Geologic Structure - A Primer

Geologists use terminology to confuse the layman and to enable them to amass a huge library of terms that are undeniably useless in most social situations. Luckily, our Geology classes and field trips are an exception. We will not try to bury you in a mountain (how about a deeply eroded mountain range?) of terms to help you understand the major types of structures and geologic features that you will read- and hear about today. But, if you are to understand what we are talking about, you need to know some important definitions. In the following section, we describe folds, faults, surfaces of unconformity, sedimentary structures, structures in sedimentary- vs. metamorphic rocks, and tectonostratigraphic units.

We begin with some concepts and definitions based on the engineering discipline known as **strength of materials**. Given today's sophisticated laboratory apparatus, it is possible to subject rocks to temperatures- and pressures comparable to those found deep inside the Earth.

Imagine taking a cylinder of rock out of the Earth and torturing it in a tri-axial compression machine to see what happens. Some geologists get a big charge out of this and tell us (the field geologists) that they really understand how rocks behave under stress. [CM thinks they need to perform these experiments over a longer time frame than a few generations of siblings will allow and thus relies more on field observation and inference than from rock-squeezing data to gain a feel for the complex nature of how rocks are deformed in nature.]

Despite the limitations of the experimental work, measurements in the laboratory on specimens being deformed provide some fundamental definitions. One key definition is the **elastic limit**, which is the point at which a test specimen no longer returns to its initial shape after the load has been released. Below the elastic limit, the change of shape and/or volume (which is known as **strain**) is proportional to the stress inside the specimen. Above the elastic limit, the specimen acquires some permanent strain. In other words, the specimen has "failed" internally. Irrecoverable strain manifests itself in the distortion of crystal lattices, grain-boundary adjustments between minerals composing the rock, and minute motions along cleavage- or twin planes.

When differential force is applied slowly (or, according to CM, over long periods of time), rocks fail by *flowing*. This condition is defined as behaving in a **ductile fashion** (toothpaste being squeezed out of a tube is an example of ductile behavior). Folds are the result of such behavior. If the force is applied under low confining pressure or is applied rapidly (high strain rates), rocks do not flow, but *fracture*. This kind of failure is referred to as rocks behaving in a **brittle fashion** (as in peanut brittle). The result is faults or joints. Once a brittle failure (fracture) has begun, it will propagate and may produce offset thus forming a fault surface. Joint surfaces commonly exhibit distinctive "feathers" which show the direction of joint propagation.

In some cases, during deformation, rocks not only undergo simple strain, but also recrystallize. New metamorphic minerals form and newly formed metamorphic minerals acquire a parallel arrangement. More on metamorphic textures later. From the laboratory studies of rock deformation, a few simple relationships are generally agreed upon regarding brittle- and ductile faulting and these are discussed below.

When subjected to differential forces, under high confining pressures and elevated temperatures, rocks (like humans) begin to behave foolishly, squirming in many directions and upsetting the original orientation of primary- or secondary **planar- and linear features** within them. Geologists try to sort out the effects of deformation by working out the order in which these surfaces or linear features formed using a relative nomenclature based on four letters of the alphabet: D, F, S, and M. Episodes of deformation are abbreviated by (D_n), of folding by (F_n), of the origin of surfaces (such as bedding or foliation) by (S_n), and of metamorphism by (M_n), where n is a whole number starting with 1 (or in some cases, with zero). Bedding is commonly designated as S_0 (or surface number zero) as it is commonly overprinted by S_1 (the first foliation). To use this relative nomenclature to describe the structural history of an area, for example, one might write: "During the second deformation (D_2), F_2 folds formed; under progressive M_1 metamorphic conditions, an axial-planar S_2 foliation developed."

In dealing with the geologic structures in sedimentary rocks, the first surface one tries to identify positively is **bedding** or **stratification**. The boundaries of strata mark original sub-horizontal surfaces imparted to sediments in the earliest stage of the formation of sedimentary rock. Imagine how such strata, buried by the weight of overlying strata and laterally compressed by the advance of lithospheric plates, are subjected to the differential force necessary for folds to form. Contrary to older ideas, we now realize that vertical burial cannot cause regional folds (although small-scale slumping, stratal disharmony, and clastic dikes are possible). Rather, resolved tangential force that creates differential stress must be applied to provide the driving force to bring about folds and faults.

It's now time to turn to some geometric aspects of the features formed as a result of deformation of rocks in the Earth. We start with folds.

Folds

If layers are folded into convex-upward forms we call them **anticlines**. Convex-downward fold forms are called **synclines**. In Figure 1, note the geometric relationship of anticlines and synclines. **Axial planes** (or **axial surfaces**) physically divide folds in half. Note that in Figure 1, the fold is deformed about a vertical axial surface and is cylindrical about a linear **fold axis** that lies within the axial surface. The locus of points connected through the domain of maximum curvature of the bedding (or any other folded surface of the fold) is known as the **hinge line** (which is parallel to the fold axis). This is geometry folks; we have to keep it simple so geologists can understand it.

