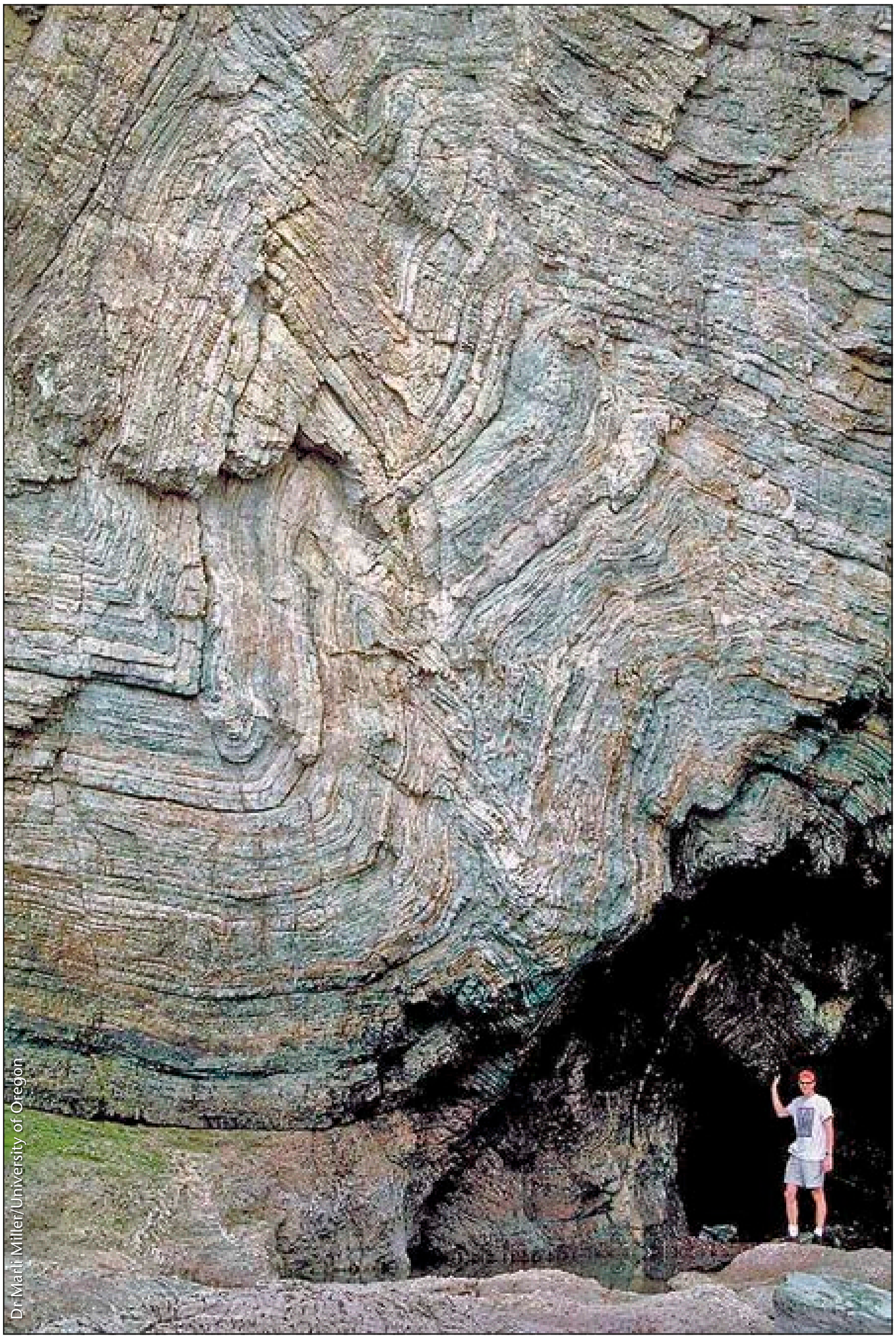
Folds and Folding Part I

Rock folds are found in various shapes and sizes on Earth, and people are often amazed to see how large blocks of hard rocks have been folded like ocean waves. But fascination with folds is also shared by the petroleum industry. In this two-part article we unfold rock 'folds' to better understand their geometry and genesis.

RASOUL SORKHABI, Ph.D.

