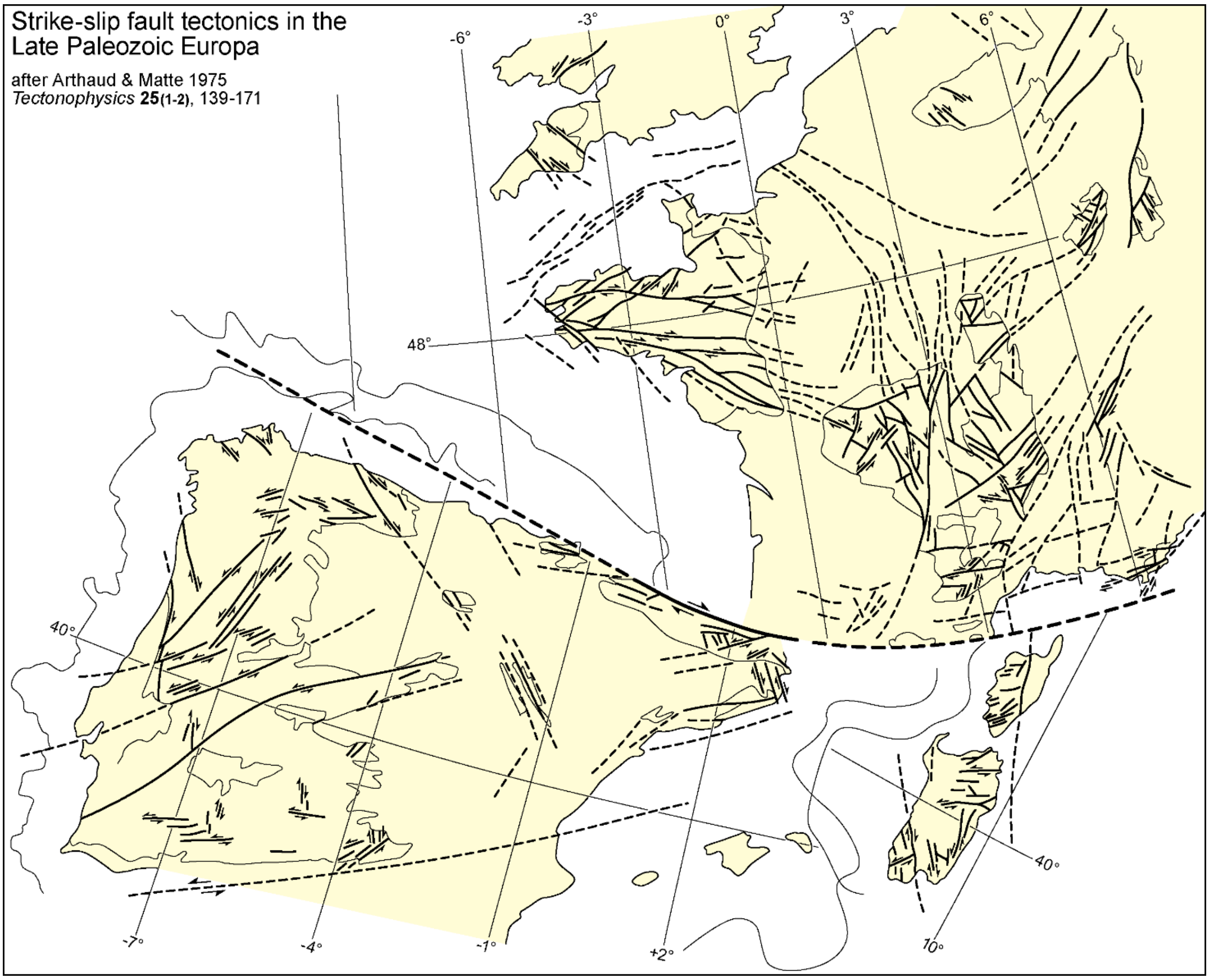
STRIKE-SLIP AND OBLIQUE-SLIP TECTONICS

Strike–slip faulting is a common mode of deformation in both continental and oceanic crust and occurs at a wide range of scales. Strike slip systems are relatively narrow and subvertical **wrench zones** along which two adjacent blocks move sideways, horizontally, parallel to the strike of the fault zone. For example, they are produced at transform plate boundaries where plates horizontally slide past one another. There is no net addition or subtraction of area to the crust. It is classically accepted that strike slip faulting occurs in a triaxial stress field in which the maximum and minimum principal stresses σ_1 and σ_3 lay in the horizontal plane and the intermediate principal stress σ_2 is vertical. In a trigonometric system, a strike slip fault at an angle $0 < \theta < 90°$ to σ_1 is **sinistral**; it is **dextral** if $90 < \theta < 180°$.



Nearly 45% of plate boundaries have a relative velocity vector markedly oblique (> 22°) to the boundary normal. 14% of plate boundaries have vectors nearly parallel to boundaries (within 22°). This implies that strike-slip tectonics is important, whether alone or as a component. Present-day plate tectonics document four main types of strike-slip systems:

Conservative plate boundaries	
Transform fault at oceanic plate boundaries	Mid-Atlantic ridge
Transform fault at continental plate boundaries	Basin and Range
Passive margins	Bay of Biscay