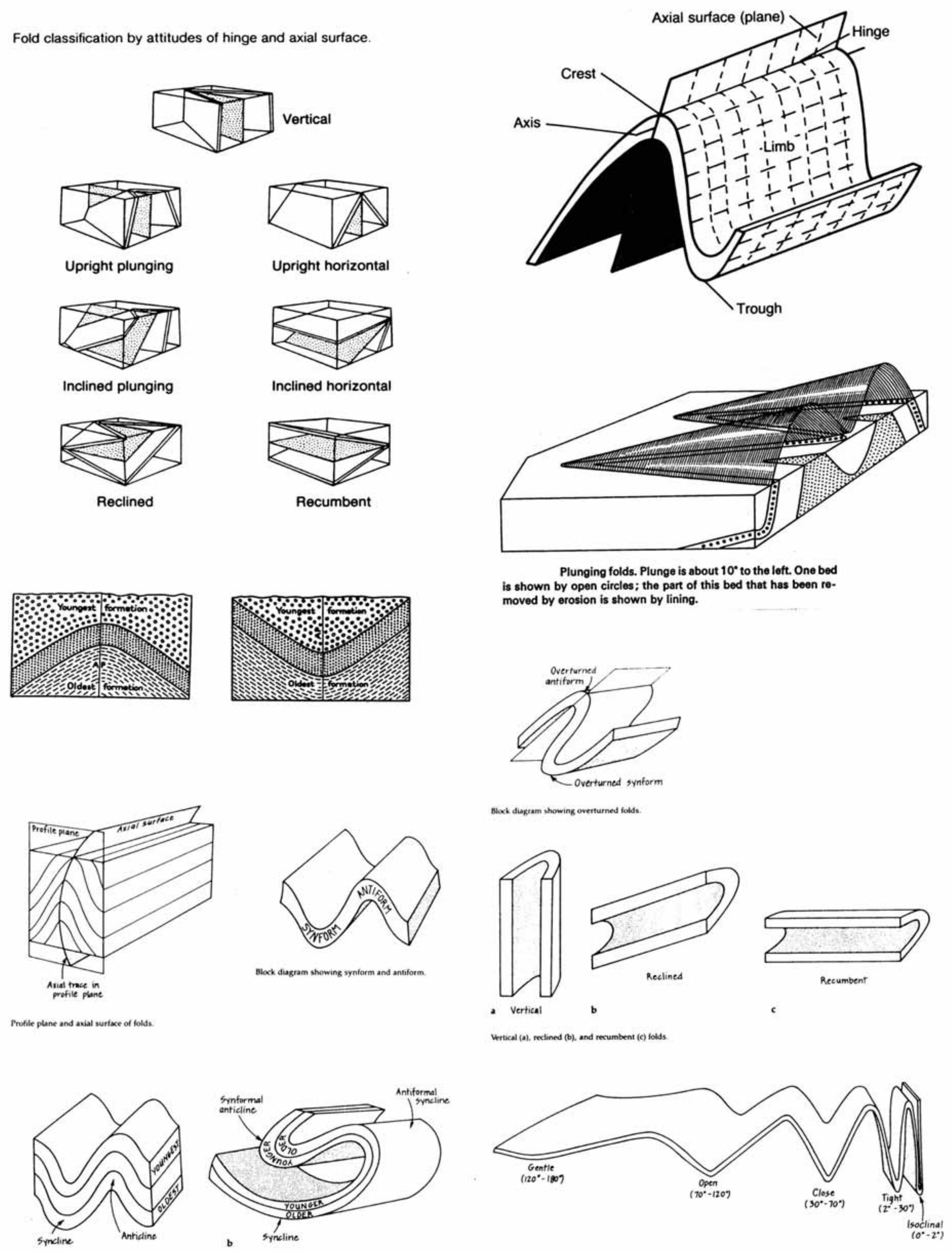

Figure 1 - Composite diagram from introductory texts showing various fold styles and nomenclature as discussed in the primer text.

In eroded anticlines, strata forming the limbs of the fold *dip away from* the central hinge area or core (axis) of the structure. In synclines, the layers forming the limbs *dip toward the hinge area*. Given these arrangements, we expect that in the arches of eroded anticlines, older stratigraphic layers will peek through whereas in the eroded troughs of synclines, younger strata will be preserved.

In metamorphic terranes, field geologists are not always sure of the correct age relationships of the metamorphosed strata. Therefore, it is helpful to make use of the general terms **antiform** and **synform** which describe the folds by whether they are convex upward (antiform) or concave upward (synform) but do not imply anything about the relative ages of the strata within them.

Realize that in the upright folds shown in Figure 1, axial surfaces are vertical and fold axes, horizontal. Keep in mind that folding under metamorphic conditions commonly produces a penetrative mineral fabric with neocrystallized minerals (typically micas and amphiboles) aligned parallel to the axial surfaces of folds. Such penetrative metamorphic fabrics are called **foliation**, if primary, and **schistosity**, if secondary. Minerals can also become aligned in a linear fashion producing a **metamorphic lineation**. Such features can be useful in interpreting a unique direction of tectonic transport or flow direction. Because folds in metamorphic rocks are commonly **tight-** to **isoclinal** (high amplitude-to-wavelength aspect ratio) with limbs generally parallel to axial surfaces, a penetrative foliation produced during regional dynamothermal metamorphism will generally be parallel to the re-oriented remnants of stratification (except of course in the hinge areas of folds). Thus, in highly deformed terranes, a composite foliation + remnant compositional layering is commonly observed in the field. Departures from this common norm are important to identify as they tend to mark regional fold-hinge areas.

Folds could care less about the orientation of their axes or axial surfaces and you can certainly imagine that axial surfaces can be tilted, to form inclined or **overturned folds**. Or the axial surfaces may be sub-horizontal, in which case the term **recumbent fold** is used. In both overturned and recumbent folds, the fold axes may remain subhorizontal. (See Figure 1.) It is also possible for an axial surface to be vertical but for the orientation of the fold axis to range from horizontal to some angle other than 0° (thus to acquire a plunge and to produce a **plunging fold**). Possible configurations include plunging anticlines (or -antiforms) or plunging synclines (or -synforms). **Vertical folds** (plunging 90°) are also known; in them, the terms anticline and syncline are not meaningful. In **reclined folds**, quite common in ductile shear zones, the fold axes plunge directly down the dip of the axial surface.

In complexly deformed mountain ranges, most terranes show the superposed effects of more than one set of folds and faults. As a result of multiple episodes of deformation, the ultimate configuration of folds can be quite complex (i. e., plunging folds with inclined axial surfaces and overturned limbs).

