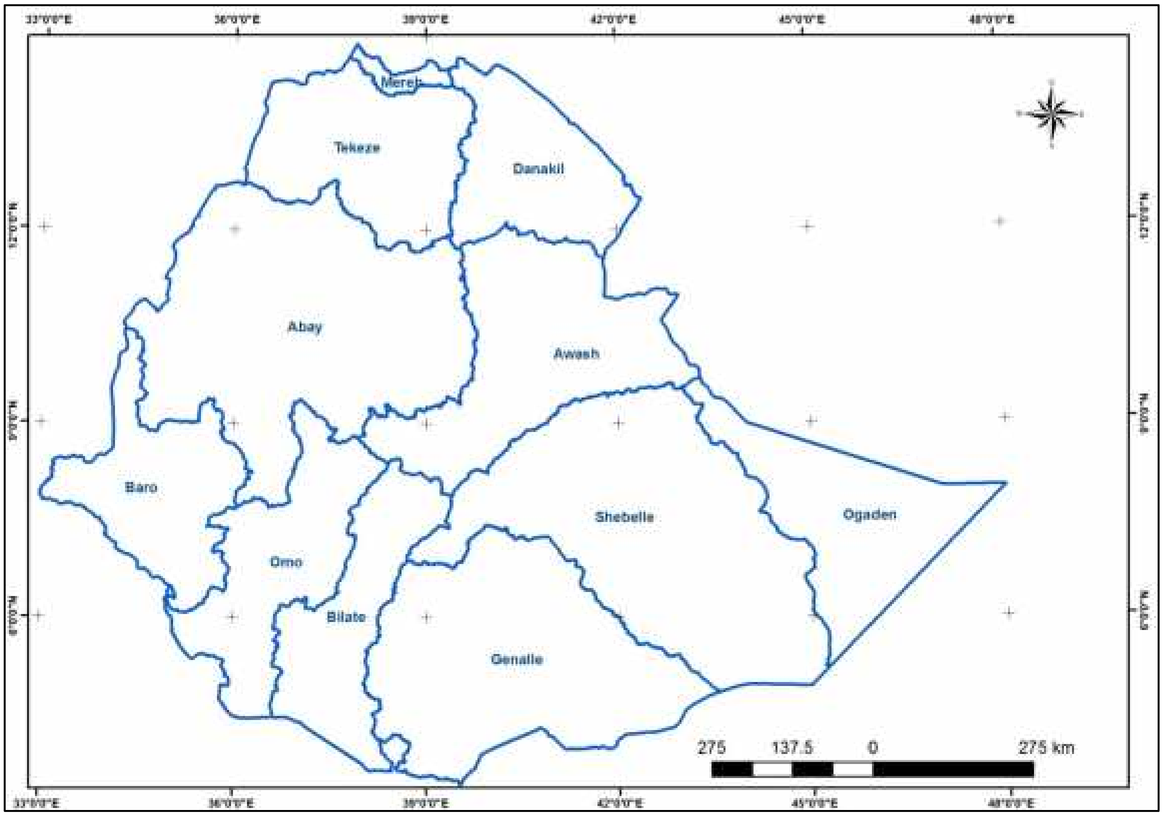


Figure 5.3. Drainage basins of Ethiopia.

Drainage systems can fall into one of several categories, depending on the topography and geology of the land (Fig. 5.4):

Dendritic drainage system

Dendritic drainage systems (from Greek δενδρίτης, dendrites, "of or pertaining to a tree") are the most common form of drainage system. In a dendritic system, there are many contributing streams (analogous to the twigs of a tree), which are then joined together into the tributaries of the main river (the branches and the trunk of the tree, respectively). They develop where the river channel follows the slope of the terrain. Dendritic systems form in V-shaped valleys; as a result, the rock types must be impervious and non-porous.

Parallel drainage system

A parallel drainage system is a pattern of rivers caused by steep slopes with some relief. Because of the steep slopes, the streams are swift and straight, with very few tributaries, and all flow in the same direction. This system forms on uniformly sloping surfaces, for example, rivers flowing southeast from the Aberdare Mountains in Kenya.

Trellis drainage system

The geometry of a trellis drainage system is similar to that of a common garden trellis used to grow vines. As the river flows along a strike valley, smaller tributaries feed into it from the steep slopes on the sides of mountains. These tributaries enter the main river at approximately 90 degree angles, causing a trellis-like appearance of the drainage system. Trellis drainage is characteristic of folded mountains, such as the Appalachian Mountains in North America.

Rectangular drainage system

Rectangular drainage develops on rocks that are of approximately uniform resistance to erosion, but which have two directions of jointing at approximately right angles. The joints are usually less resistant to erosion than the bulk rock so erosion tends to preferentially open the joints and streams eventually develop along the joints. The result is a stream system in which streams consist mainly of straight line segments with right angle bends and tributaries join larger streams at right angles.

Radial drainage system

In a radial drainage system the streams radiate outwards from a central high point. Volcanoes usually display excellent radial drainage. Other geological features on which radial drainage commonly develops are domes and laccoliths. On these features the drainage may exhibit a combination of radial and annular patterns.

Deranged drainage system

A deranged drainage system is a drainage system in drainage basins where there is no coherent pattern to the rivers and lakes. It happens in areas where there has been much geological disruption. The classic example is the Canadian Shield. During the last ice age, the topsoil was scraped off, leaving mostly bare rock. The melting of the glaciers left land with many irregularities of elevation, and a great deal of water to collect in the low points, explaining the large number of lakes which are found in Canada. The watersheds are young and are still sorting themselves out. Eventually the system will stabilize.

Annular drainage pattern

In an annular drainage pattern streams follow a roughly circular or concentric path along a belt of weak rock, resembling in plan a ring like pattern. It is best displayed by streams draining a maturely dissected structural dome or basin where erosion has exposed rimming sedimentary strata of greatly varying degrees of hardness, as in the Red Valley, which nearly encircles the domal structure of the Black Hills of South Dakota.