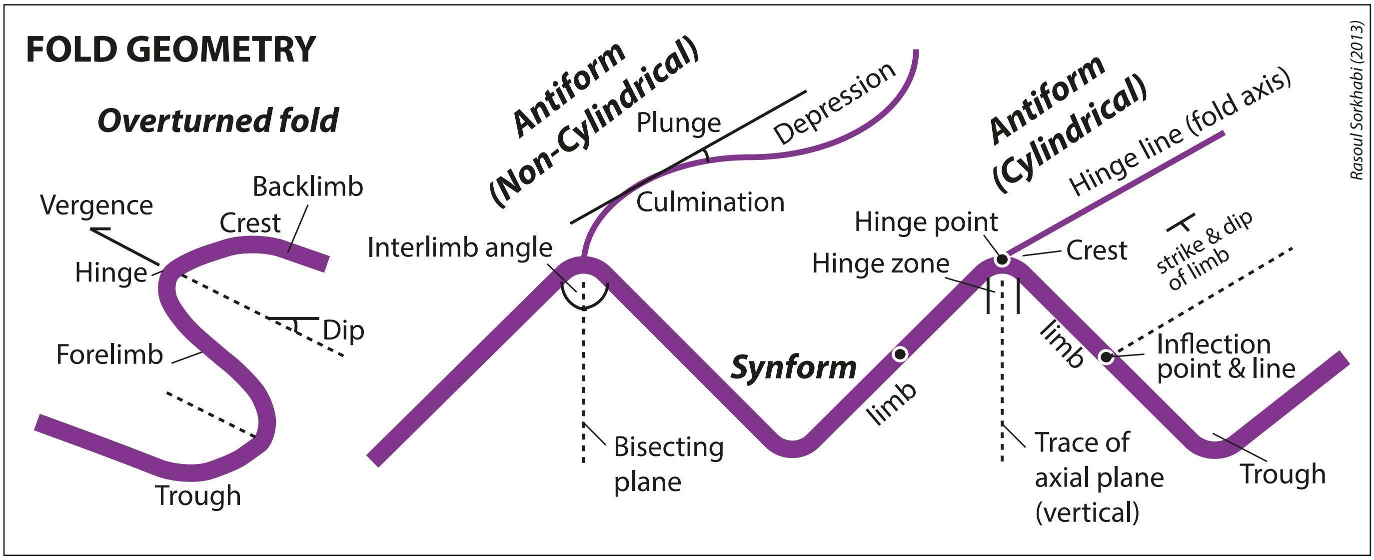
Chevron folds on Ribbon Chert (deepwater radiolarian chert, part of the Franciscan accretionary complex), Oregon



Dr. Mark Miller/University of Oregon

Folds, faults and joints are the main types of structural deformation in the Earth's crustal rocks. Of these, folds often create the most spectacular geological scenes. Petroleum exploration has historically been associated with folds more than with any other geological structure. In 1861, two years after Drake's successful discovery well in Pennsylvania, E.B. Andrews, a professor at Marietta College, Ohio published an article in the *American Journal of Science*, in which he observed: "I have recently found a most interesting line of uplift and dislocation… As seen in Ohio it presents a well-marked anticlinal axis but with the eastern slope more steep than the western. Near the anticlinal axis are the oil and gas springs." In the same year, T. Sterry Hunt of the Geological Survey of Canada also proposed that oil accumulations "occur along the line of a low broad anticlinal axis which runs nearly east and west through the western peninsula of Canada" (*Smithsonian Institute Annual Report,* 1861). Thus was born the 'anticlinal theory of oil accumulation.' The industry's fascination with folds still continues.

Fold structures are found in various shapes and sizes, and can be very complex. Nomenclature of folds can also be confusing. We can observe folds on rock samples (hand specimens), outcrops, seismic images, and on satellite and aerial photographs. Millimetre-scale folds can be observed in thin-sections. The complete picture of a fold structure may not be visible in an outcrop due to erosion or non-exposure. Therefore, to reconstruct and analyse fold structures



it is important to understand their basic elements – their anatomy.

Hinge and Limbs: Fold Geometry

For simplicity, let us consider a single fold. A fold is a rock structure in which two curved surfaces, or **limbs (flanks)**, are joined at a **hinge line** (or a **hinge point** on a 2D profile) or practically speaking a **hinge zone**. The hinge is the line of maximum curvature. The hinge line may be straight, in which case it forms a **cylindrical fold**, or it may have a **plunge** (vertical angle between the hinge line and intersecting horizontal line) which creates a **non-cylindrical fold**. According to the plunge of the hinge line, we classify folds as horizontal (negligible plunge up to 10°), plunging (10–80°) or vertical (80–90°).

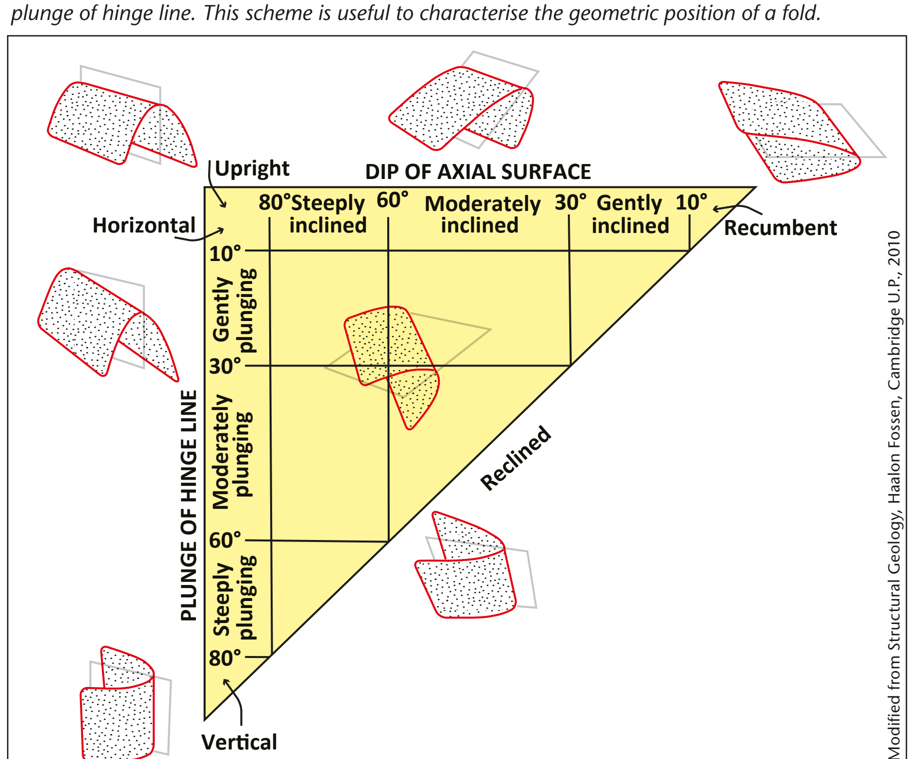
Large folds with long hinge lines undulating along the strike will have **culminations** and **depressions**. Folds plunge away from culminations and plunge toward depressions. A **doubly-plunging fold** is one in which the hinge line plunges in two opposite directions. Large doubly-plunging anticlines are especially important because they provide **four-way dip closures** for oil and gas accumulations.