We need to mention one additional point about the alphabet soup of structural geology. Seen in cross section, folds fall into one of three groups, the S's, the M's, and the Z's. Looking down plunge in the hinge area of a northward-plunging anticlinal fold, for example, dextral shearing generates asymmetric Z folds on the western limb and sinistral shearing forms S folds on the eastern limb. Usually only one variety of small, asymmetric folds will be found on a given limb of a larger fold. Therefore, if one notices a change in the pattern from S folds to Z folds (or vice versa), one should be on the lookout for a fold axis. The hinge area is dominated by M folds (no sense of asymmetry).

One final note on folding -- it is generally agreed, in geologically simple areas, that axial surfaces form perpendicular to the last forces that ultimately produced the fold. Therefore, the orientation of fold elements give some hint as to the direction of application of the active forces (often a regional indicator of relative plate convergence). In complex regions, the final regional orientation of the structures is a composite result of many protracted pulses of deformation, each with its unique geometric attributes. In these instances, simple analysis is often not possible. Rather, a range of possible explanations for a given structural event is commonly presented.

Faults

A **fault** is defined as *a fracture along which the opposite sides have been displaced*. The surface of displacement is known as the fault plane (or fault surface). The enormous forces released during earthquakes produce shiny surfaces along the fault surface called **slickensides** as well as elongate gouges within the fault surface called **slickenlines.** These possess asymmetric linear ridges that enable one to determine the relative motion between the moving sides (Figure 2, inset). The block situated below the fault plane is called the **footwall block** and the block situated above the fault plane, the **hanging-wall block**. Extensional force causes the hanging-wall block to slide **down** the fault plane producing a **normal fault**. [See Figure 2 (a).] Compressive forces drive the hanging-wall block **up** the fault plane to make a **reverse fault**. A reverse fault with a low angle (<30°) is called a **thrust fault**. [See Figure 2 (b).] In all of these cases, the slickenlines on the fault will be oriented more or less down the dip of the fault plane and the relationship between the tiny "risers" that are perpendicular to the striae make it possible to determine the relative sense of motion along the fault. Experimental- and field evidence indicate that the asymmetry of slickenlines is not always an ironclad indicator of relative fault motion. As such, displaced geological marker beds or veins are necessary to verify relative offset. Fault motion up- or down the dip (as in normal faults, reverse faults, or thrusts faults) is named **dip-slip motion**.

Rather than simply extending or compressing a rock, imagine that the block of rock is sheared along its sides (*i. e*., that is, one attempts to rotate the block about a vertical axis but does not allow the block to rotate). This situation is referred to as a shearing couple and could generate a **strike-slip fault**. [See Figure 2 (c).] On a strike-slip-fault plane, slickenlines are oriented subhorizontally and again may provide information as to which direction the blocks athwart the fault surface moved.

Two basic kinds of shearing couples and/or strike-slip motion are possible: **left lateral** and **right lateral**. These are defined as follows. Imagine yourself standing on one of the fault blocks and looking across the fault plane to the other block. If the block across the fault from you appears to have moved to the left, the fault is **left lateral** [illustrated in Figure 2 (c)].