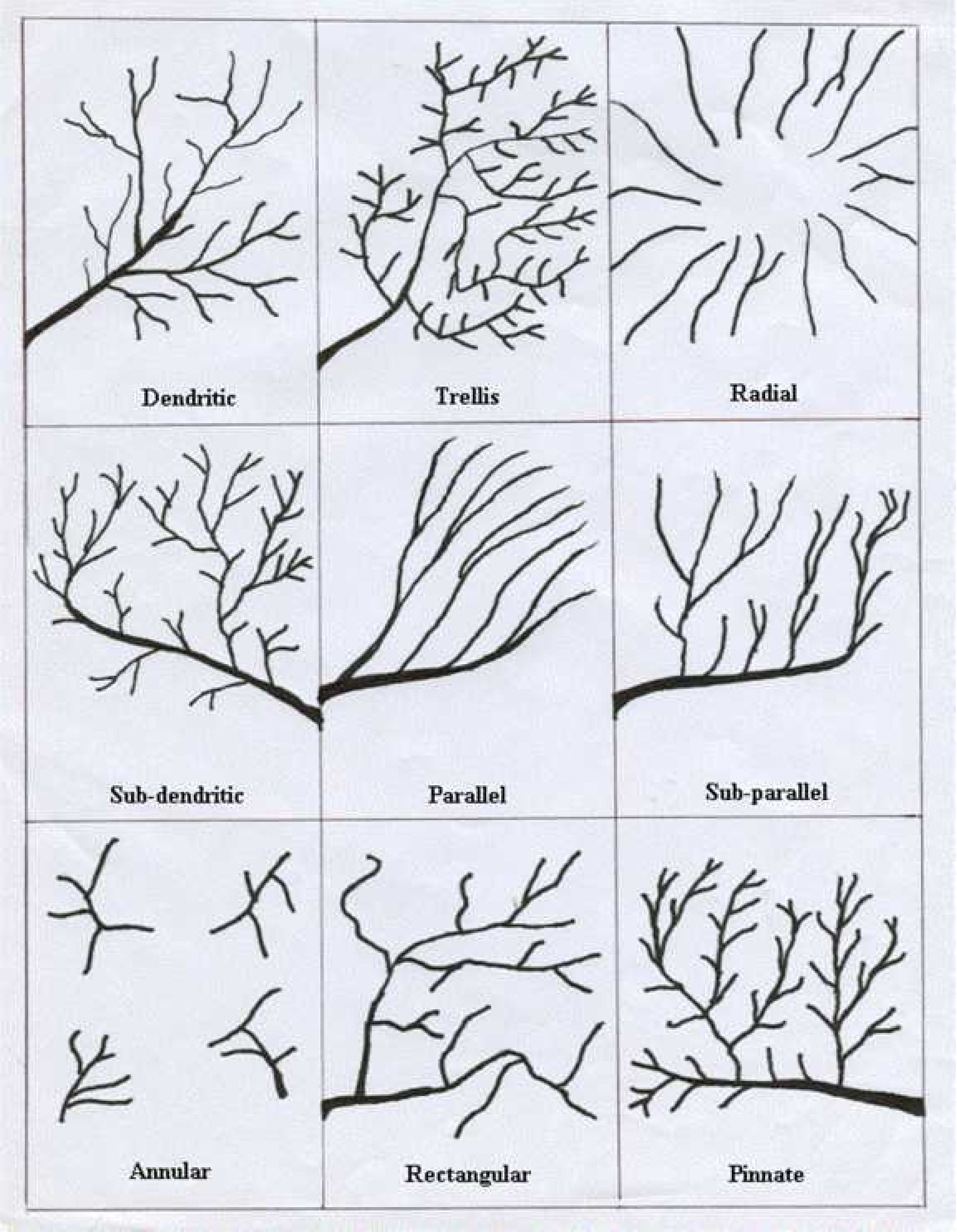


Figure 5.4. Drainage patterns.

5.4. Hydrogeology and Groundwater

Hydrogeology (*hydro*- meaning water and -*geology* meaning the study of the Earth) is the area of geology that deals with the distribution and movement of groundwater in the soil and rocks of the Earth's crust (commonly in aquifers). Water is vital for most life forms on the planet and there is a lot of it. It is one of the most mobile substances on the planet and it is constantly being recycled from one form to another through the hydrologic (or hydrological) cycle. The **hydrological cycle** (Fig. 5.3) is a bit like the rock cycle, but instead of relating rocks and processes to one another, it relates water and processes. It is defined as *all of the water on, over and in the Earth, and the processes by which that water moves between* ***reservoirs***.

The hydrologic cycle consists of 5 main reservoirs (storage places for water). In order of descending volume, they are:

1) Oceans (98% of all water)
2) Ice caps (1.8%)
3) Groundwater (0.6%)
4) Lakes and rivers (0.01%)
5) Atmosphere (0.001%)

Most people understand that the oceans and ice caps contain most of the planet’s water, but they are usually surprised that **groundwater** not river/lake water is the 3rd most important reservoir in the hydrologic cycle. Truth be told, groundwater contains 40x as much water as all the rivers and lakes on the surface of the Earth which is the reason why it is so important to much of the world’s population.

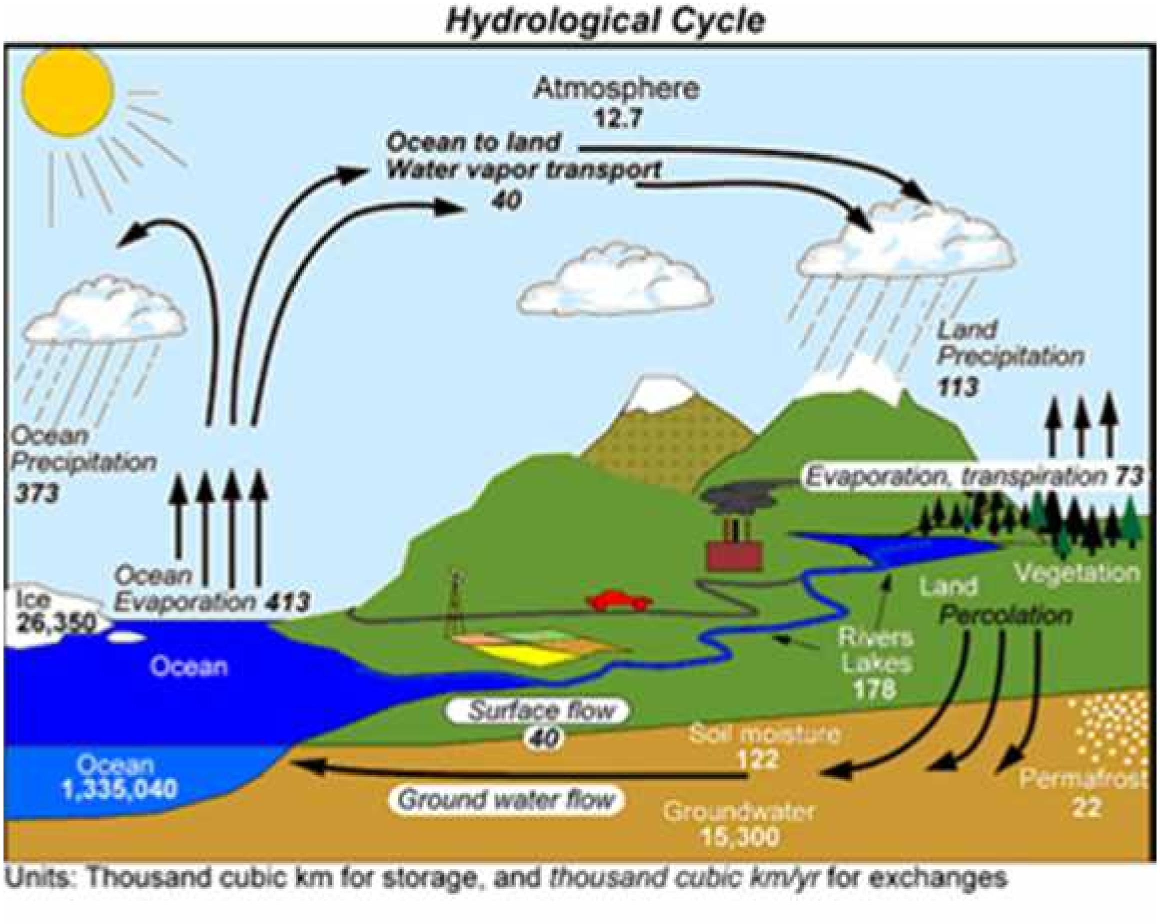


Figure 5.5. The hydrologic cycle.