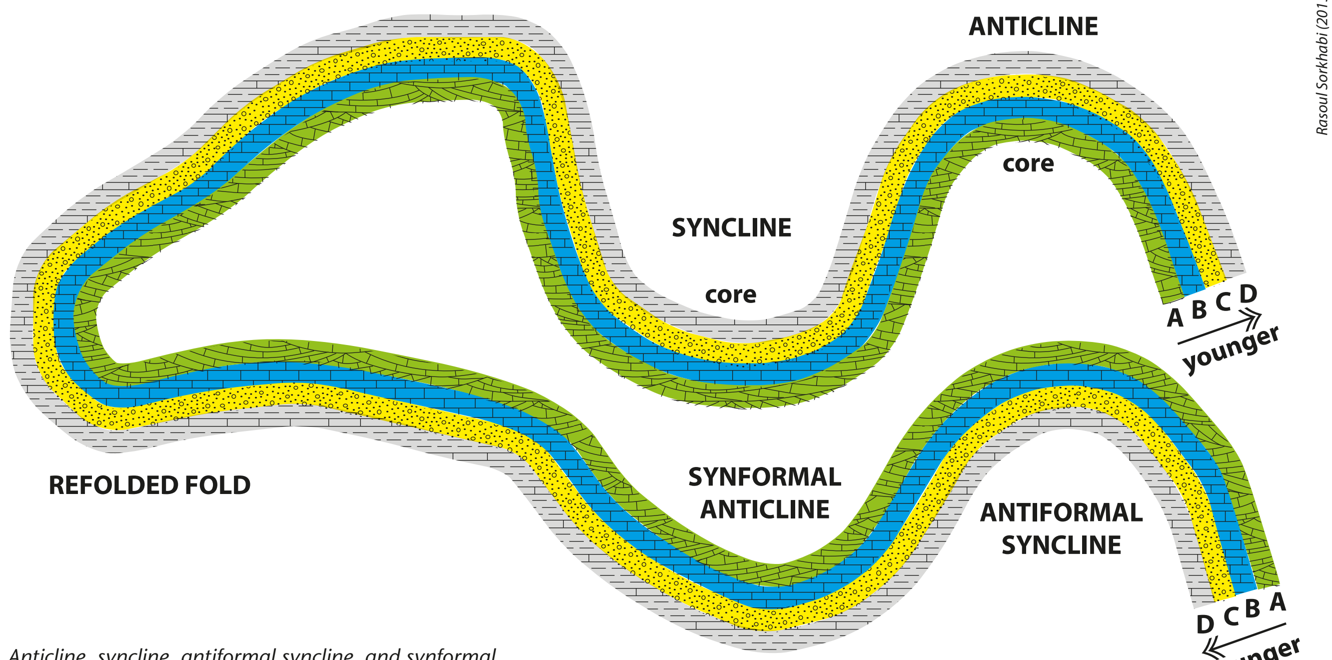
Horizontal and vertical folds have straight hinge lines which can be considered as **fold axis**. A fold axis is a geometric (imaginary) straight line which when moved parallel to itself through space generates the shape of the fold. Non-cylindrical folds (with curved hinge lines) do not have fold axes, and for the purpose of detailed structural analysis (for example, stereographic representation), it is necessary to subdivide them into several cylindrical folds, each with a relatively short, nearly straight hinge line.

For each rock layer in a folded structure we can represent a hinge. The **axial plane** connects all the hinge lines in a folded stack. The axial plane is also called **axial surface** because it may be a curved plane. In profile (cross-section) view, the trace of the axial surface of a fold passes through all the hinge points; such line is called the **axial trace** of the fold. The **attitude** (orientation) of an axial surface is measured by its strike and dip (inclination). According to axial plane dips, a fold may be **upright** (dips of 90–80°), **inclined** (80–10°) or **recumbent** (10–0°).

Vergence is the direction toward which the axial plane of fold has tilted. In other words, it is the sense (direction) of displacement of the upper limb relative to the lower limb of the fold. For example, a fold axial plane may have a strike of N 25° E and dip at angle of 30° SE, and thus a north-west vergence.

M.J. Fleuty (GSA Bulletin, 1964) has proposed a classification of folds based on dip of axial plane and plunge of hinge line. This scheme is useful to characterise the geometric position of a fold.





Anticline, syncline, antiformal syncline, and synformal anticline structures depicted on a refolded fold

An upright fold is also a **symmetric** fold; inclined folds are **asymmetric**. An **overturned** fold is an inclined (asymmetric) fold in which both limbs dip in the same direction but with different angles. In this case, the **backlimb** (the gentler limb) retains the normal stratigraphic position while the **forelimb** (the steep limb), that has rotated more than 90°, possesses overturned (reversed or inverted) stratigraphy. A recumbent fold, where the axial plane is in the 'lie-down' position, is an extreme case of an overturned fold. Highly overturned and recumbent folds of large dimensions are sometimes called **fold nappes** or nappe structures. They are found in collisional mountains like the Alps and the Himalayas. An **isoclinal** fold is one in which the two limbs have parallel dips irrespective of whether the axial plane is upright or inclined.