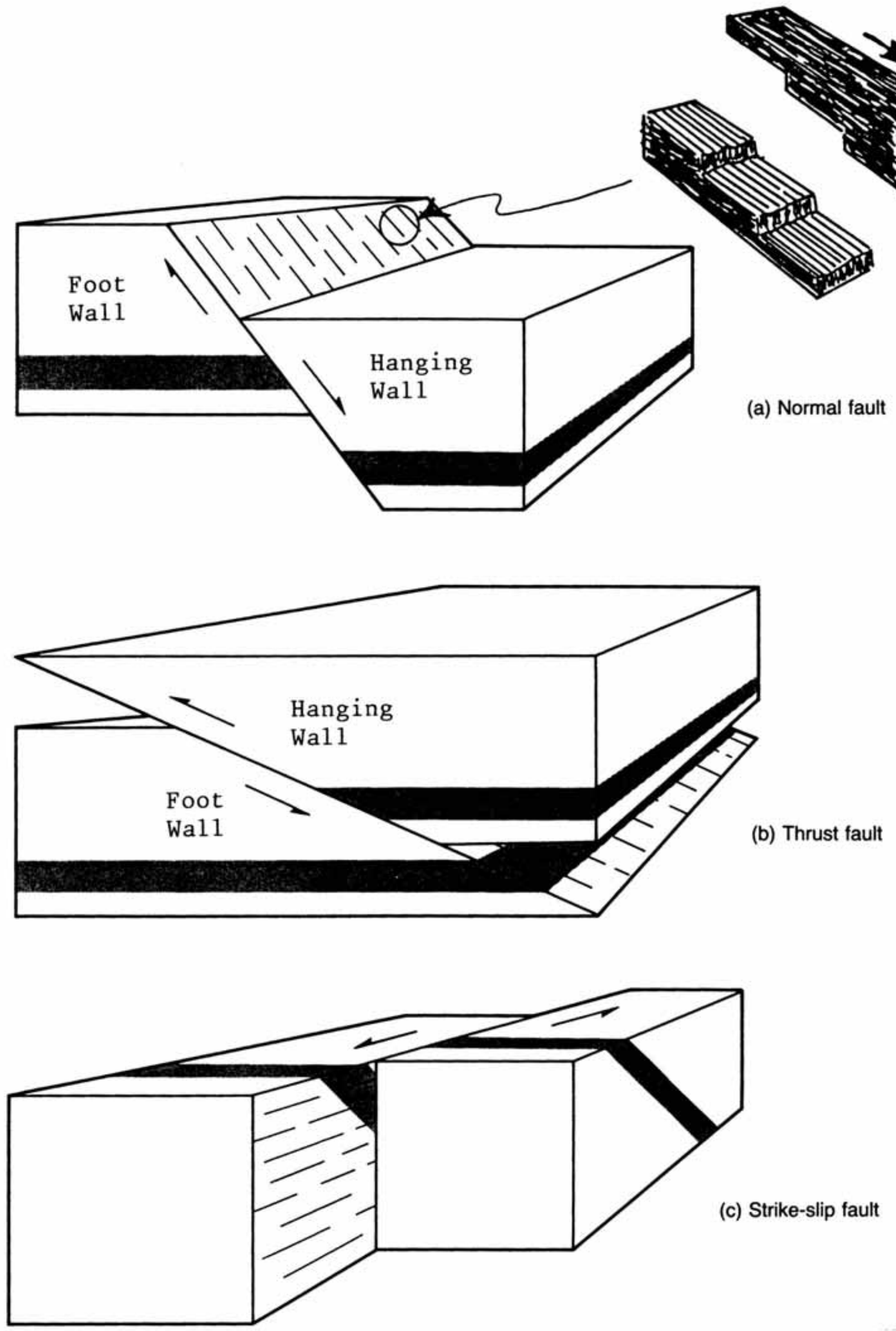

Figure 2 - The three main types of faults shown in schematic blocks. Along a normal fault (a) the hanging-wall block has moved relatively downward. On a thrust fault (or reverse fault) (b) the hanging-wall block has moved relatively upward. Along a strike-slip fault (c), the vertical reference layer (black) has been offset by horizontal movement (left-lateral offset shown here). Inset at upper right shows segments of two blocks along a slickensided surface that display slickenlines (the linear gouges characterized by jagged "risers" (stairsteps) formed as pull-apart tension fractures which can be used to infer sense of relative motion. [Adapted from Sanders (1981), fig. 16.11 (b), p. 397.]

If the block across the fault appears to have moved to the right, the motion is **right lateral**. Convince yourself that no matter from which block you can choose to observe the fault you will get the same result! Naturally, complex faults show movements that can show components of dip-slip- and strike-slip motion, rotation about axes perpendicular to the fault plane, or reactivation in a number of contrasting directions or variety. This, however, is no fault of ours.

Tensional- or compressional faulting resulting from brittle deformation, at crustal levels above 10 to 15 km, is accompanied by seismicity and the development of highly crushed and granulated rocks called **fault breccias** and **cataclasites** (including fault gouge, fault breccia, and others). Figure 3 lists brittle- and ductile fault terminology as adapted from Sibson (1977) and Hull et al. (1986). Beginning at roughly 10 to 15 km and continuing downward, rocks under stress behave aseismically and relieve strain by recrystallizing during flow. These unique metamorphic conditions prompt the development of highly strained (ribboned) quartz, feldspar porphyroclasts (augen), and frayed micas, among other changes, and results in highly laminated rocks called **mylonites** (Figure 3).

The identification of such ductile fault rocks in complexly deformed terranes can be accomplished only by detailed mapping of metamorphic lithologies and establishing their geometric relationship to suspected mylonite zones. Unfortunately, continued deformation under load often causes early formed mylonites to recrystallize and thus to produce annealed mylonitic textures (Merguerian, 1988), which can easily be "missed" in the field without careful microscopic analysis. Cameron's Line, a recrystallized ductile shear zone showing post-tectonic brittle reactivation, is an original ductile fault zone (mylonite) having a complex geologic history.

Over the years, field geologists have noted special geologic features associated with thrust faults. Because they propagate at low angles with respect to bedding, thrusts commonly duplicate strata. In addition, thrust faults can displace strata for great distances and wind up transporting rock deposited in one environment above rocks originally deposited in markedly disparate environments. In such cases, we call the displaced strata of the upper plate above a thrust fault an **allochthon** or describe an entire displaced sequence of strata as an **allochthonous terrane** (see Tectonostratigraphic Units below). In other words, *allochthonous rocks were not originally deposited where they are now found*. By contrast, regions consisting of rock sequences that were originally deposited where they are now found constitute an **autochthon** or **autochthonous terrane**.

Interesting geometric patterns result from the erosion of overthrust sheets of strata that have been folded after they were overthrust. When the upper plate (allochthon) has a "hole" eroded through it, we can peer downward through the allochthon and see the autochthon exposed in a **window**, **inlier**, or **fenster** surrounded by the trace of the thrust fault that was responsible for the dislocation (Figure 4). By contrast, if most of the upper plate has been eroded, only a remnant **outlier** or **klippe** may remain. (See Figure 4.) Both klippen and windows produce similar map-scale outcrop patterns. The difference is that the thrust surface typically dips *toward* the center of a klippe (a remnant of the allochthon) and *away from* the center of window (which shows a part of the underlying autochthon).