Water is recycled between each of the reservoirs via the processes of:

1) Evaporation (water to gas)
2) Condensation (gas to liquid; e.g., clouds)
3) Runoff (liquid water flowing over the land; e.g., rivers)
4) Infiltration liquid water flows into the ground (groundwater)

Groundwater is one of the most important resources that we have. In many parts of the world groundwater is the only viable supply of water. So how does groundwater get into the ground? The first thing you need is water (rainwater, river water, lake water etc). Then you need surface materials that are both **porous** (i.e., have lots of void spaces between grains) and **permeable** (i.e., all of the void spaces are connected). Well sorted beach sand is an excellent porous material, but broken up, fractured and mechanically weathered bedrock will all allow infiltration. Water that enters the voids is called **pore water** and it tends to move downward. The mechanism driving infiltration is gravity and it’s the same reason that water flows downhill in rivers. So as water infiltrates the subsurface, it is moving “downhill”, that is, straight down. The actual path that the water takes is tortuous because it has to flow through the pores between grains and it is a relatively slow process. But if the material at the surface of the Earth is both porous and permeable, eventually, a lot of the water that falls during rain storms will infiltrate the soil. If all of the pore spaces get filled up with water, the excess runs off into streams and rivers. Water that passes into the ground will continue to percolate downward until it hits a barrier (e.g., a non-porous layer or the bedrock), or it simply fills up all of the available pore space. You can actually identify two separate layers or horizons below the surface of the Earth that are distinguished by the amount of water that fills pore spaces. The layer where water only partially fills pore space is called the **Zone of Aeration** (or vadose zone) and the layer below this where water entirely fills pore space is called the **Zone of Saturation** (or phreatic zone). The two layers are separated by an important plane called the **water table**.

Some lakes and rivers, particularly in arid and desert areas, lose considerable amounts of water to infiltration. Some eventually dry up entirely. These rivers and lakes are said to be **influent**. Others actually receive a lot of water from groundwater draining into them (this happens a lot in our area and explains why rivers still have flowing water in the middle of prolonged droughts). These rivers and lakes are said to be **effluent**.

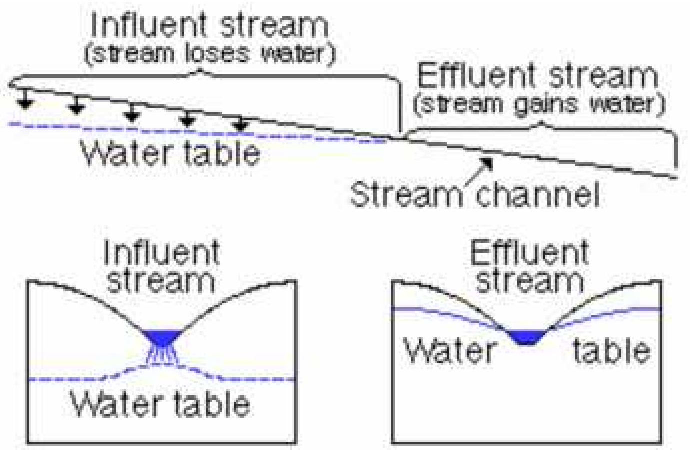


Figure 5.4. Influent and Effluent streams.

The water table is separating the zones of aeration and saturation. In order to actually get water out of the ground, it is necessary to penetrate *below* the water table. This sometimes occurs where the topography dips down deep enough (i.e., below the water table) resulting in natural **springs**. However, most of the time if you want to access groundwater, you have to dig down to it (e.g., dig a well). Groundwater will rise up to the level of the water table in the well because it leaks in laterally from the pores. This is the basic working process of all shallow wells. Any subsurface rock unit that is capable of producing water is called an **aquifer**. An **unconfined aquifer** is open to direct infiltration from rainwater. The filling of an aquifer is technically called **recharge.** Unconfined aquifers are usually close to the surface of the Earth but there are deeper aquifers that might lie underneath non-porous intervals (also called **aquicludes**). Unlike unconfined aquifers which need to have the water physically pumped to the surface, confined aquifers are commonly pressurized; water flows on its own up to the surface. These free-flowing wells are called **artesian wells** and along with springs, are important sources of water even in the driest desserts. Artesian wells are pressurized because of topographic differences between the area where recharge is occurring (conveniently called the **recharge area**) and the location of the well. If the recharge area is at a higher topographic area (e.g., mountains) than the well site (e.g., a valley), water will feel the pressure difference and attempt to flow up to the equivalent level of the water table (se diagram below). This pressure gradient is called the **hydraulic head** (or just **head** for short). Hydrologists and hydrogeologists have formulated an important mathematical relationship that determines the rate of water discharge from wells given the hydraulic head and lateral distance between the recharge and discharge points of a groundwater loop. It’s called *Darcy’s Law*.

The groundwater can flow laterally within the zone of saturation if the water table is inclined (i.e., not horizontal). Simply put, groundwater flows from areas where the water table is high (high head) to areas where it is low (low head). The rate of movement is rather slow, commonly less than a few meters a day. In contrast, even slow moving rivers flow a few meters a second. Once again, it is the job of hydrologists and hydrogeologists to model how, where and how fast groundwater flows. This is an important job because of the rate of groundwater flow and water recharge are both normally much, much, much lower that the rate of water extraction. Or to put it bluntly, we suck water out of the ground a lot faster than it flows back into the ground. This is why the water table is locally depressed in the immediate vicinity of the water well (**cone of depression**). This is normal and in most cases, not a problem. But if water pumping is too extensive, the water table can drop below the bottom level of the well making it *go dry*. If water is being pumped from a lot of separate wells, the combine cones of depression can locally drop the water table over a much large area. This is a major issue; without a supply of water, cities can not function.

5.5. Geological mapping

What *is* a map?

- ► A generalized view of an area, usually some portion of Earth's surface, as seen from above at a greatly reduced size
- ► Any geographical image of the environment
- ► A two-dimensional representation of the spatial distribution of selected phenomena

Why make maps?

- ► To represent a larger area than we can see
- ► To show a phenomenon or process we can't see with our eyes
- ► To present information concisely
- ► To show spatial relationships

Type of Maps

Contour maps: Maps that represent surfaces in terms of a series of curves. An individual curve represents a part of the surface along which the surface "value" is constant.

Given a data set (x, y, z), one can prepare a contour map of z (e.g., concentration of contamination in ground water) vs. (x, y)

Topographic contour map: contour lines represent points of equal elevation of the ground surface.

1 Streams flow downhill (contours vee upstream)

2 Contours for a ridge "point" down the ridge

Structure contour map: contour lines represent points of equal elevation along a geologic surface (e.g., the top of a geologic unit) that commonly is buried. If the values of a structure contour map are subtracted from the values on a corresponding topographic map, the difference gives the depth from the ground surface to the top of the geologic unit.

Isopach contour map: contour lines represent points of equal thickness of the geologic unit

Scale of Maps

- The scale of geological map is highly variable from very small-scale maps of entire continents or even planet to very large-scale geologic maps that show fine details of a particular locality, perhaps one of special scientific or commercial interest.

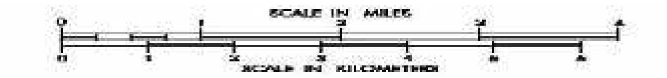
- Scale is most usually specified as a ratio, for example 1 :100, 000, where one unit on the map represents 100,000 of the same units on the ground. Thus one centimeter on a map at this particular scale would be equivalent to 100,000 centimeters, that is, 1000 meters or 1 kilometer.