Anticlines, Synclines and Monoclines

A fold that is convex upward, that is the limbs dip down, is called **antiform**, while one that is concave upward, that is the limbs dip up, is **synform**. If we know the stratigraphy of the folded layers, then we can respectively use the terms anticlines and synclines. In an **anticline**, the rocks become older toward the core of the fold; in a **syncline** the rocks become younger. It is also possible for the fold to have the shape of an antiform but strata become younger toward the core; it is then called an **antiformal syncline**. Or the fold has the shape of a synform but strata become older toward the core; it is then called a **synformal anticline**. A fold that is neither antiform nor synform is called neutral fold. Examples include vertical plunging folds and recumbent folds.

Orogenic belts usually have regional anticlines and synclines. When the limbs of a major anticline are further folded into second-order and third-order anticlines (composite anticlines), it is called an **anticlinorium**. Similarly, when

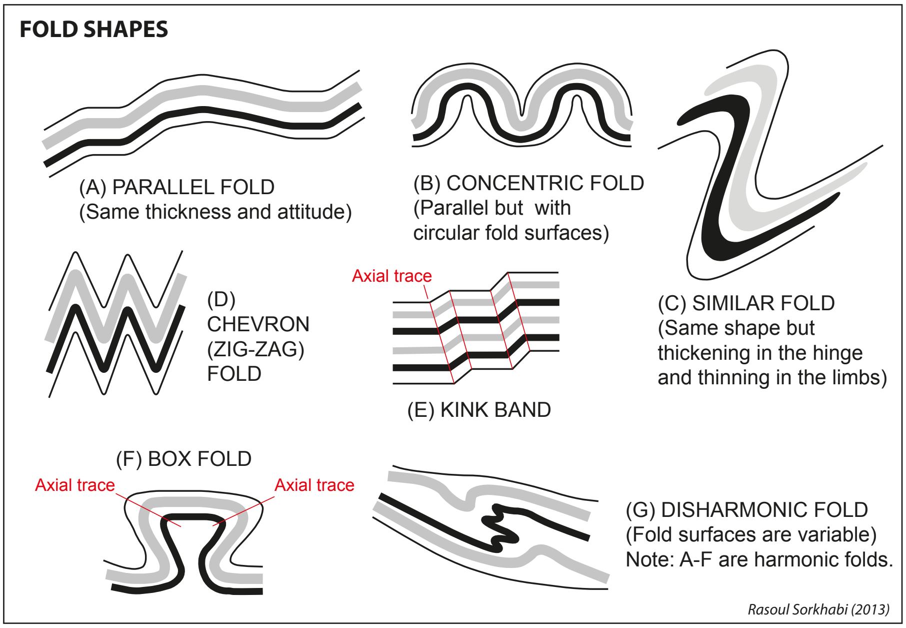
An anticlinal fold of Miocene sediments in Sarawak

the limbs of a major syncline are further folded into second-order and third-order synclines (composite synclines), it is called a **synclinorium**. The second, third and higher order folds are also called **parasitic folds** because they develop on the main, regional fold structures.

Folds have **crests** and **troughs**. In a symmetric (upright) fold, the crest corresponds to the hinge of the antiform, and the trough to the hinge of the synform. But in an asymmetric or overturned fold, the crest is the highest topographic part of the fold and the trough its lowest topographic part. Circular antiforms and synforms are sometimes called **domes** and **basins**, respectively.

A **monocline** is a local steepening of an otherwise horizontal sequence of strata. A monocline is thus a sub-cylindrical fold with only one inclined limb. **Homocline** ('same inclination') is a general term for any structures that have the same attitude (strike and dip), for example beds tilted in a parallel direction, one limb of an anticline or syncline, an isoclinal fold, or monoclines. ■

Part II to be continued



An anticline structure on Marble Cathedral in the General Carrera Lake in Patagonia, Chile.