Destructive plate boundaries with oblique convergence	
Transpression at continental plate boundaries	New Zealand, California
Constructive plate boundaries with oblique extension	
Back-arc basins	Philippines, the Kuril Archipelago
Intra-plate strike slip faults	
Tectonic escape	Asien
Transtension	Mid-Atlantic ridge

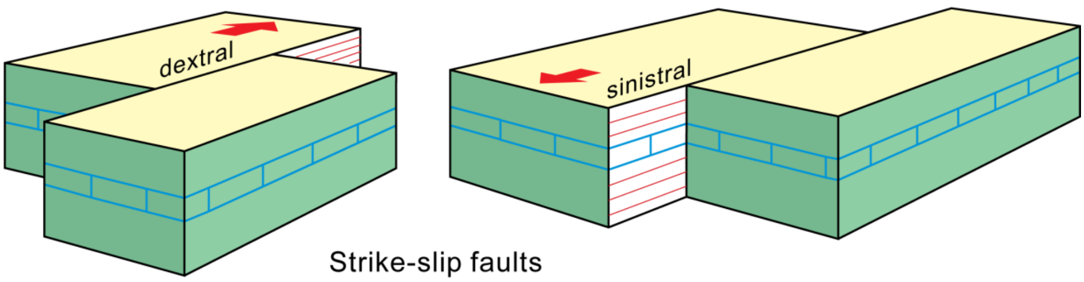
In general, the strike-slip tectonic regime is characterized by feeble magmatic and metamorphic activity.

GEOMETRIC RULES OF STRIKE SLIP FAULTING

Strike-slip fault systems are usually narrower and more continuous than either compression or extension systems. At depth strike slip zones become ductile shear zones characterised by vertical foliation and a horizontal stretching lineation (e.g. the South Armorican Shear Zone). They can be several kilometres wide.

Basic terminology

Strike-slip faults are generally vertical faults that accommodate horizontal shear within the crust. The horizontal displacement is either **dextral** (clockwise), or **sinistral** (anticlockwise).



Strike-slip faults

Symbols in sections are circles, with a point (tip of the arrow) on the block moving towards the observer, and a cross (back-end of the arrow) on the block moving away from the observer.

<u>Remember:</u> A fault is sinistral if, to an observer standing on one block and facing the other, the opposite block appears to have been displaced to his left. Conversely, the fault is dextral if the movement is to the right.