Examples of the kinds of scales typically used for maps

No.	**Scale**	**Use**
1	1:10, 000, 000 and smaller	Maps of entire continent, oceans, or planets on a single sheets
2	1:5, 000, 000, 1:2,000,000 and 1:1,000,000	Synoptic views continents or countries, sometimes on several sheets
3	1:500,000	Maps of countries, provinces, states (depending on size); little detail but of use for general planning and overviews
4	1:250,000	For Regional geological mapping coverage of different sheets; in Ethiopia there are 81 sheets (1°30’long.x1°lat. quadrangles). Usually have topographic base map*
5	1:50,000, 1:25,000 and thereabouts	The standard scales for reasonably detailed published geological maps of well-investigated areas
6	1:10,000 and larger	Larger scale maps or plans of sites of scientific or commercial interest; mines, quarries, etc.

Type of scale representations:-

1. Graphic:
   - Stays the same when photocopied
   - Might not be right for the whole map



2. Verbal:

1 inch equals 10 miles

- ► Easy to understand
- ► Can change if photocopied

3. Representative fraction or ratio:

   1:24,000

- ► Units don't matter
- ► Can change if photocopied

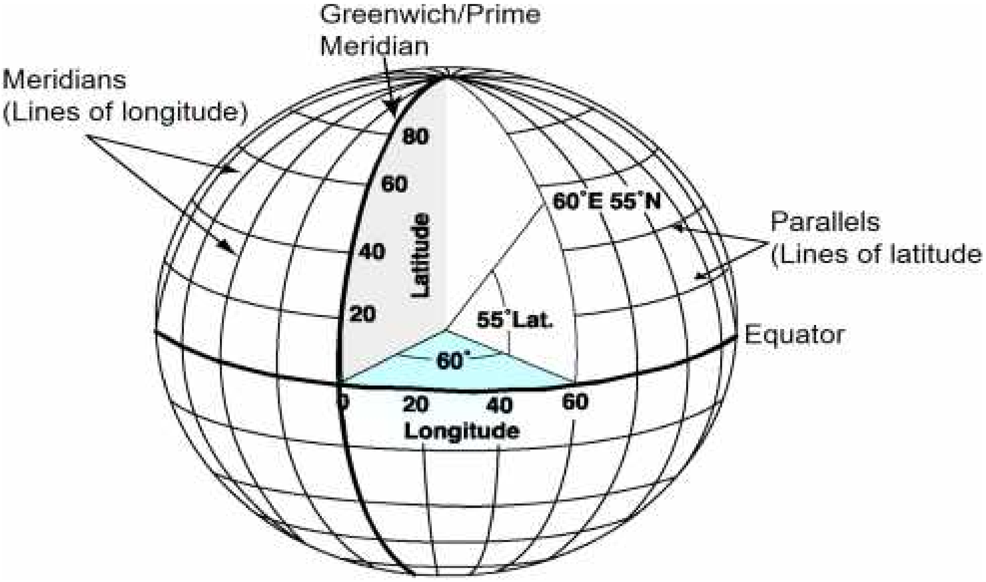
Map Projections

1. Location (Geospatial) Component:

The location can be in one of the following formats:

- ▪ Latitude & longitude (geographic coordinate system)
- ▪ X, Y (projected coordinate system like UTM)

Spherical coordinate system
(Geographic Coordinate System)



The Universal Transverse Mercator (UTM) system:

- Intended for mapping areas : 84^0N – 80^0S
- Unit of measure is meter
- The world is divided into 60 zones of 6^0 of longitude in width (next slide)
- Zone 1 starts at 180^0 W and Each zone has its own coordinate system

- A second zoning is made along the latitudes following 8^0 intervals (except the northern most zone-12^0)- they are given letters from C, D, E,
- The easting of the origin of each zone is assigned a value of 500,000
- The northing: for the Southern hemisphere the equator is assigned a northing value of 10,000,000 m, while for the Northern hemisphere it is 0
- The UTM might use one of the following spheroid: International, Clarke 1880 (Africa), Clarke 1866 (N. America), Everest or Bessel (Asia)
- When there is a map that covers more than one UTM zone, the zone that occupies the major part of the map (the middle zone) is used, extending the borders of the zone over the $+3^0$ and -3^0 boundaries.

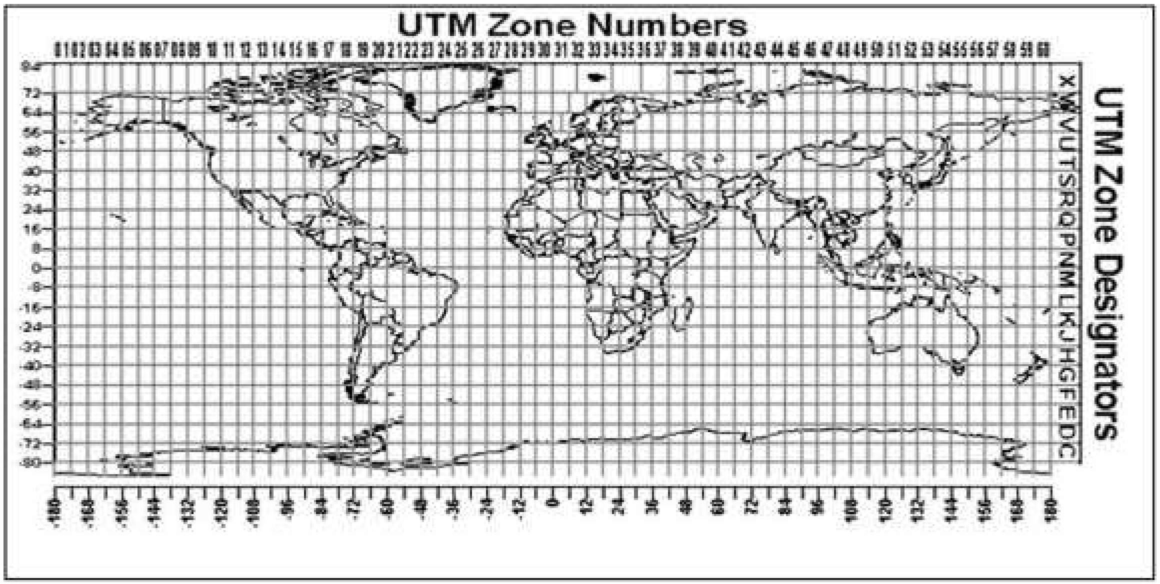


Figure 5.5. UTM zones of the world.

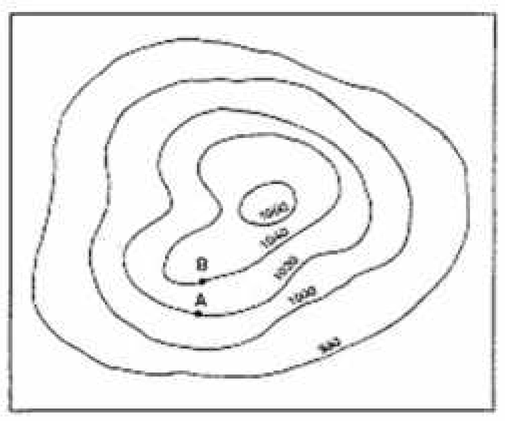
Topographic map

- A topographic map shows the shape of the land using contour line.
- A topographic map illustrates the topography, or the shape of the land, at the surface of the Earth. The topography is represented by **contour lines**, which are imaginary lines.
- It is a map that shows elevation, meaning how high and low the ground is in relation to sea level.