Folds and Folding Part II

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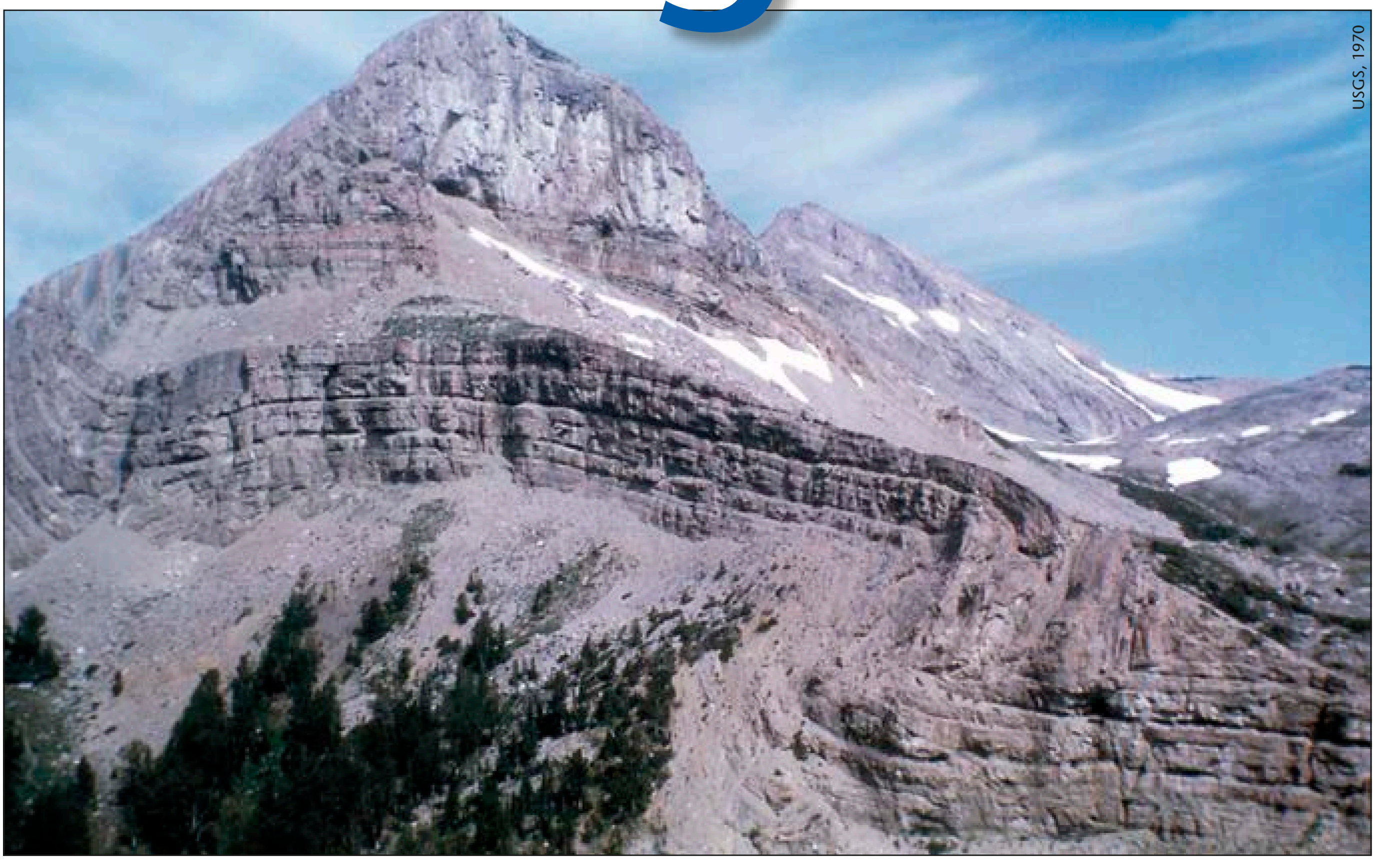
The Alps, the Himalayas and other similar high mountains on Earth owe their existence to a series of giant rock folds. But how do stiff, solid rocks fold?



Spectacular folding of Paleozoic carbonate strata in Scapegoat Mountain, Montana

In the nineteenth century, the predominant theory was that since its hot, molten formation, the Earth has been slowly cooling and thus shrinking and collapsing, like the skin of a drying apple, which produces mountain-building structures such as faults and folds. This theory has been refuted and is outdated. With the advent of the plate tectonic theory and structural geologic research grounded in field mapping, mathematical analysis, analog experiments and numerical simulations, we now have sophisticated and detailed explanations for rock folds. In Part I of this article (*GEO ExPro,* Vol. 10, No. 3), we looked at the geometry and shape of folds. Part II discusses folding processes in relation to their form and development.

Fold Dimensions

Rock folds come in various sizes, from micro-structure scale features observable on a thin-section of a rock sample to mountain-size folds. Nevertheless, folds in geology are what waves are in physics. Therefore, certain geometric measures can characterize rock folds, and these can be used to analyze them .

The size of a single fold is measured by its **height** (distance between crest and trough), **width** (distance between the inflection points bounding a fold), and **amplitude** (distance from crest to width, measured parallel to the axial plane). Another measure to note is **wavelength** or distance between two consecutive crests or troughs. The **aspect ratio** of a fold is the ratio of its amplitude to its width. Robert Twiss of University of California at Davis (*Journal of Structural Geology*, 1988, Vol. 10,) has suggested the following terms to describe a fold's aspect ratio: Wide (0.1 to <0.25); broad (0.25 to <0.63); equant (0.5 to 2.0); short (1.50 to <4); and tall (4 to <10).

Tightness of a fold is measured by its **interlimb angle** (the angle between the two limbs of a fold). In a classic paper published in 1964 (*Proceedings of the Geologists' Association*, Vol. 75) Michael Fleuty of Imperial College in London outlined several categories for fold tightness. The following is modified from his paper: Gentle (interlimb angle <180° to 170°), broad (170° to 120°), open (120 to 70°), closed (70° or 30), tight (<30° to 10°), and isoclinal (<10° and the limbs have the same dip).

In a stack of sedimentary layers, each individual layer may deform independently due to its own or surrounding rock properties. Therefore, changes in fold wavelength and amplitude among layers result in **disharmonic folds**. In a sedimentary stack where folds keep the same shape across the layers they are called **harmonic folds**.

