*GEO Education is a new column that will be published occasionally in Geo Expro. Each article briefly explains some geoscience topic that is relevant to energy exploration and development and is written in a language comprehensible to a broad range of readers, including college students and non-specialists in the field.*

# Know Your Faults!

## PART I: A proper understanding of faults is key to understanding the basic tenets of hydrocarbon geology. First, we take a look at fault geometry

**RASOUL SORKHABI, PH.D.**

In 1921, Richard Oldham delivered his presidential address at the annual meeting of the Geological Society of London; taking inspiration from an ancient maxim that 'to know your faults is the greatest wisdom', Oldham entitled his talk, 'Know Your Faults'. Decades later, detailed mapping and improved visualisation techniques have revealed even more the association of faults of various types and sizes with petroleum basins. Faults play key roles in the genesis and evolution of sedimentary basins and petroleum traps and in the migration of fluids and compartmentalisation of reservoirs. That all these processes are associated with faults indicates their complex, varied nature and necessitates a proper understanding of faults in basin tectonics, subsurface mapping, seismic interpretation, petroleum system modelling, and reservoir simulation.

Faults are a core subject in structural geology and may be studied from three different perspectives: (1) the geometry and architecture of faults, (2) the stresses that form faults (geomechanics), and (3) the sequential, temporal development of faults in a given area (kinematics). All these aspects are inter-related and need to be incorporated in a comprehensive study; fault geometry is the end-member of kinematics, which is, in turn, caused by stresses. Here we look at some key terms and concepts that describe the geometry of faults.

*Surface evidence of a fault: the Ruahine Fault in the Ruahine Range, near Napier, east coast of New Zealand. The fault has offset valleys and ridges both vertically and horizontally. Uplift of the Ruahine Range has been of the order of 1 km in just 1 million years.*

Dougal Townsend, GNS Science

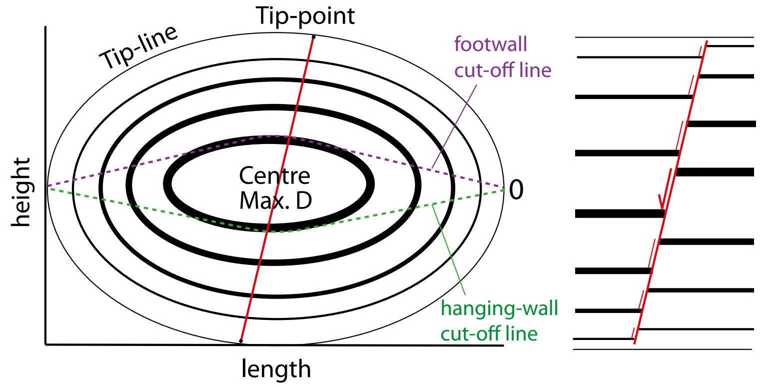
## Fault Definitions

The concept of faults entered geology in the late 18th century via observations made by coal miners in mountain excavations. In his celebrated *Principles of Geology* (volume 4, 1835) Sir Charles Lyell wrote: "A Fault, in the language of Miners, is the sudden interruption in the continuity of strata in the same plane, accompanied by a crack or fissure varying in width from a mere line to several feet, which is generally filled with broken stone, clay, etc."

Using this statement as a portal of entry into our discussion, two points are noteworthy. First, **faults** are fractures or rupture planes along which the opposite walls of a rock column have moved relative to each other. The rock block above the inclined fault plane is called the **hanging-wall** because miners could hang their lamps on that block; the block below the fault plane is called the **footwall** where the miner placed his feet.