What are contour lines?

- Contour lines are lines that connect points that are of the same elevation.

- They show the exact elevation, the shape of the land, and the steepness of the land's slope.
- Contour lines never touch or cross.



What is a contour interval?

- Individual contour lines on a topographical map are a fixed interval of elevation apart known as a **contour interval**. Common contour intervals are 5, 10, 20, 40, 80, or 100 feet.
- A contour interval is the difference in elevation between two contour lines that are side by side.
- If the contour lines are close together, then that indicates that area has a steep slope.
- If the contour lines are far apart, then that indicates the land has a gentle slope (low slope).
- Contour lines form V's that point upstream when they cross a stream. It is important to remember that they point in the opposite direction as the flow of water.

What do the colors on the topographic map represent?

- Blue lines/shapes - represent water features, such as streams and lakes.
- Brown – contour lines
- Black – Roads, buildings, railroads, other man made objects.
- Green – Woodland areas
- Red - Highways

Reading a topographic map

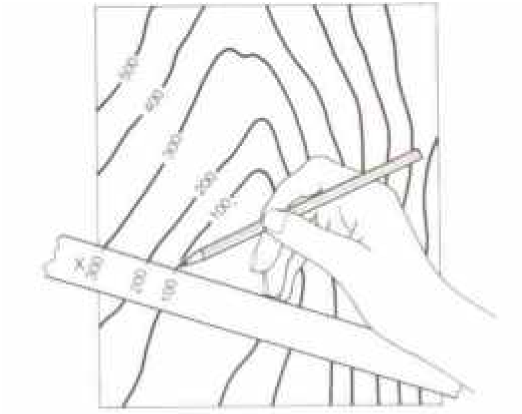
- First determine the contour interval (the distance between each contour line)

- Then determine the map scale (usually at the bottom of the map)
- Identify any hills or depressions
- Use the legend to identify man made features.
- Look for areas where the contour lines are close together – they indicate a steep area.
- Look for areas where the contour lines are spread apart – they indicate a gentle slope.

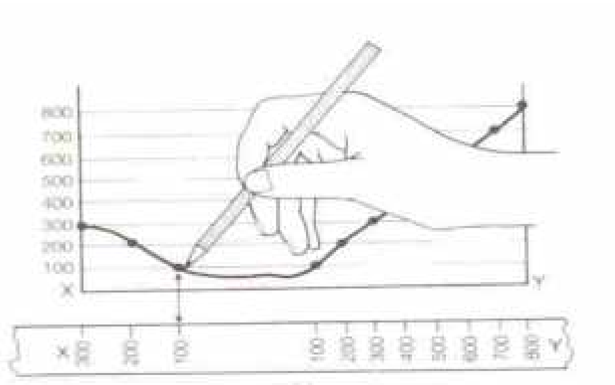
The 7 Rules of Contours

1) Contour lines NEVER split. Contour lines can never cross one another.
2) Contour lines NEVER cross, EXCEPT in the case of an overhanging cliff (very rare).
3) Contour lines form a "V" when they cross a stream or canyon, and the point of the "V" points to the higher ground. Therefore, a stream will flow opposite to the "V" points.
4) A bull's eye pattern of concentric circles indicates a hill or peak.
5) A bull's eye pattern of concentric circles with "tick marks" on the contour lines indicates a depression.
6) Spacing between contour lines indicates the slope: closely spaced = steep slope, widely spaced = gentle slope.
7) Contour lines always form closed loops, although many times the loops are closed somewhere off the map itself.

Instructions for drawing a topographic profile from a map



(a)



(b)

(a) 1. Lay a strip of paper along the line of section, in this example X-Y

2. Mark on the paper the position of intersection of each contour and label the altitude

(b) 3. Draw a grid of width X-Y, and height to correspond with the contour attitudes. Except in certain circumstances, use a vertical scale equal to the horizontal scale.

4. Place paper strip at base of grid to bring X-Y into register with the grid. Project the labeled contour intersections on the strip up to the appropriate altitudes.
5. Smoothly connect the projected points to form the topographic profile.

GEOLOGIC MAPPING

- Is the observation, study and investigations of natural materials, features, phenomena and processes in their natural setting.
- Involves surprises and complications, so it requires patience, keen interest, awareness, systematic analysis and decision.
- Generates essential information on the distribution, composition, structure, origin of lithologic units and their evolution in space & time.
- Is helpful in the development of natural resources, infrastructure, identification of natural hazards, planning land-use and environmental management

Why make geologic maps?

- Documentation of structural geometry (and sequence of events)
- To force us to look closely; maps act like a tool for observation
- Pattern recognition at a useful and appropriate scale._Many structures are too large or outcrop is too poor to see otherwise.
- To develop conceptual models for kinematic and mechanical reconstructions of how structures form
- To help define boundary conditions for mechanical models

Geologic maps

- Show the intersection (**trace**) of geologic features with the ground surface, a surface that is generally sub horizontal but irregular (i.e., with some limited 3-D relief).
- Are not top views of subsurface features as projected into a horizontal plane.
- The strike of a geologic surface is obtained by determining the azimuth between two points on the geologic surface that have the same elevation (i.e., that lie along the intersection of the geologic surface and a horizontal plane).
- A strike view cross section is taken perpendicular to the strike of a geologic body. It shows the true dip and true thickness of the body.
- The contacts of horizontal layers parallel elevations contours.
- The contacts of vertical geologic surfaces appear as straight lines on geologic maps with a topographic base.

Reading geologic maps

- Horizontal beds do not have a dip and therefore neither does they have a strike. The boundaries will follow topographic contours.
- The outcrop pattern of vertical beds will be unaffected by the topography and boundaries will cut straight across the landscape.
- For the majority of strata with dips intermediate between these two extremes, the topography will affect the outcrop pattern.
- Make sure that you take this into account when you are plotting boundaries or transferring them onto your final map.

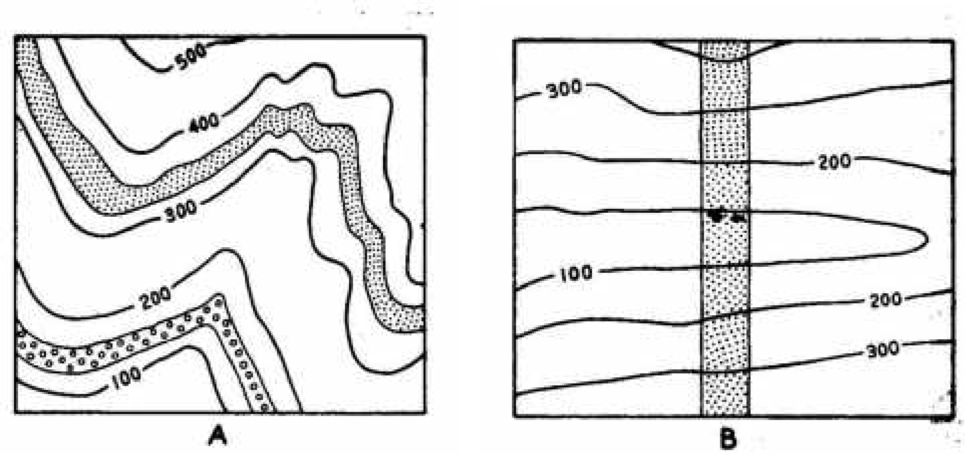


Figure 5.6. (A) Horizontal bedding and (B) Vertical bedding.