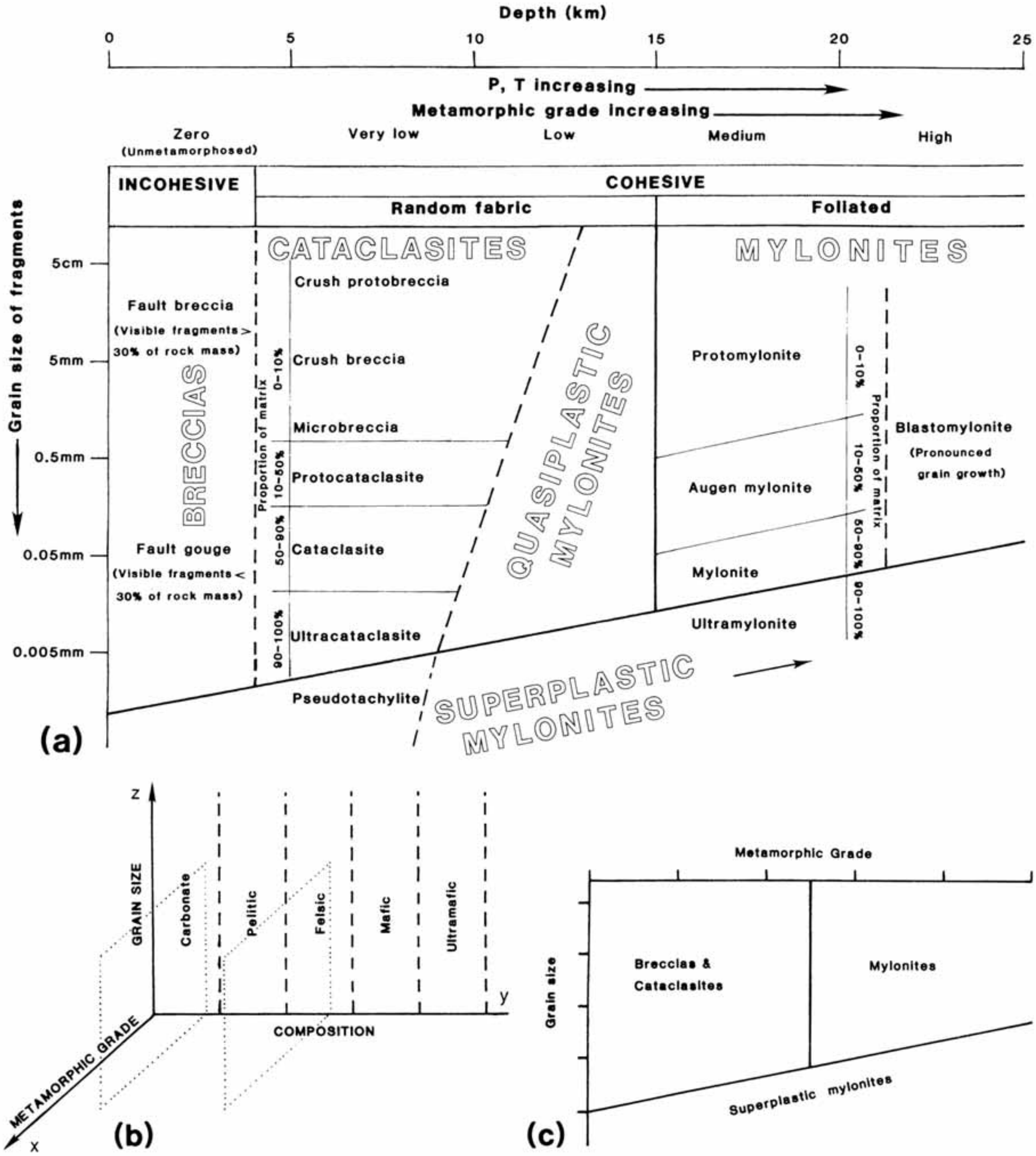

Figure 3 - Fault-rock terminology. (a) Classification of fault rocks that have been derived from quartzo-feldspathic lithologies (e. g. granite) (adapted from Sibson, 1977); (b) the grain size - metamorphic grade - lithologic composition grid used for classifying fault rocks (after Hull et al., 1986); (c) fault-rock diagram for marl showing expanded mylonite and superplastic mylonite fields as compared to those shown on the diagram for granite in (a) (from Marshak and Mitra [1988]).

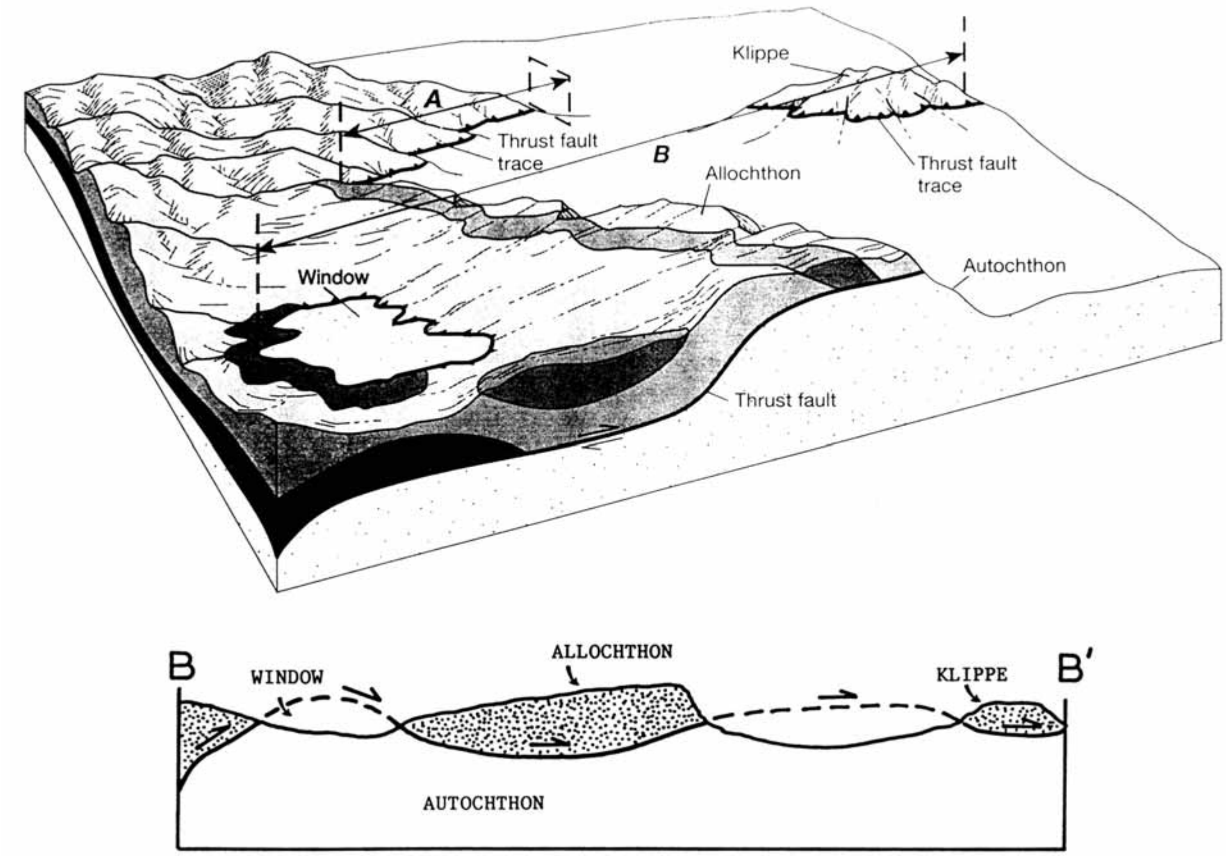

Figure 4 - Block diagram illustrating the relationships between allochthons, autochthons, klippen, and windows. (Twiss and Moores, 1992, p. 99) with section B-B' drawn by CM.