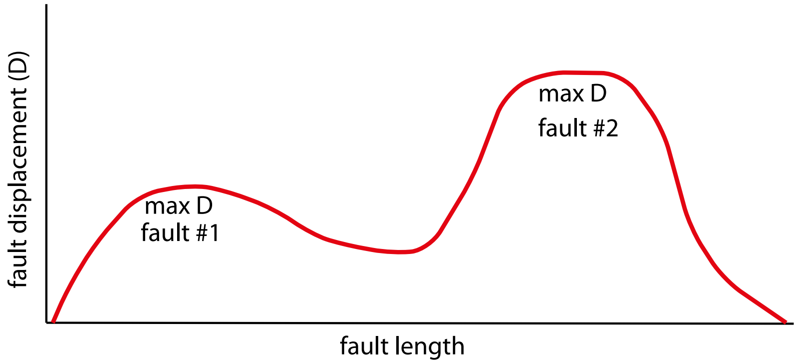
The second point is that a fault is not a smooth plane (as textbooks show for simplicity) but a concentrated zone of deformation. A **fault zone** often consists of crushed, brecciated or highly sheared **fault rock** surrounded by a damage zone characterised by fractures, hydrothermal veins, etc. Faults with greater lengths also have thicker fault zones. The nature of the fault zone depends firstly on the type of host rock; hard sandstones may show intense fracturing along the fault while ductile mudstone may smear into fault plane. Secondly, the nature of the fault zone depends on crustal depth. At deeper levels, where temperatures of over 300°C and higher pressures are prevalent, fault zones will undergo **ductile deformation** (as in metamorphic terrains); while in the upper eight kilometres of the crust, which also includes the majority of sedimentary basins, fault zones will show **brittle deformation**.

*A fault is not really a smooth plane; it has undulations and heterogeneities called fault 'asperities'. Nevertheless, every fault is generated by a predominant tectonic event and has finite geometric shape. A given fault surface may be theoretically imaged as an ellipsoid whose centre (where the fault presumably nucleated) has the maximum amount of displacement, and as we move away, the displacement is reduced until it becomes zero at the circumference or tip-line of fault surface. Note, however, that many factors such as lithologic variations, cross-fault linkages, tectonic inversions, etc. alter this idealised image as shown in C.*



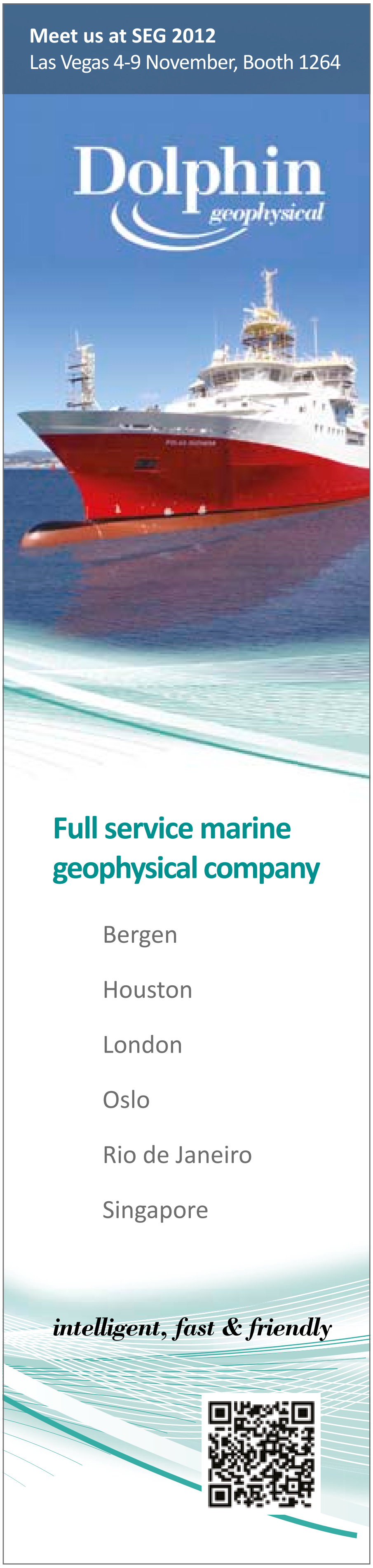
(A) Idealised fault surface with counters of varying displacements

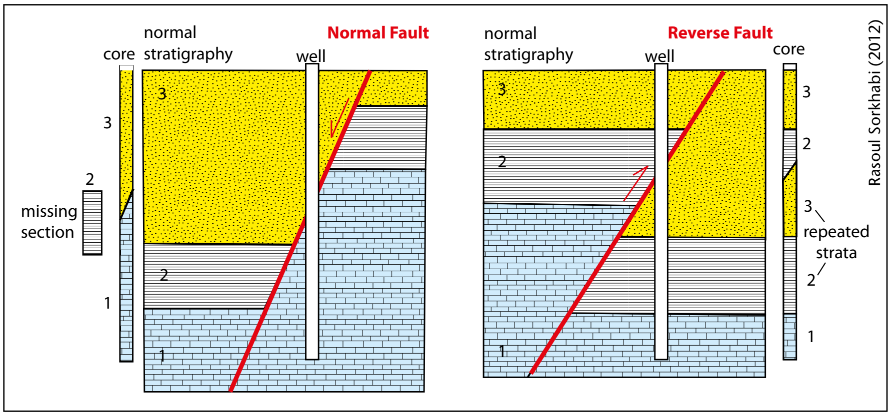
(B) Fault profile with max. displacement at fault centre