Attitude, Strike and Dip

The term **attitude** describes the orientation in space of rock strata, but it is not acceptable to simply conclude that beds are inclined. Geologists long ago came up with a means of orientating bedding that has been deformed. Two components are required in this scheme; (1) the direction of the inclination (**strike**) and (2) the amount of inclination (**dip**; Fig. 5.7). The strike is usually reported as a measurement of compass direction. Due north is considered to be 000°, due east is 090°, due south is 180 °, due west 270°, northwest 045° etc. The dip is reported as degrees measured downward from a horizontal plane. By convention, the dip of an inclined bed cannot exceed 90°. Beds with dips of 90° are said to be **vertical** (or to have a vertical attitude). Beds that have been overturned have technically been rotated more than 90°, but their dips are still reported as less than 90°. It is both desirable and necessary to show the orientation (strike and dip) of beds on geological maps and there are symbols that do this. Special symbols also indicate overturned bedding, vertical bedding and even horizontal bedding. The standard symbol for strike and dip is shown on Fig. 5.7 inset. The long axis gives the direction of strike and the short axis gives the direction of dip. The number refers to the amount of inclination (measured from the horizontal). If we assume that "up" is due north as it usually is, then the orientation of the strike of the bedding as indicated by the symbol is 045° or 225° (northeast-southwest) and the dip is 30° toward the southeast. By convention, most geologists specify only one strike direction (usually the smallest number). There are many ways by which to write the strike and dip, but the easiest is as follows:

30°, 135°

Which reads as 30° degree dip toward 135°.

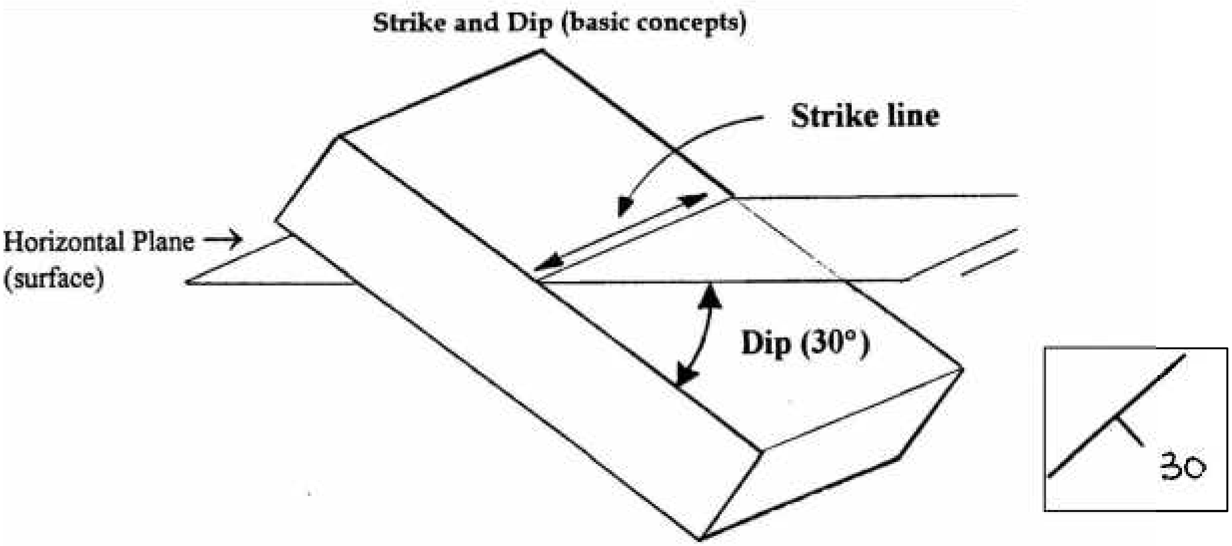


Figure 5.7. Schematic illustration of strike and dip using a single (idealistic) inclined bed. Inset shows standard symbol for strike and dip.

Describing lineations on outcrop:

- Identify the type of lineation: - intersection lineation, mineral lineation, stretching lineation and etc (refer to your lecture notes).
- Measure and record the orientation of linear structures. Linear structures are measured as plunge or as pitch (amount of plunge/trend of plunge or pitch) (Fig. 5.8)
- Classify the lineation on the basis of the amount of plunge (strike-slip, oblique-slip and dip-slip) (Fig. 5.9)
- Develop a sequence of lineations with subscripts indicating successive and related generations. Use subscripts to indicate sequence of Lineations (L_1, L_2, L_3….)

Figure 5.8. Recording the orientation of linear structures. Linear structures are measured as plunge (amount of plunge/trend of plunge)

Figure 5.9. (A) Strike-sip lineation (0-15î), (B) Oblique-slip lineation (15-45î), (C) Normal-slip lineation (>45î).

Geological Maps: Folded Strata

The three broad classes of folds are (1) **anticlines,** (2) **synclines** and (3) **monoclines**.
The term anticline is used for any fold structure consisting of two **limbs** spread apart in a downward fashion (concave downward; Fig. 5.10a). Synclines are bi-limbed folds where the limbs open upward (concave upward; Fig. 5.10b) Monoclines, as the name implies, have only one limb (Fig. 5.10c). The symmetry and orientation of these fold structures can be highly variable. They can be **symmetrical**, **asymmetrical** or **overturned** (Fig. 5.11). In some instances, anticlines and synclines may lie on their sides. These folds are said to be **recumbent**. They may also be inclined rather than horizontally orientated. This

class of folds are said to be **plunging** and they are among the most difficult of the geological structures to visualize and to interpret.

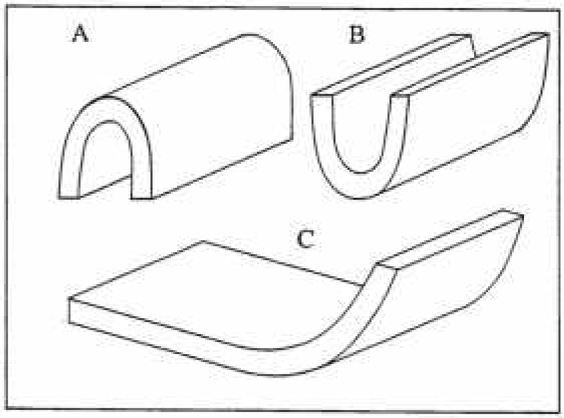


Figure 5.10. Schematic diagrams of ideal fold structures. (A) symmetrical anticline; (B) symmetrical syncline; (C) monocline.