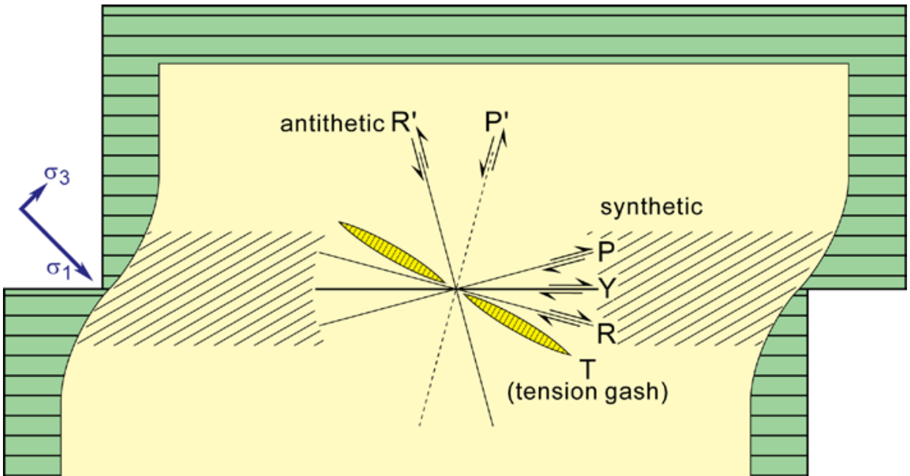
A **scissor fault** changes dip and offset sense along strike so that the hanging-wall becomes the footwall.

Tip line; branch line; cut-off line

These geometrical features have the same definitions as for other fault types. Tip lines are isolated ends of fault segments.

Subsidiary fractures = Riedel shears

Strike slip faulting has been abundantly reproduced with analogue experiments. Such experiments have revealed the role of **Riedel shears**, which are subsidiary shear fractures that propagate a short distance out of the main fault but are coeval with it. Riedel shear is also used on a large-scale fault pattern and may refer to as many as five direction families of associated fractures. In that case, individual fractures remain active after the other types developed so that synchronous movement on all fractures accommodate strain in the fault zone. The geometrical arrangement of Riedel shears is indicative of the sense of movement within the wrench zone and is therefore widely used for the interpretation of its kinematic evolution.



Terminology of Riedel shears in a fault zone

- **R** Riedel shears are normally the first subsidiary fractures to occur and generally build the most prominent set. They develop at an acute angle, typically 10-20° clockwise to a dextral main fault, anticlockwise to a sinistral strike-slip fault. They often form an *en échelon* and overstepping array synthetic to the main fault; they evolve as a sequence of linked displacement surfaces. Their acute angle with the fault points in the direction of the relative sense of movement on the main fault. This angle is equal to $\phi/2$, where ϕ is the material internal friction angle.
- **R' shears** are antithetic faults (i.e. with a sense of displacement opposite to the bulk movement) oriented at a high angle (approximately 75°, i.e. $90°-(\phi/2)$ clockwise to a dextral, anticlockwise to a sinistral main fault plane), conjugate with the R(iedel) shears. They preferentially occur in the overlap zone between two parallel R shears and often connect these two R shears. They may develop with or after R shears.
- **P shears** are synthetic minor faults symmetrically oriented to the R shears with respect to the fault plane (at $\phi/2$ from the fault plane, anticlockwise and clockwise to dextral and sinistral faults, respectively). P shears also form an *en échelon* array contemporaneous with R shears or later as links between R shears. P-shears are contractional and accommodate fault parallel shortening as shearing proceeds. They are less common as R and R' shears and may require more displacement to form. As for R Riedel shears, there may be **P' shears** conjugate with P shears but these have relative minor importance and are difficult to separate, in terms of orientation, from R-shears.

- **Y shears** are synthetic microfaults sub parallel to the main fault, apparently the last to form.