(C) Fault displacement-distance curve for two linked faults

Rasoul Sorkhabi (2012)





*Stratigraphic identification of normal and reverse faults in wells. Note also that unit 3 is syntectonic sediment thickening in the down-going fault block.*

## In Search of Faults

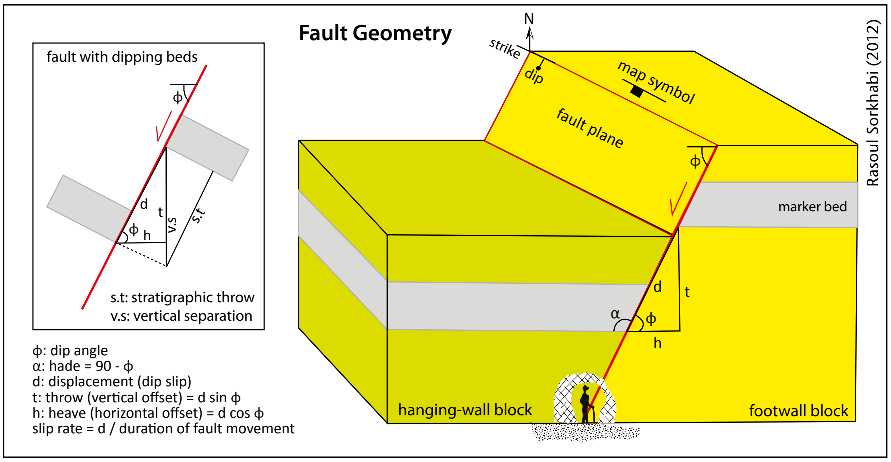
Tectonic faults are generated at crustal depths. A **blind fault** is one that still lies beneath the Earth's erosional surface (although it may have a topographic expression). An **emergent fault** is marked by a **fault line** (or fault trace) and may produce a steep topographic surface called a **fault scarp**.

Depending on the type of available data, there are several indicators to identify fault structures. These include: (1) topographical features such as lineaments, offset streams, fault scarps, etc.; (2) discontinuity in a marker bed in an outcrop section; (3) juxtaposition of rocks of different ages (reverse faults often bring older rocks atop younger rocks while normal faults have younger rocks at their hanging-wall contacts); (4) features associated with fault zones such as gouge ('fault flour'), slickenside (smooth, striated fault surface), intense fracturing, sheared rock fabric, hydrothermal veins, etc.; (5) geophysical indicators such as displaced seismic reflectors or gravity anomalies in a particular pattern; (6) repetition (by reverse faults), omission (by normal faults) or downthrown-side thickening (by growth faults) of strata in borehole records (cores and logs). Ideally, several indicators should be used to better characterise a fault system.

Whether a fault is active or not has enormous relevance not only for construction of dams, bridges and other structures but also for oil and gas fields. An **active fault** is usually defined as one for which there is earthquake evidence in the past 10,000 years (the Holocene) while inactive faults have not moved for the past 1.6 million years (the Quaternary). Nevertheless, any fault is a plane of weakness and is prone to reactivation if sufficient stress is applied.

Faults come in various sizes. Fault structures are on the scale of at least metres, minor faults or sheared fractures on the scale of centimetres, and **microfaults** (or microfractures) on the scale of millimetres. On seismic images, faults are prominent features as they