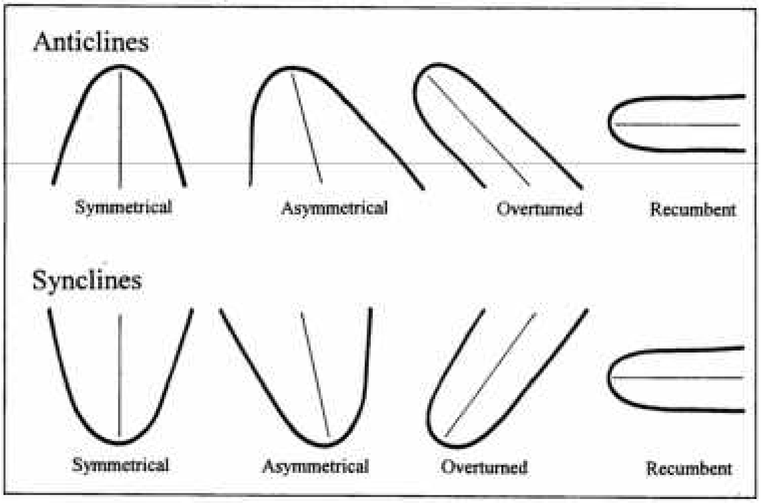


Figure 5.11. Schematic diagrams of symmetrical, asymmetrical, overturned and recumbent anticlines and synclines.

Two other fold structures are **domes** and **basins**. These geological features are perhaps best described as doubly folded folds. Domes consist of strata that have been folded upwards where as basins consist of strata that is inclined downwards (down-warped). Domes can be very large; in fact whole mountain ranges may consist of a single dome structure. Basins are formed through a much different mechanism more related to sedimentation than to simple rock deformation. Down-warping is produced by **subsidence** which may or may not be tectonic in origin. The main point is that down-warping produces a depression which gradually becomes filled in with sediment. The Law of Superposition applies here. The oldest strata occur at the bottom of the basin.

Folds are really not all that difficult to interpret, but some of the terminology is shown in Fig. 5.12.

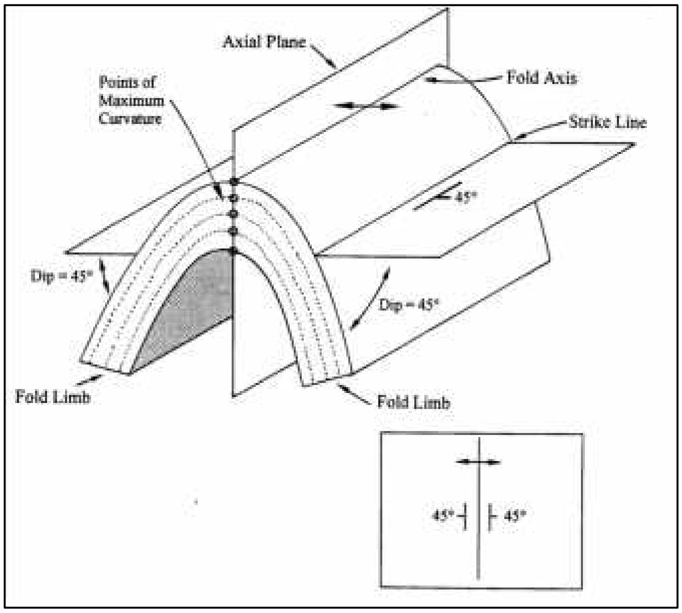


Figure 5.12. Oblique schematic of a horizontal symmetrical anticline with all important parts and features labeled. Refer your lecture notes for discussion of each of these features. The inset summarizes a plane-section (map view) of the anticline. Note the orientation of the strike and dip symbols for each fold limb relative to the fold axis.

Data to be collected on the mapping of the folded strata includes:

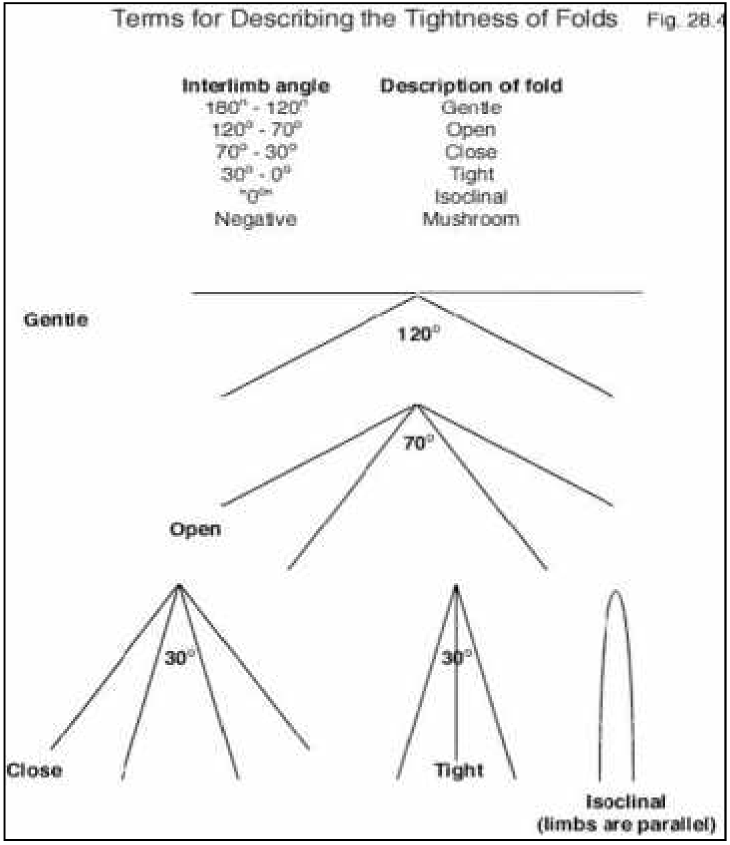
1. **The attitude of a fold**

   Record the attitude of it's:
   - Axial plane (strike, dip)
   - Hingeline (trend, plunge)

Folds are classified based on the relative values of the dip of the axial plane, and the plunge of the hingeline as follows:

- **Vertical fold:** vertical axial plane and vertical axis
- **Upright plunging:** vertical axial plane, plunging axis
- **Upright horizontal:** vertical axial plane, horizontal axis
- **Inclined plunging**: inclined axial plane, plunging axis
- **Inclined horizontal:** inclined axial plane, horizontal axis
- **Reclined:** plunging axis trends along the dip of the inclined axial plane
- **Recumbent fold**: horizontal axis and axial plane

2. **Tightness of a fold**

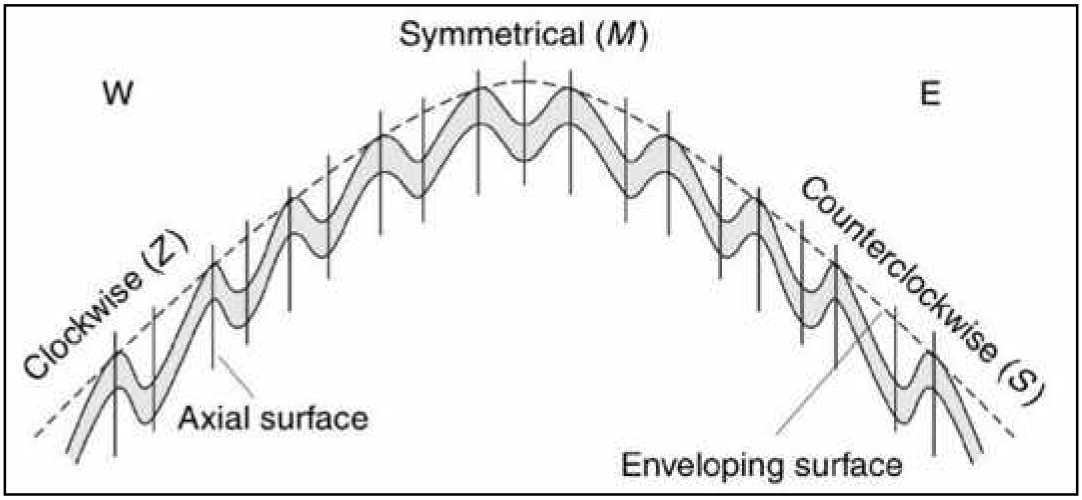


Terms for Describing the Tightness of Folds Fig. 28.4

Interlimb angle	Description of fold
180° - 120°	Gentle
120° - 70°	Open
70° - 30°	Close
30° - 0°	Tight
"0°"	Isoclinal
Negative	Mushroom