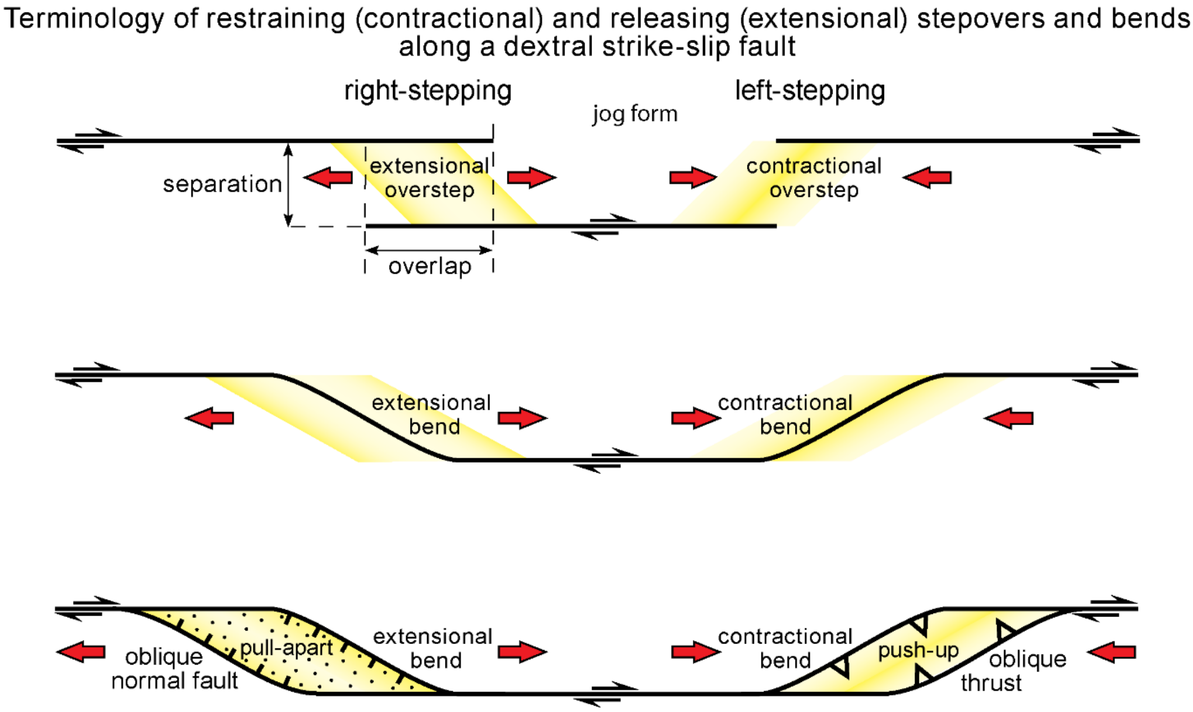
Riedel microfaults may all connect one another to form an anastomosing network of fractures in a narrow fault zone whose bulk borders are parallel to the main fault. Complications are introduced when Riedel-within-Riedel shears form.

Strike slip trajectory; Map trace

Because slip is horizontal and parallel to the commonly straight fault trace, the kinematics and mechanics of strike–slip faulting are well displayed from maps. A perfectly planar strike-slip fault causes neither extension nor shortening; consequently there is no associated topography. However, long strike slip faults follow a staircase-like trajectory made up of offset long and a straight trace (vertical equivalent to flats) connected by oblique bends or jogs (vertical equivalent to ramps). The resulting undulation of fault-surfaces is also documented by 3D seismic and remote-sensed data. The wavy shape is attributed to linkage of alternating fault-segments through time.

Linkage

Strike slip faults are commonly segmented at all scales and levels of exposure, typically in the form of *en échelon*, non-coplanar faults separated by **offsets** (or **step-overs**). These step-over zones of host rock between the end and the beginning of two adjoining *en échelon* shear fractures deform in order to accommodate continued strike slip displacement. This local deformation may lead to the formation of short fault segments that connect adjacent *en échelon* fault segments and result in a through-going fault zone. The geometry of these step-over zones and linking faults, in turn, controls contractional or extensional deformation according to the sense of slip and stepping direction of the *en échelon* fault segments.



Left-stepping refers to the arrangement in which one fault segment occurs to the left of the adjacent segment from which it is being viewed. The contrary is **right-stepping**. Hard-linkage occurs where faults directly link together. Soft-linkage occurs where strained zones without through-going fault link individual fault segments.