*Geometric relations in a fault*

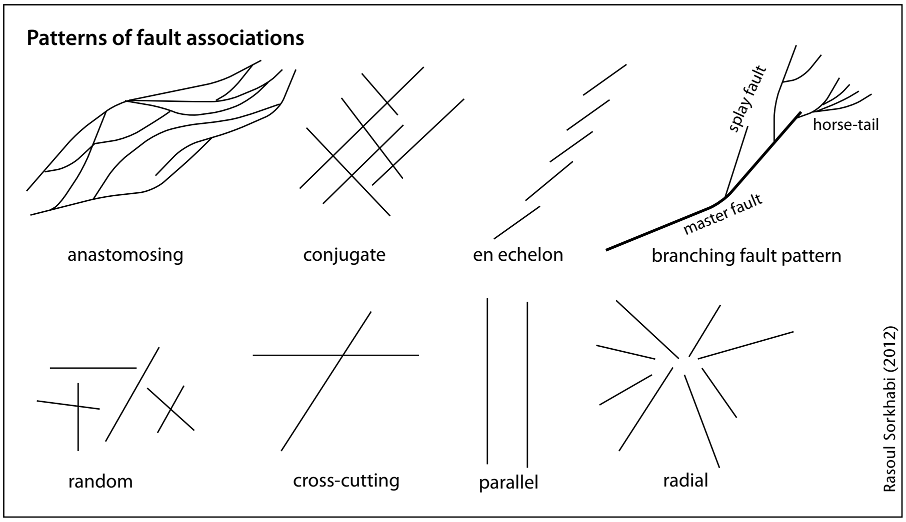


displace and distort the reflectors from sedimentary layers. However, even with the best seismic images, the population of smaller faults (say with offsets of less than 5 or 10m depending on seismic quality), which are below the seismic resolution, are not visible; these are called **sub-seismic faults**.

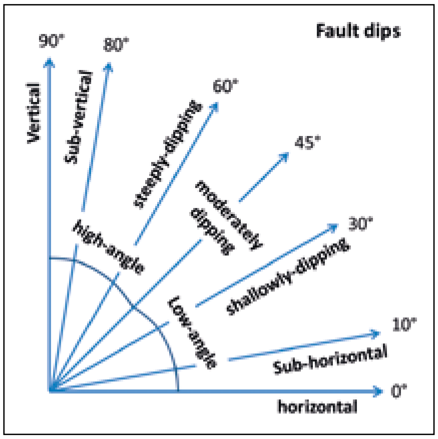
In the early 20th century, the American geologist Raphael Pumpelly suggested that in a given area small faults mimic the shape and orientation of larger structures of the same generation. In 1970, J. S. Tchalenko published an influential paper in the *GSA Bulletin* showing how tectonic stresses can give rise to self-similar shear structures at various scales. With the rise of the fractal theory of natural phenomena, geologists have tried to model populations of faults as a scale-invariant fractal distribution. While this is theoretically a powerful tool, for instance to predict the population of sub-seismic faults in a basin, its application is far from perfect and requires better calibrations from massive empirical data and detailed understanding of fault development.

## Geometric Representation

A fault is geometrically characterised by its strike, dip, displacement, throw (vertical offset), heave (horizontal offset), and sense of movement. Faults with dip angles of over 45° are **high-angle**, while those dipping less than 45° (or less than 30° according to some geologists) are **low-angle** faults. The amount of fault displacement typically depends on fault length: a 100 km long fault may have a displacement of 1 km. Quantifying the relationship between these two parameters is the subject of many recent studies because by knowing one parameter we may predict the other; however, empirical data also show complexities resulting from lithology, fault type, and methods of analysis.



Rasoul Sorkhabi (2012)



Depending on the type of data acquisition, faults are depicted in various ways: surface (2D planar), maps views (geologic maps on topographic sheets and lineament maps on satellite images), cross-sections (profiles), 3D block diagrams, subsurface structural counter maps, 2D or 3D seismic images, and fault surface maps with juxtaposed strata, curvature, and so forth. ■

*Part II continued in the next issue.*

Dr. Michael C. Rygel of State University of New York, College at Potsdam.

*This outcrop photo shows a normal fault in the Bozeman Group (continental Tertiary sediments) near the Harrison Reservoir, Montana, USA*

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# Know Your Faults!

Part II: In the first part of this feature, we looked at the geometric representation and identification of faults. In this concluding article, we review the slip classification, stress orientations and tectonic styles of faults.