3. **Asymmetry and vergence of the fold**

Vergence of asymmetric folds is defined as the horizontal direction of movement of the upper component of a fold (measured in the profile plane) by considering the relative lengths and attitudes of the long-short-long limbs of folds. Always analyze folds in profile section; looking down the plunge of the fold axis.



Geological Maps: Faulted Strata

A **fault** can be defined as *any brittle deformation-induced fracture where there has been movement of the blocks on either side of the plane defining the fault* (the **fault plane**). Fault nomenclature can be rather cumbersome. The fault plane is the actual surface where the strata has been broken (Fig. 5.13). The **fault line** is the line made by the intersection of the fault plane and the surface of the Earth (Fig. 5.13). The **fault blocks** are the strata on either side of the fault plane and the **fault scarp** is the cliff formed on the "uplifted" fault block where the fault plane rises above the surface of the Earth (Fig. 5.13). Faults are among the most studied of the geological features on the planet because they are where earthquakes occur.

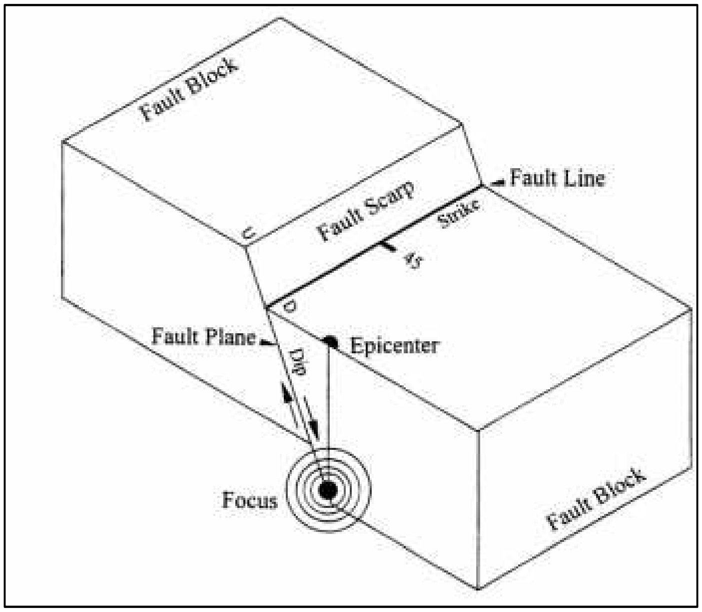


Figure 5.13. Schematic diagram illustrating key components of fault-systems. The fault illustrated is of a normal dip-slip variety.

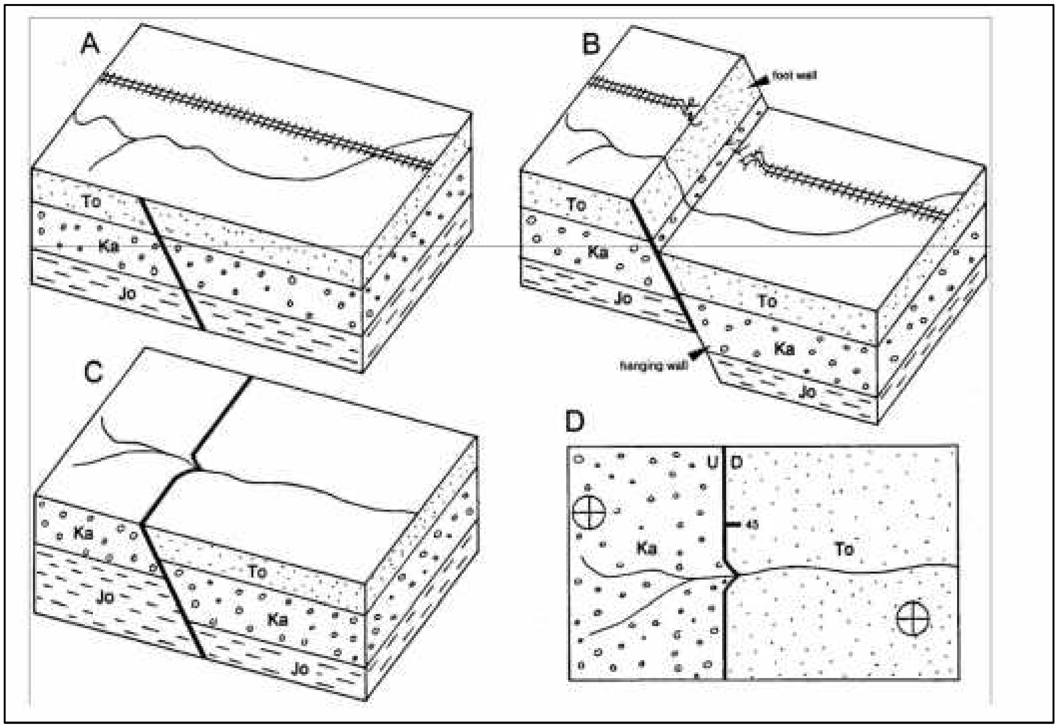


Figure 5.14. Perspective diagrams of a normal fault produced following release of tensile stress. The pre-faulting situation is illustrated in (A). Note that the underlying strata are horizontally bedded and obeys the Law of Superposition. After slippage, one fault block moves *downward* relative to the other resulting in a stretching of the strata (B). The relative position of the hanging wall and footwall is also indicated on the diagram. Erosion tends to remove strata from the topographically higher fault block (C). Notice the "V" produced where the stream crosses the fault plane. A geological map showing all necessary symbols is illustrated in (D). U and D refer to relative up and down motion of the fault blocks.

Data to be collected from observations on Faults include:

1. Nature and orientation of fault plane (strike and dip)
2. Orientation of displaced units on both sides of fault
3. Lineations on fault plane: grooving, slickenside, and etc.

JOINTS: Data to be collected

- Strike and dip. Or strike of linear features from aerial photos and Landsat images. Studies of joint and fracture orientation from LANDSAT and other satellite imagery and photographs have a variety of structural, geomorphic, and engineering applications
- Width of the joint block and space
- Identify the joints are open or filled
- Establishing time relationships among joint systems

Data obtained from joints is plotted in rose diagram or equal area net. Equal area net for strike and dip and rose diagram for strike only.

A few criteria of establishing time relationships:

1. If joints beneath an unconformity have been opened up by weathering and filled by rocks above the unconformity, the joints are older than the overlying rocks.
2. Joints are older than dikes or veins that have utilized them for emplacement.
3. Short joints that abut against longer joints are probably the younger ones.