Bedding-plane thrusts are more-localized features but are geometrically the same as thrust faults in that they involve layer-parallel shortening of strata and produce low-angle imbrication of strata. They can easily be "missed" in the field but result in overthickening of strata and can produce anomalous stratigraphic thickness in sedimentary units. The field geologist can identify them by careful bed-by-bed examination of known sequences based on duplication of key- or marker beds and by identification of highly veined dislocation surfaces.

During episodes of mountain building associated with continuous subduction and/or collisions near continental margins, thrusting is typically directed from the ocean toward the continent. Accordingly, one of the large-scale effects of such periods of great overthrusting is to impose an anomalous load on the lithosphere that causes it to subside and form a **foreland basin**. These basins receive tremendous quantities of sediment that fill the basin with debris derived from erosion of uplifted areas within the active collision zone. In the late stages of convergence, forces transmitted from the collision zone into the developing foreland basin create a diachronous secondary stage of folding and continent-directed overthrusting of the strata filling the foreland basin. Thus, a thrust may override debris eroded from it.

Surfaces of Unconformity

Surfaces of unconformity mark temporal gaps in the geologic record and commonly result from periods of uplift and erosion. Such uplift and erosion is commonly caused during the terminal phase of regional mountain-building episodes. As correctly interpreted by James Hutton at the now-famous surface of unconformity exposed in the cliff face of the River Jed (Figure 5), such surfaces represent mysterious intervals of geologic time where the local evidence contains no clues as to what went on there. By looking elsewhere, the effects of a surface of unconformity of regional extent can be recognized and piecemeal explanations of evidence for filling in the missing interval may be found.

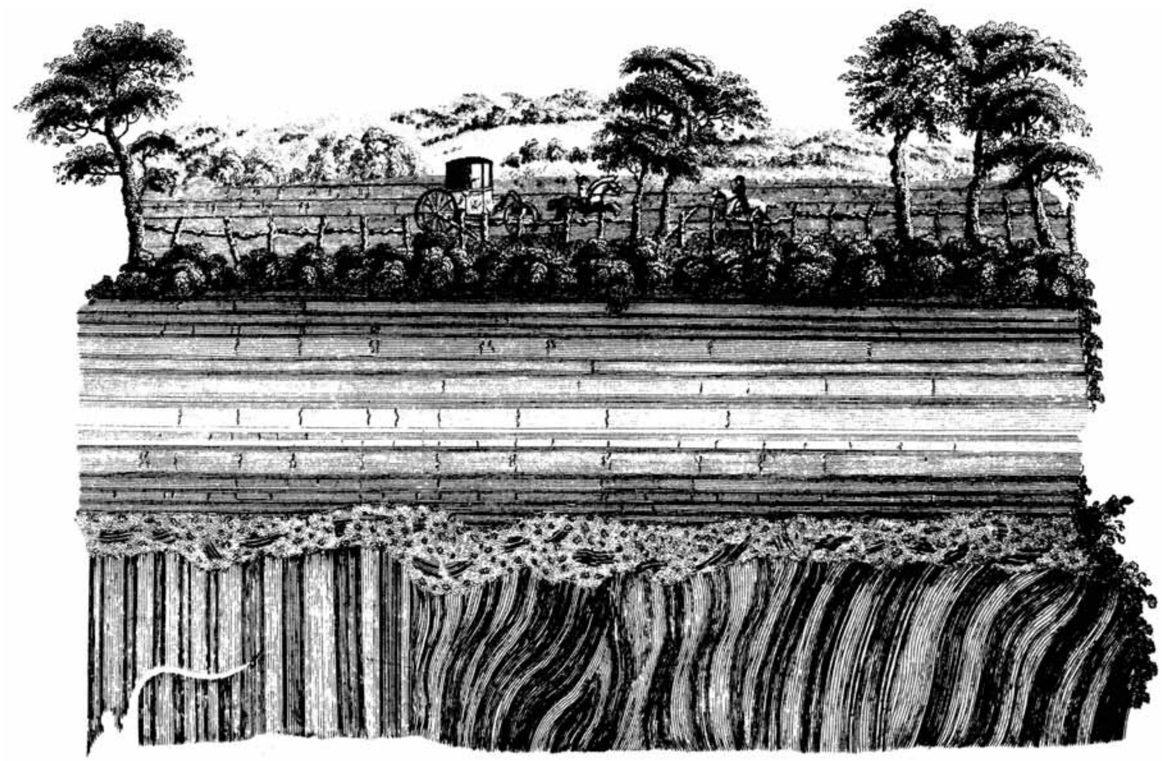

Figure 5 - Unconformity with basal conglomerate along the River Jed, south of Edinburgh, Scotland. From James Hutton's "Theory of the Earth", (1795).

Unconformities occur in three basic erosional varieties - angular unconformities, nonconformities, and disconformities (Figure 6). Angular unconformities (such as the River Jed) truncate dipping strata below the surface of unconformity and thus exhibit angular discordance at the erosion surface. Nonconformities separate sedimentary strata above the erosion surface from eroded igneous- or metamorphic rocks below. Disconformities are the most-subtle variety, separating subparallel sedimentary strata. They are commonly identified by paleontologic means, by the presence of channels cut into the underlying strata, or by clasts of the underlying strata in their basal part. The strata above a surface of unconformity may or may not include clasts of the underlying strata in the form of a coarse-grained, often bouldery basal facies.