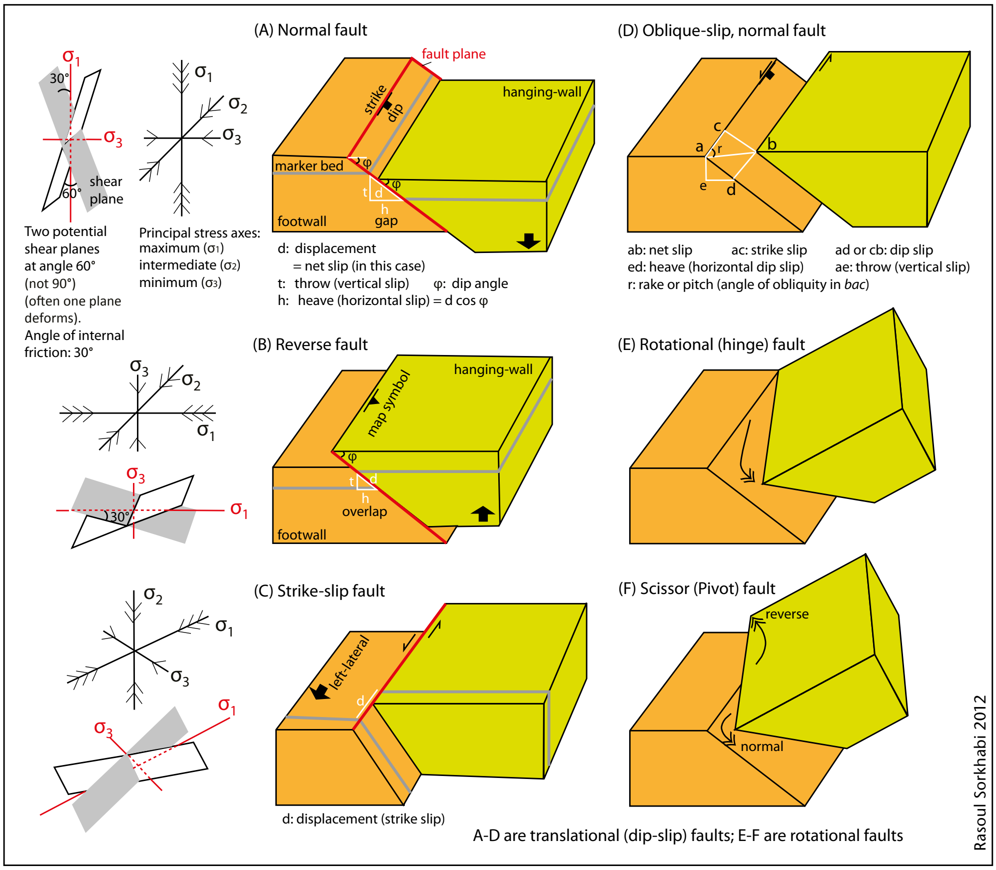
**RASOUL SORKHABI, PH.D.**

One of the greatest geologists of the past century was the Scottish geologist Ernest Masson Anderson (1877–1960), who in his (now classic) work *The Dynamics of Faulting and Dyke Formation with Application to Britain* (Edinburgh, 1942, 1951) systematized our knowledge of the geometry and stress-fields of various faults.

For a three-dimensional rock volume, Anderson visualized three **principal axes of stress**, all of which are compressional but with different magnitudes: maximum ($\sigma_1$), intermediate ($\sigma_2$) and minimum ($\sigma_3$). He reasonably assumed that shear stress at the ground-air or ground-water interface is zero: no shear occurs in fluids (of course, hurricanes may uproot trees and blow off roofs, but they are too weak to produce faults and earthquakes). Therefore, one of

*Conjugate normal faults cut the Noonday Dolomite (about 800 Ma) at the entrance to Mosaic Canyon, Death Valley National Park, California.*

Dr. Marli Bryant Miller, University of Oregon, Eugene



*Sketches showing principal stress axes and slip classifications of various faults. Note that in theory all faults have a rotational component because displacement even in a dip-slip fault varies along the fault length. However, in a rotational fault the variation is too great between two nearby points along the fault strike.*

the principal stress axes must be vertical and increase with depth as the rock overburden (lithostatic pressure) increases; the other two stress axes are horizontal.

The direction of fault movement is such that fracture *opens* along the minimum stress axis and the *slip* occurs as the rock wedge containing the maximum stress axis moves inward. The angle between the maximum stress axis and the shear plane is called the angle of internal friction, and studies show that this angle is about 30° for most rocks.

Anderson's stress model is strictly applicable if we assume that the deforming rock is isotropic (homogeneous throughout fault surface) and that structural deformation is coaxial (the stress axes do not rotate). In reality, rock types exhibit different mechanical strengths and inherit pre-existing fractures, and in the larger frame of the Earth's crust, stresses may rotate. Nevertheless, Anderson's elegant model provides a basic scheme for studying the **geomechanics** of faulting.