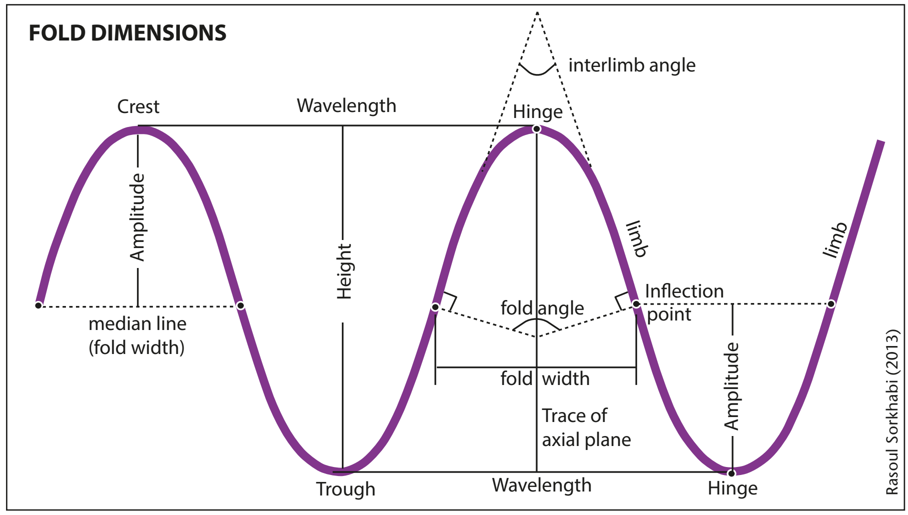
Fold is a kind of strain in the rock, and knowledge of the attitude and dimensions of folds helps us understand the direction and degree of stresses that has deformed the rock.

Bends, Buckles and Flows

Fred Donath and Ronald Parker in 1964 (*GSA Bulletin*, Vol. 75) presented a totally different classification of folds based on the mechanism of their formation, for which they considered the 'mean ductility' and 'ductility contrast' in the folded strata. On this basis, folds are categorized into **flexural folding** in which layering and mechanical anisotropy between the layers play the dominant role (in other words, mean ductility is low to moderate); **passive folding** in which interlayer anisotropy is ineffective (mean ductility is high); and **quasi-flexural folding** in which the geometry of the fold appears to be flexural but the overall behavior of the folded sequence is passive (mean ductility is very high). The last category largely corresponds to disharmonic folding. The first two categories, flexural and passive, can be further subdivided into slip (between layers) and flow (within layers).

The Donath and Parker classification directs us to the genetic mechanisms of folding and the tectonic environments in which folds form. Three distinct mechanisms have been identified for the folding of rocks: bending, buckling, and passive folding.

Bending of rocks occurs when the deforming force is applied across (at



Fold geometry and various lines and angles used to measure fold dimensions

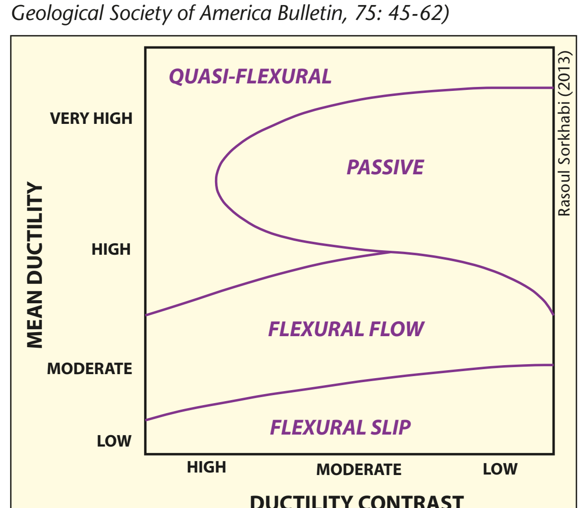
high angle to) rock layers. For example, basement uplift along a fault, magma intrusion or salt diapirs all produce bends (folds) in the overlying sedimentary rocks. Bending often produces gentle or broad folds, especially in continental interiors (cratons) situated far from plate boundaries but subjected to some vertical stresses.

Buckling occurs when the deforming force is applied parallel to rock layers. This is usually caused by horizontal compressional tectonic forces and results in layer-parallel shortening of rocks and thickening (relief) of the rock body perpendicular to stress direction. Geologists have worked out mathematical relationships between wave-length of a buckle fold and thickness of the stiff layer embedded in a ductile rock mass. As a general rule, in a given stress field and ductility contrast between the layers, thicker stiff beds will have longer fold wavelengths and thinner stiff beds will have shorter wavelengths.

Bending and buckling may also be described as two modes of **active folding** in which rock layers with their inherent mechanical properties (notably stiffness or ductility) take part in the deformation process and control the fold shape. In contrast, in **passive folding**, rock layering itself does not play an active role in folding, and instead the rock mass as a whole is subjected to folding and is usually marked by penetrative **cleavage** developed in a direction nearly parallel to the axial surface of fold. Rock cleavage is a set of planar discontinues that develop as secondary features in the rock fabric; it also refers to the ability of a rock to split (cleave) along those planes. Well-developed (continuous, spaced) cleavage occurs at temperatures of 200–350°C, corresponding to burial depths of 7–12 km.

Passive folding takes place in a mechanically isotropic rock mass and on a grain scale rather than a layer scale. Passive folds may be subdivided into passive-slip folds and passive-flow folds. In **passive-slip folds** there is minor but discrete displacement across (perpendicular to) rock layers and more conveniently along cleavage planes; they are also called **shear folds**. In **passive-**

Fields of folding related to mean ductility and inter-layer ductility contrast of folded rocks (from F.A. Donath and R.B. Parker, 1964, Geological Society of America Bulletin, 75: 45-62)



flow folds, there is across-layering material flow in a ductile environment and in the direction of folding.