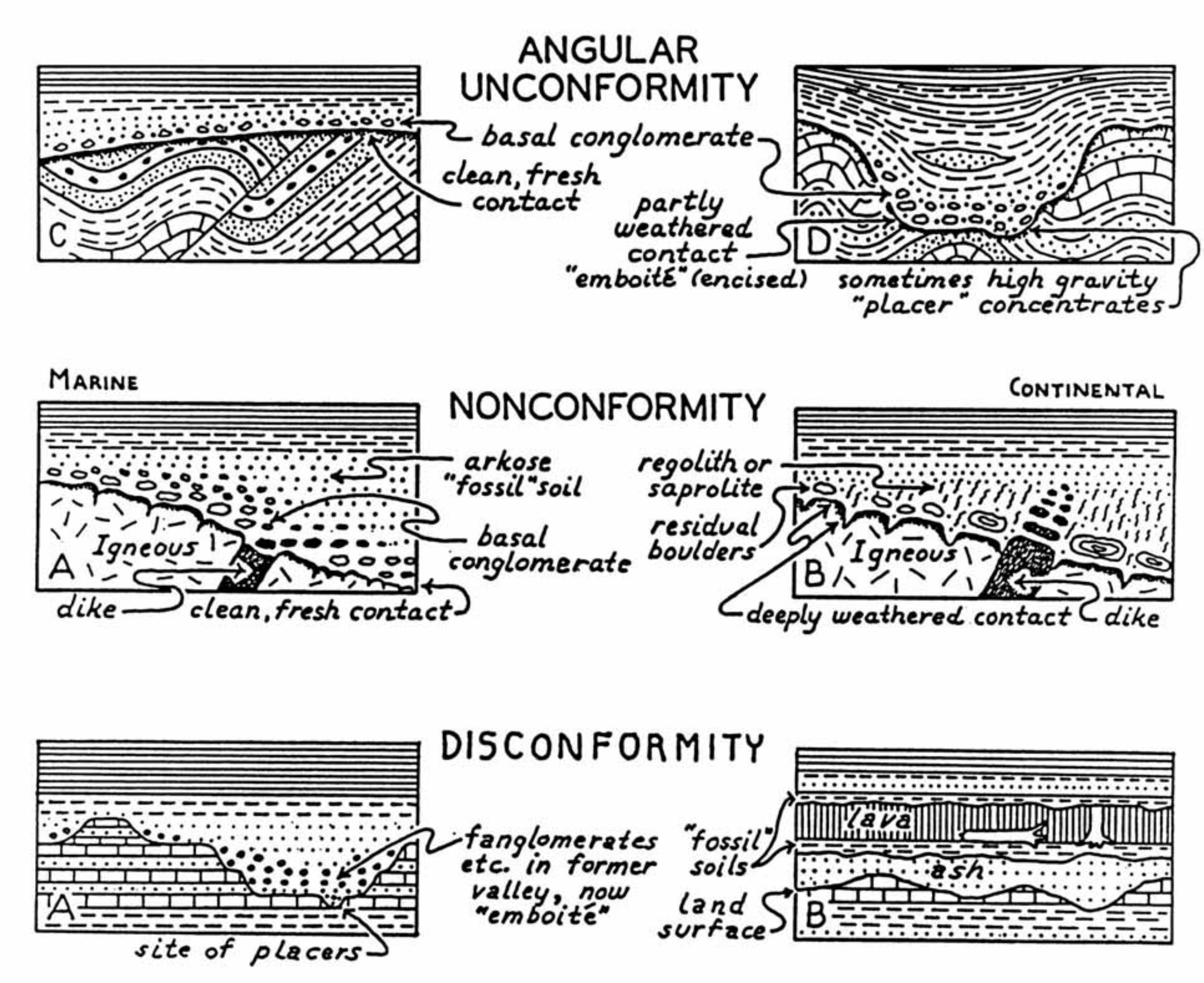

Figure 6 - Various types of unconformities, or gaps in the geologic record. Drawings by Rhodes W. Fairbridge.

Following the proposal made in 1963 by L. L. Sloss, surfaces of unconformity of regional extent within a craton are used as boundaries to define **Stratigraphic Sequences**.

Sedimentary Structures

During deposition in a variety of environments, primary- and secondary sedimentary structures can develop above-, below-, and within strata. During normal deposition, or settling from a fluid in a rainfall of particles, massive, essentially poorly stratified successions may result. The presence of **strata** implies a change in deposition and as a result most geologists appreciate the significance of layering in sedimentary rocks as marking **CHANGE** in big letters, be it a change in parent area of the sediment, particle size, or style of deposition. Thus, **bedding** can best be viewed as marking the presence of mini-surfaces of unconformity (diastems). During high-energy transport of particles, features such as **cross beds, hummocky strata,**

asymmetric current ripple marks, or **graded beds** result. Cross- and hummocky bedding, and asymmetric current ripple marks are deposited by moving currents and help us unravel the paleocurrent directions during their formation. Graded beds result from a kind of a "lump-sum distribution" of a wide range of particles all at once (usually in a gravity-induced turbidity flow). Thus, graded beds show larger particle sizes at the base of a particular layer "grading" upward into finer particles.

Secondary sedimentary features are developed on already deposited strata and include **mud (or desiccation) cracks, rain- drop impressions, sole marks, load-flow structures, flame structures, and rip-up clasts**. The last three categorize effects produced by a moving body of sediment on strata already in place below. A composite diagram illustrating these common structures is reproduced in Figure 7.

Together, these primary- and secondary sedimentary structures help the soft-rock structural geologist unravel the oft-asked field questions - namely.... **Which way is up?** and **Which way to the package store?** The direction of younging of the strata seems obvious in horizontal- or gently tilted strata using Steno's principle of superposition. But steeply tilted-, vertical-, or overturned beds can be confidently unravelled and interpreted structurally only after the true topping (stratigraphic younging) direction has been determined. As we may be able to demonstrate on this field trip, simple observations allow the card-carrying geologist to know "Which way is up" at all times.