## Classification of Faults

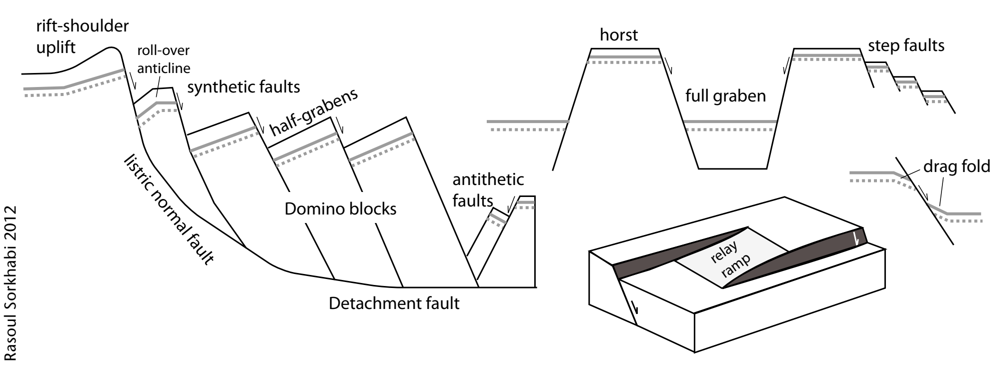
Faulting is a kind of **strain** (permanent deformation) in rock in response to stress which is usually supplied by the motion of tectonic plates relative to one another. As stress (force applied per unit area) builds up in a block of rock, a point reaches when the stress surpasses the rock strength and the rock then ruptures (yields to the stress).

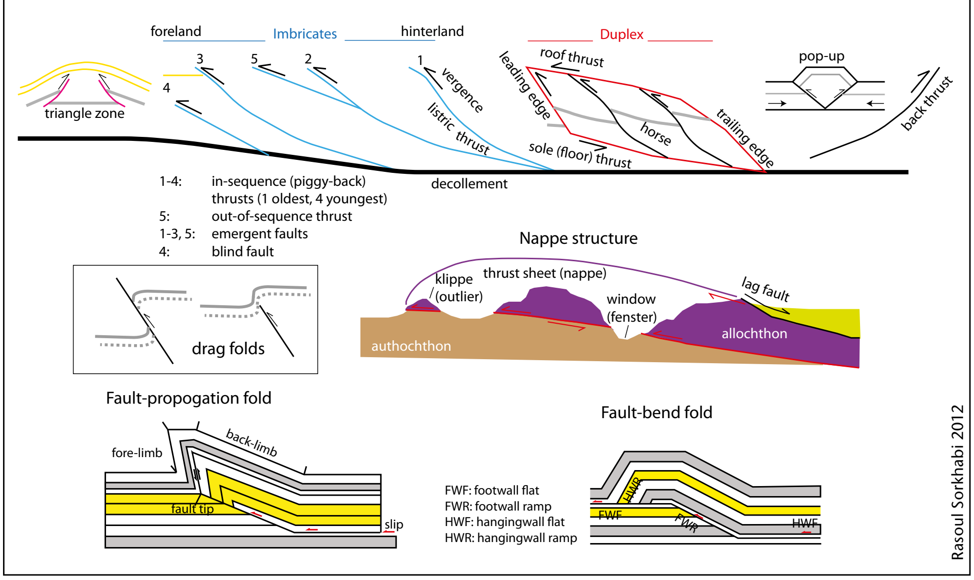
Based on slip (direction of movement) of fault section and orientation of the stress axes, faults are broadly categorized into three types: normal, reverse, and strike-slip faults.

A **normal fault** is a dip-slip fault in which the hanging-wall has moved down relative to the footwall. Normal faults are produced by extensional stresses in which the maximum principal stress (rock overburden) is vertical. The faulting takes place at a point at depth when lithostatic pressure exceeds the rock strength and horizontal stress is reduced along an axis. Geometrical considerations dictate that such a fault plane dips at greater than 45°, or more precisely at 60° (that is, 45° plus 30°/2, where 30° is the angle of internal friction). Although the majority of normal faults are indeed high-angle, low-angle normal faults also occur because fault surface is not necessarily isotropic.