Passive folding produces **similar folds** in which the fold shape is preserved throughout the layered sequence because of the lack of mechanical differences between layers. Examples of passive folding include folding of rocks in ductile shear zones and drag folds along brittle faults.

Flexural Slip and Flexural Flow

Bending and buckling produce **flexural folds** in which (as stated before) viscosity contrast between competent (stiff) and incompetent (ductile) rock layers plays an important role in the folding process. In flexural folds, competent layers do not change their thicknesses and incompetent layers are marked by cleavage sets nearly parallel to fold axial surface. Flexural folds are the most common folds in sedimentary basins.

Flexural folds are subdivided into flexural-slip folds and flexural-flow folds. In **flexural-slip folds**, there are displacements along bedding surfaces, much like the bending of a telephone directory book. These slips are greatest along the fold limbs and approach zero along the fold hinge. Flexural slip typically produces parallel or concentric folds in which the attitude and thickness of layers remain the same throughout the folded sequence. (For illustrations of similar, **parallel**, and **concentric folds**, see Fold and Folding I, *GEO ExPro*, Vol. 10, No. 3.)

In **flexural-flow folds**, rock material in incompetent layers flows from fold limbs toward fold hinges, and therefore appreciable thickness changes occur in the rock layer. Obviously, flexural-flow requires more ductility contrast between layers than flexural slip. Flexural flow produces **similar folds** in the weak layers.

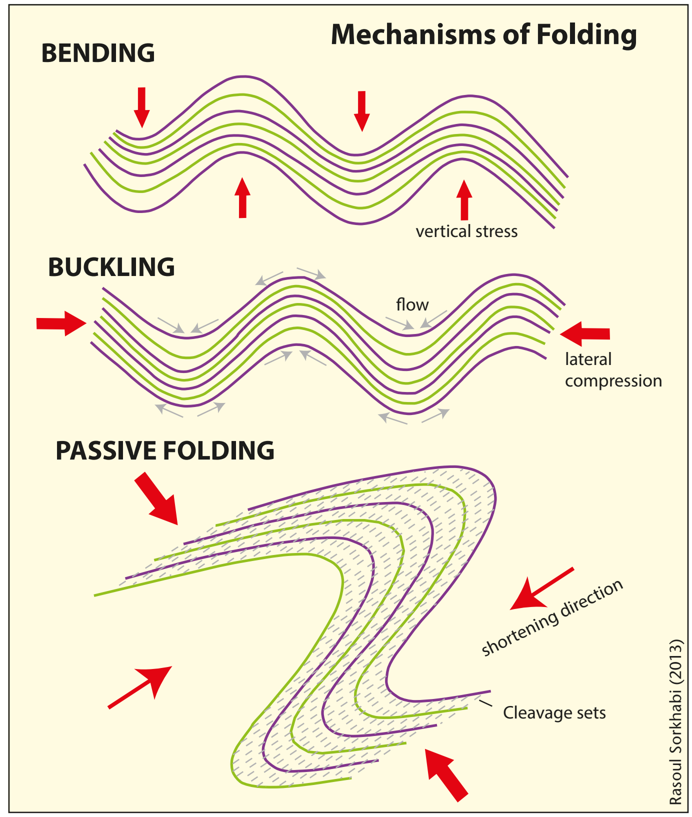
Free and Forced Folding

In **free folding**, rock layers are free to exert their mechanical properties on the development and shape of the folded stack and thus layer-parallel strain dominantly takes place. Buckling discussed above typically produces free folds.

In **forced folding**, the shape and geometric features of the folded stack are 'forced on' the layers usually by a fault that is the primary structure. In this case, to quote American geologist George Davis in his textbook *Structural Geology* (1996), the rock layers "just go along for a ride." Notable examples of forced folding include **drape fold** (folding of sediments overlying a high-angle basement fault), **fault-bend fold** (bending and slip of an anticlinal fold as a thrust block overrides the footwall block along a ramp), and **fault-propagation fold** (asymmetric bending of rock strata along a thrust ramp). In these examples, folding depends on faults, and bending is the main process of folding.