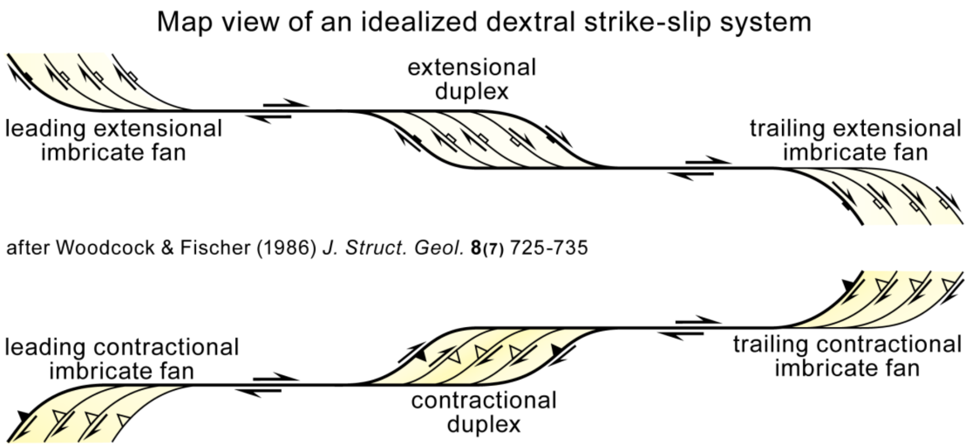
- Contractional or **restraining bends** and offsets are local zones of convergence where material is pushed together by the dominant fault movement. The linkage of adjacent fault segments is typically through the development of P-shear splay faults. At a constant volume of the deforming transpression zone, local shortening will produce vertical lengthening and thus surface uplift. This **push-up** area will be eroded.

- Extensional, **releasing** or dilatant bends and offsets are local zones of extension where material is pulled apart by the dominant fault movement. The linkage of adjacent fault segments is typically through the development of R-shear splay faults. At a constant volume of the deforming transtension zone, local extension will produce vertical shortening and surface depression. This **pull-apart** area will be site for sedimentation.

A strike-slip fault system commonly shows a braided pattern of **anastomosing** contemporaneous faults. Contractional and extensional bends and offsets can thus alternate along a single yet complex strike-slip zone.

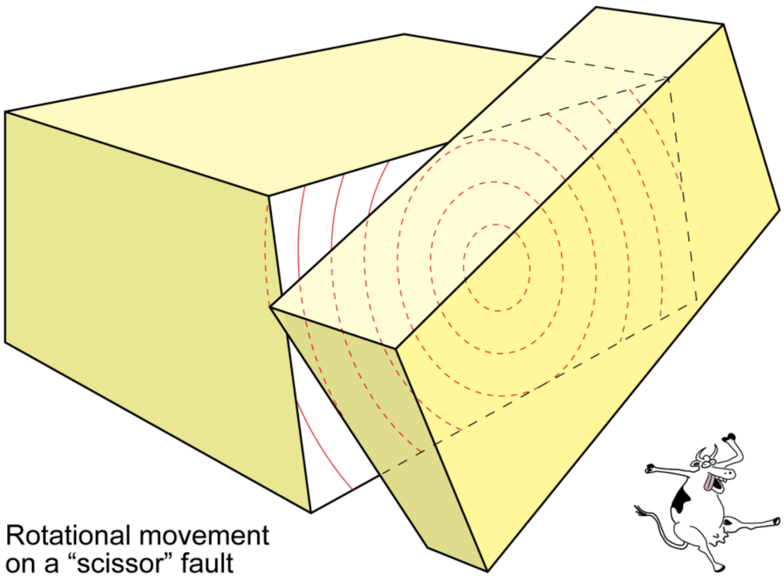
Strike-slip duplexes

Multiple linking of closely-spaced R- and P-shears may create fault-bound lenses (elongate horses) imbricated between overlapping en échelon segments. Such sets of horizontally stacked and isolated rock lenses are bounded on both sides by parallel segments of the main fault and thus define **strike-slip duplexes** (like thrust or normal-fault duplexes, but tilted to the vertical). They develop in **transfer zones**, where displacement is conveyed from one fault segment to another in systems of stepped strike-slip faults, and in **bends**, where the orientation of the main fault is deflected.