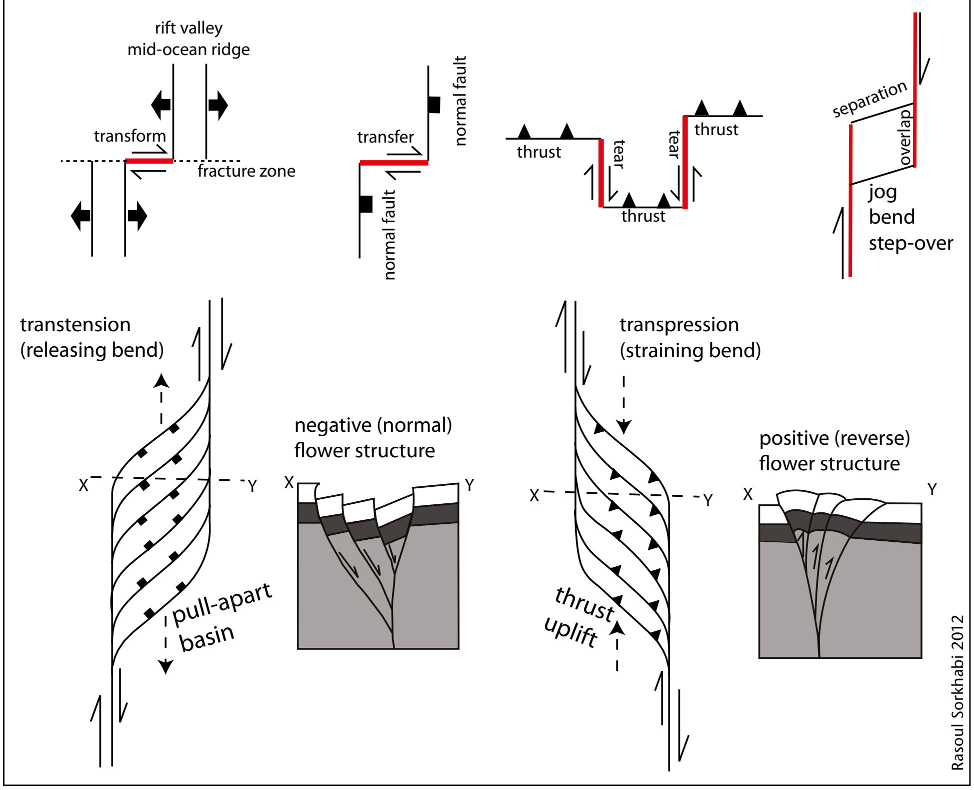
A very low-angle normal fault at the base of an extending block is called a **detachment fault**. In this case, a series of extensional faults, sometimes having a listric ('spoon-shape' or 'concave upward') shape, join at the detachment. A low-angle normal fault that develops on top of, parallel but in an opposite direction to a thrust sheet is a **lag fault**. Such an extensional fault forms almost simultaneously with the thrust fault at the base of the thrust sheet, and plays an important role in the tectonic

**Extensional tectonics: styles of normal faults**





**Contractional tectonics: styles of reverse and thrust faults**



**Styles of strike-slip tectonics**

exhumation of deep-seated rocks.

A **reverse fault** is a dip-slip fault in which the hanging-wall has moved upward, over the footwall. Reverse faults are produced by compressional stresses in which the maximum principal stress is horizontal and the minimum stress is vertical. In this way, the fault section is shortened in the direction of maximum compression and the fault dips at less than 45°, or in theory, strictly at 30° (i.e. 45° minus 30°/2, where 30° is the angle of internal friction). However, in nature steeply or shallowly dipping reverse faults do occur because of variations in the properties of rocks (such as their relative strength) on a fault surface.

A **thrust** is a low-angle reverse fault. In orogenic belts, such as the Alps, a thrust fault may transport a thick package of folded rocks over many kilometers; such a **thrust sheet** is called **nappe** in French and **decke** in German. Nappes, some of which have moved for over 100 km, have long been a paradoxical phenomenon in structural geology, and geologists have tried to explain them as a result of gravity gliding of rock on an orogenic slope (towards foreland); hydrothermal fluid lubrication along thrust planes; and incremental movement of the thrust over millions of years. Probably all these processes happen. Plate collisional tectonics provides the fundamental stress mechanism for the generation of large thrust sheets.