Structures in Sedimentary- vs. Metamorphic Rocks

For hard-rock geologists working in metamorphic terranes, simple sedimentary observations will not allow the card-carrying geologist to know "Which way is up" **at all**. Rather, because of intense transposition and flow during ductile deformation, stratification, fossils for age dating, tops and current-direction indicators are largely useless except to identify their hosts as sedimentary protoliths. Thus, according to CM, "*at the outcrop scale, metamorphism can best be viewed as the great homogenizer*." Commonly during metamorphism, the increase in temperature and -pressure and presence of chemically active fluids severely alter the mineral compositions and textures of pre-existing rocks. As a result, in many instances, typical soft-rock stratigraphic- and sedimentologic analysis of metamorphic rocks is not possible.

Tectonostratigraphic Units

In metamorphic terranes, **tectonostratigraphic units** can best be described as large-scale tracts of land underlain by bedrock with similar age range, protolith paleoenvironment, and structure. Such terranes are generally bounded by ductile-fault zones (mylonites), surfaces of unconformity, or brittle faults. Unravelling the collisional plate-tectonic history of mountain belts is greatly facilitated by identifying former cratonic (ancient crustal), continental-margin, continental-slope-, and rise, deep-oceanic, and volcanic-island tectonostratigraphic units. The major distinction in unravelling complexly deformed mountain belts is to identify former shallow-water shelf deposits (originally deposited on continental crust) and to separate them from deep-water oceanic deposits (originally deposited on oceanic crust). The collective adjectives *miogeosynclinal* (for the shallow-water shelf deposits) and *eugeosynclinal* (for the deep-water oceanic deposits) have been applied to the products of these contrasting depositional realms.

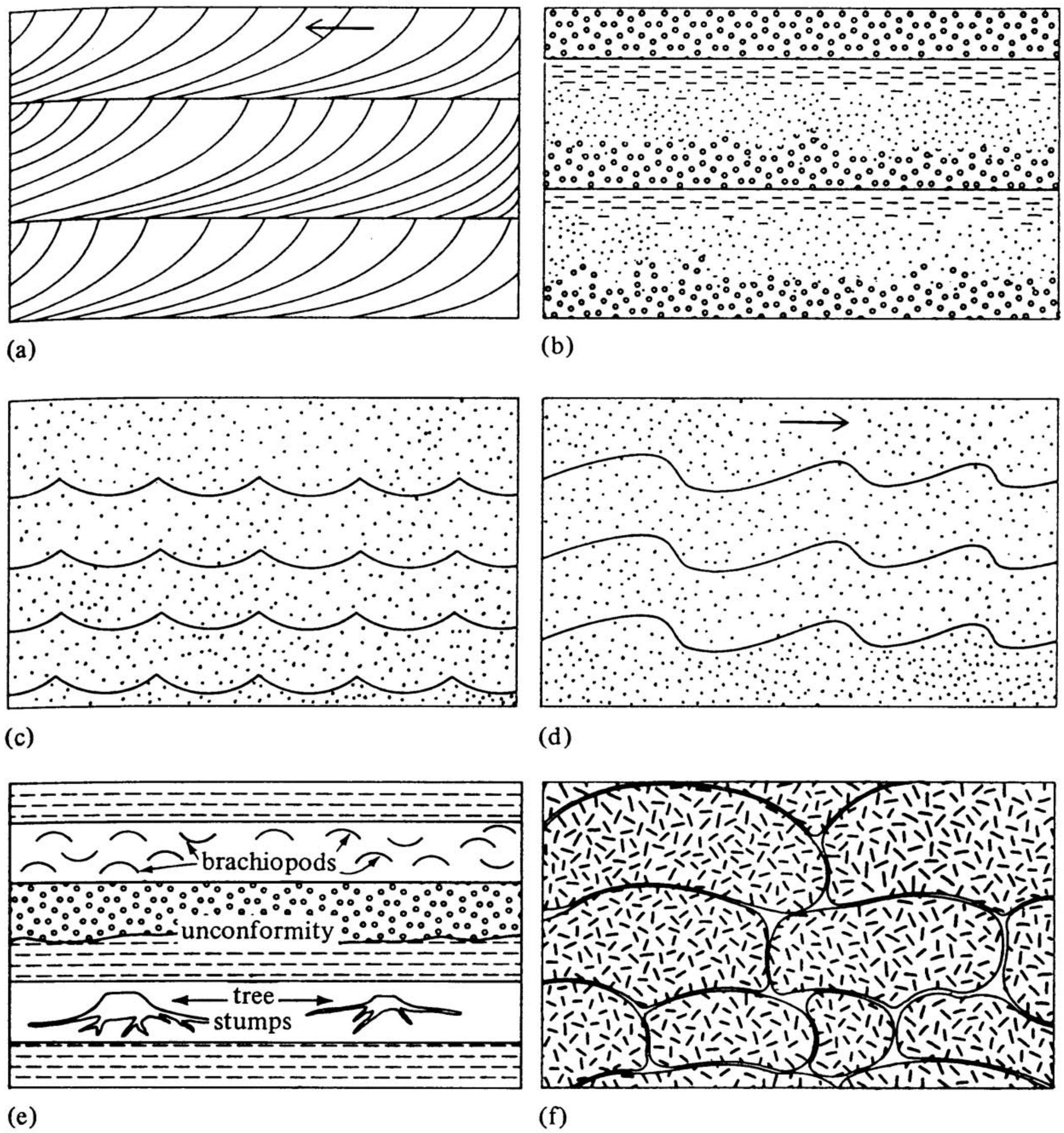

Figure 7 - Diagrammatic sketches of primary sedimentary structures (a through e) and cross sections of pillows (f) used in determining topping (younging) directions in rocks.

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