Strike-slip duplexes may be compressional or extensional, depending on whether they formed at an extensional (facing towards the movement direction) or contractional (facing against the relative movement) bend. Thrust or normal-fault duplexes accommodate vertical thickening (through stacking of vertical slabs that rise upward and outward over the adjacent blocks) or thinning (through separation of horses) of the crust. For strike-slip duplexes, the corresponding thickening or thinning would have to occur in a horizontal direction, which is difficult owing to the constraint imposed by the rest of the crust. The required deformation can be easier accommodated vertically, and, therefore, strike-slip duplexes involve oblique movements. In a compressional strike-slip duplex, fault must combine strike- and reverse slip; in an extensional strike-slip duplex, faults combine strike- and normal slip.

Rotation of horses around a horizontal axis may produce **scissor-faults**, which change from a normal fault at one end to a reverse fault at the other. Duplexes are commonly breached by faults that connect the stepping segments.



In large systems, pieces (horses or sidewall ripouts) from one side of the main fault may be sliced off and transferred to the other side as the active fault takes a new course. This may produce far-travelled blocks that are exotic to the block with which they are associated. Blocks of this type have been transported to considerable distance from their sites of origin; they are termed **displaced** or **exotic terranes**.

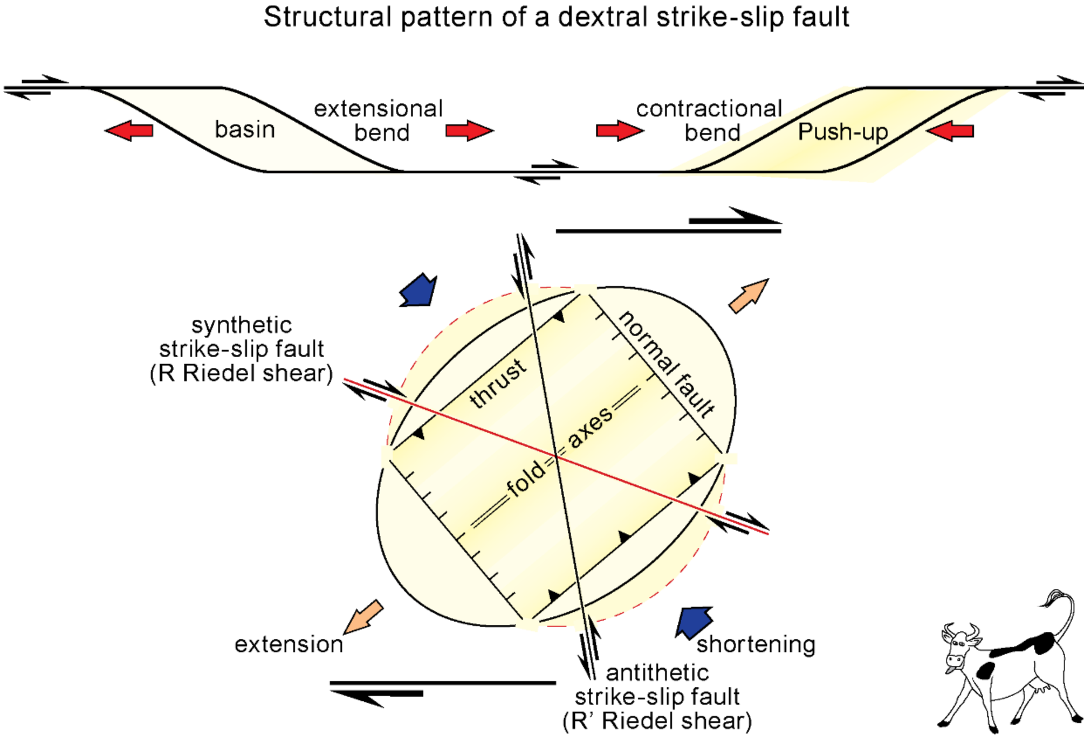
Horsetail splay

Like any other fault, strike-slip faults may terminate in zones of ductile deformation. In brittle terminations, the displacement is distributed through several branching splay faults. These small faults, curved away from the strike of the main fault, form an open, imbricate fan called a **horsetail splay**.