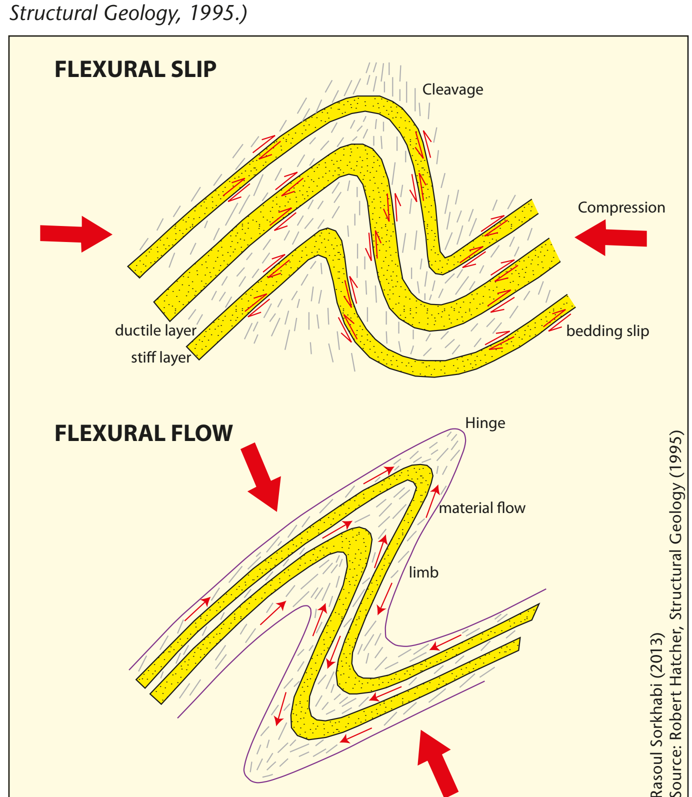
Folds and Petroleum Fields

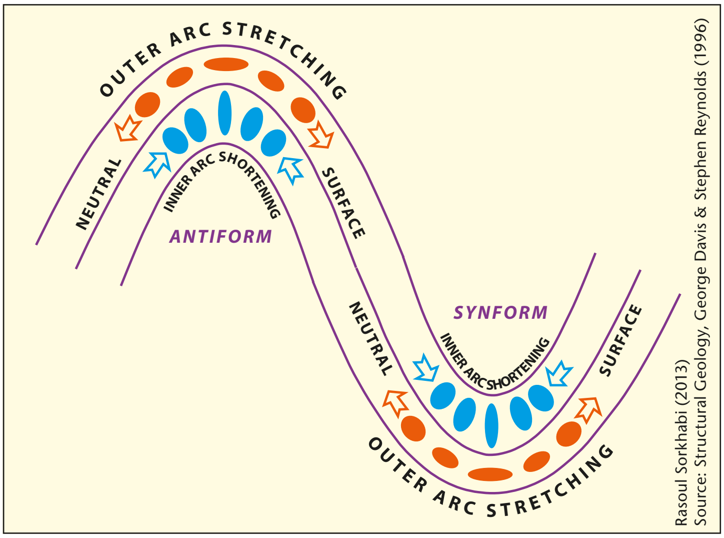
In summary, various forces produce rock folds. **Horizontal compression** resulting from the motion of tectonic plates is the most dominant force which produces series of regional and basin-scale folds. But other forces can also create localized or even widely distributed fold structures. These include **vertical stresses** (such as magma intrusion or basement upwarping); **slope instability** (such as rollover anticlines on



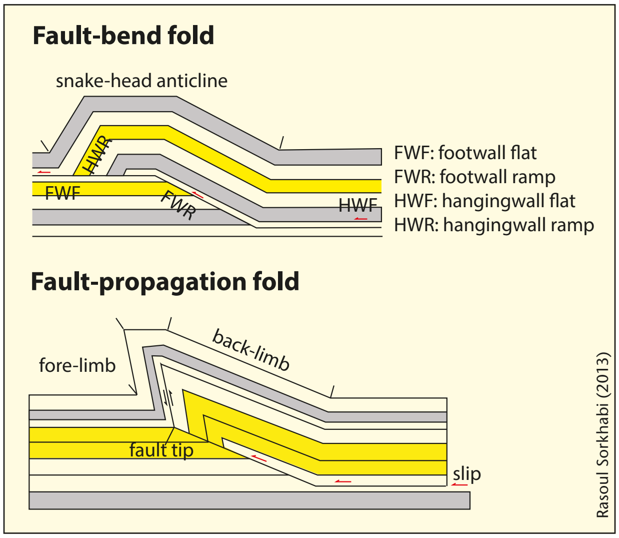
Three main mechanisms of rock folding: bending, buckling and passive folding. Note changes in thicknesses of rock layers related to bending and buckling. (Bending and bucking figures modified from Hans Ramberg, 1963, AAPG Bulletin, 47: 484-505. Passive folding figure from Robert Hatcher, Structural Geology, 1995.)

Two modes of flexural folding: layer-parallel flexural slip of sedimentary rocks in a parallel fold at relatively lower temperatures and pressures; and flexural flow of weak layers in a simple fold. (Modified from Robert Hatcher, Structural Geology, 1995.)





Individual buckle folds show internal deformation in two contrasting styles: layer-parallel stretching (marked by extensional fractures, minor normal faults or boudins) in the outer arc of the fold, and layer-parallel shortening and thickening (marked by minor folds or reverse-faults) in the inner arc of the fold. These internal strains decrease toward the middle of the fold layer called the neutral surface of no strain. (Modified from George Davis & Stephen Reynolds, Structural Geology, 1996.)



Fault-bend fold and fault-propagation fold are two important styles of 'forced folding' in which the fold shape is controlled by thrust fault. (After John Suppe, Principles of Structural Geology, 1985.)

normal-fault surfaces and toe-thrust folds on continental slopes); and **density instability** (for example, salt diapirs below denser sediments).

Folds are important structures to study in petroleum fields for a variety of reasons. Large folds provide important petroleum traps, such as anticlines or fold-bend folds in foreland basins, rollover anticlines in extensional basins, and deepwater toe-thrust folds. In these kinds of traps, three-dimensional mapping of fold structures are thus necessary for reserve estimates. In addition folding creates natural fractures which provide crucial permeability for oil and gas production in tight reservoirs, which is why **curvature analysis** of rock strata is sometimes made on seismic images to gain an understanding of the distribution and relative population of fractures. ■

An anticline in the Miocene Barstow Formation exposed in the parking lot at Calico Ghost Town County Park in the Mojave Desert of Southern California