Seismic images from orogenic belts show that thrust faults are often rooted in a basal detachment or **decollement**. Moreover, in orogenic belts, thrust faults become younger toward the foreland; this sequence is referred to as foreland-propagating or piggy-back faults.

The terms **overthrust** and **underthrust** are sometimes used for low-angle, regional thrust faults with the implication that hanging-wall and footwall respectively was the active element in the thrust movement (although it is difficult to verify this). **Upthrust** is a high-angle thrust with a great amount of uplift, often involving basement rupture.

Reverse faults and associated folds may deform the basement rocks (**thick-skinned** deformation), or only sedimentary cover detached from the basement (**thin-skinned** deformation), or occasionally both the basement and sedimentary cover respectively in the hinterland and foreland of a mountain system.

A **strike-slip** fault is a nearly vertical dip-slip fault in which fault blocks move horizontally, parallel to the fault strike. In this kind of fault, both the maximum and minimum principal stresses are horizontal while the intermediate stress is vertical. The direction of strike slip may be left-lateral (**sinistral**) or right-lateral (**dextral**) with respect to an observer. Large strike-slip faults are also called **wrench** or **transcurrent faults**. A **mega-shear** is a continental-scale zone of deformation produced by strike-slip movement.

Regional strike-slip faults are usually composed of several strands. Sometimes two segments of a strike-slip fault partly overlap but are also separated by a step-over, jog or bend; the latter area is usually deformed by **transtensional** (releasing bend) or **transpressional** (straining bend) structures depending on the directions of strike-slip movements and step-overs.

## Fault Inversion and Growth Fault

**Tectonic inversion** is the reactivation of a dip-slip fault resulting in the reversal of the sense of fault throw. Positive inversion is the changing of a normal fault to a reverse fault (reverse-reactivation); negative inversion is the changing of a reverse fault to a normal fault (normal-reactivation). Tectonic inversion occurs when a basin is a subjected to a new but contrasting tectonic regime, and stresses find it easier to build up in pre-existing faults.

Non-tectonic **gravity-driven faults** are also common, especially in sedimentary basins. These include faults generated by ductile movement of salt and shale, and also those caused by gravity gliding of strata on a slope. The latter include **growth normal faults** and **toe-thrusts** on passive continental margins, triggered by deltaic sediment overburden and continental slope.

An important way of analyzing faults in sedimentary basins is to note their relations to strata. For example, a **bedding-parallel fault** or 'flat' often moves along an incompetent (weak) layer, while a **ramp** develops in more competent (rigid) layers. **Syntectonic sedimentation** results in thicker growth strata on the down-thrown block which can then be used to identify pre-tectonic and post-tectonic sediments. ■

## A Historical and Bibliographic Note

Historically, fault terminology is biased toward the regions which have been studied in greater detail than other regions. For example, the terminology of thrust faults and folds was primarily developed in the Alps and in the Rockies, that of extensional faults in the East African-Red Sea rift system and the south-west USA Basin-and-Range province, and that of strike-slip faults in the San Andreas fault system. Fault terminology can be complex. Geologists have tried to standardize definitions of fault-related terms as structural geology has advanced. Key papers include: R. Butler (*Journal of Structural Geology*, 1982, vol. 4, p. 239-245), S.E. Boyer and D. Elliot (*AAPG Bulletin*, 1982, v. 66, p. 1196-1230), K. R. McClay (in *Thrust Tectonics*, London, 1992, p. 419-433) on thrust faults; D.C.P. Peacock, R.J. Knipe and D.J. Sanderson (*Journal of Structural Geology*, 2000, v. 22, p. 291-305) on normal faults; K.T. Biddle and N. Christine-Rick (in *Strike-Slip Deformation, Basin Formation and Sedimentation*, SEPM Special Publication 37, 1985, p. 375-386) on strike-slip faults.

*Chief Mountain (2,768m), Glacier National Park, Montana, near USA-Canada border, is a 'klippe' (outlier or isolated remnant) of a thrust sheet transported by the Lewis Thrust during the formation of the Rocky Mountains. Here, Mesoproterozoic dolomite (the Altyn formation, about 1400 Ma) is thrust eastward over the Upper Cretaceous sandstone and shale (the St. Mary River and Willow Creek formations) for a distance of about 80 km.*

Glacier National Park, Montana