Antithetic and synthetic splay faults at tips of major strike slip faults have often a small vertical component consistent with the extensional or compressional character of the fault termination. Large-scale, extensional horsetail splays may host sedimentary basins at tips of major strike-slip faults. Conversely, compressional horsetail splays may display thrust faults and folds at tips of major strike-slip faults.

Map-view geometrical complexity

Strike slip faulting in the basement may not cut through the cover. Instead, the bulk cover displacement is distributed among sets of structures in a long and narrow wrench-zone, parallel to and over the basement strike-slip fault. The geometrical complexity of the wrench zone reflects a bulk strain that combines pure shear across the strike slip faults, and simple shear parallel to the strike-slip faults. The pure shear component arises from the compressional or extensional component across the zone, and the simple shear component from the strike-slip displacement. For infinitesimal simple shear of an idealized homogeneous body, the strike-slip zone boundary is a line of no extension. The directions of instantaneous extension and compression are given by the orientation of the horizontal strain-ellipse and are predicted to occur at 45° to the strike-slip zone boundary. Because the earth's surface is easily deformed, various types of structures may form simultaneously, according to their orientation with respect to the ellipse orientation.



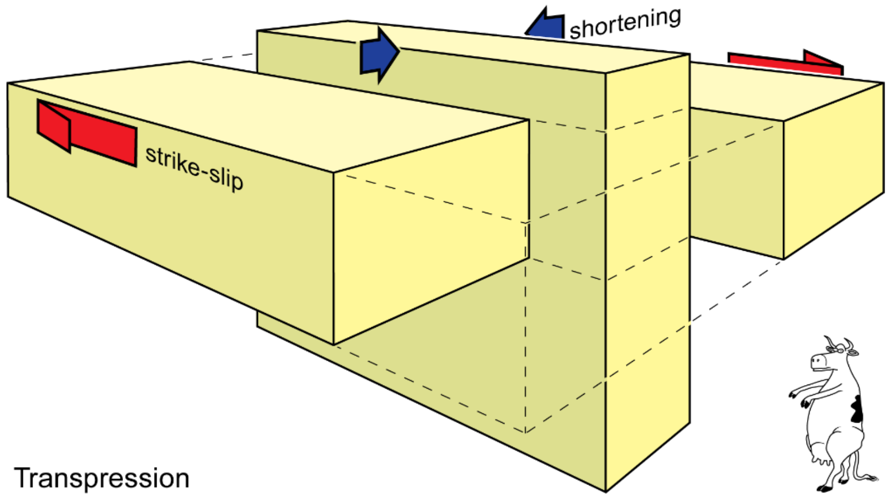
- Folds and thrusts form parallel to the ellipse long axis, typically in *en échelon* arrays whose acute angle to the main fault is opened in the direction of shear.
- Normal fault and tension fractures are parallel to the ellipse small axis, typically in *en échelon* arrays whose acute angle to the main fault is opened in the direction opposite to that of shear. The orientation of these structures will depend on the intensity of transpression or transtension.
- Conjugate sets of strike-slip faults form oblique to the main fault (synthetic and antithetic Riedel shears, i.e. with the same and opposite sense of displacement as the master fault, respectively).

In reality, progressive general shear is likely to result in the folding and rotation of faults soon after their initiation. Besides, pre-existing structures are reoriented and eventually destroyed, while new folds and faults are growing.

Transpression and transtension

Transpression means that shortening is taking place across a dominantly strike-slip fault (oblique convergence, like along the San Andreas Fault Zone). Conversely, **transtension** means that extension is a deformation component of bulk strike-slip faulting (California Gulf).

Combined yet usually partitioned slip components refer to particular boundary conditions at the regional scale such as oblique convergence or divergence at plate margins, or to local conditions as in restraining (in compression) or releasing (in extension) bends.



Transpression and transtension are defined by the angle α between the fault zone and the horizontal, convergence or extension direction, respectively. Experimental results show a sharp contrast between structures formed at $\alpha \leq 15°$ and $\alpha \leq 30°$. For small values of α, deformation is localised on steep faults (dipping > 70°) and structures are typical of strike-slip regime with Riedel faults. For high α deformation is more distributed on shallow dipping faults that build asymmetric uplift zones on thrusts or basins on normal faults, according to the regime.

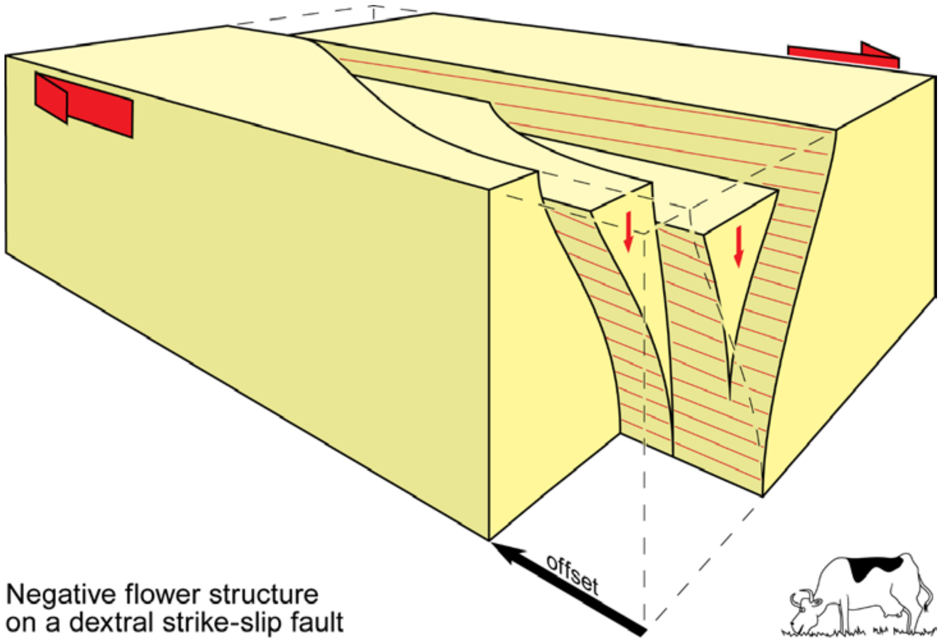
Flower structures

Seismic profiles across main faults of transpressive and transtensive strike-slip duplexes such as in restraining and releasing offsets / bends, respectively, have revealed the following characteristics:

- Fan-like, rather steep faults converge at depth into a single and subvertical fault.
- The deep main fault (the **stem**) is subvertical.
- Facies and thickness strongly vary for a same stratigraphic layer on both sides of faults.
- Normal and reverse offsets along a single fault plane often result from inversion of the relative movement on the fault.

This upward splay shape of subsidiary faults is termed a **flower structure**.

- If the vertical component is normal, faults tend to be listric and to form a **negative flower structure**, which forms a depressed area. This subsiding, commonly synformal area has generally, in map-view, a wedge- or a rhomb-shape. It forms a **sagpond,** a **rhomb graben** or, on a larger scale, a **pull-apart** basin. Strike-slip faults bound the basin on the two parallel sides of the stepover and normal faults bound the basin on the two end sides. Negative flower structures are also called **tulip structures**.



Negative flower structure
on a dextral strike-slip fault

- If the vertical component is reverse, the splay faults tend to be convex upward, with gentle dips at the surface. They form a reverse or **positive flower structure**, which appears as an uplifted, commonly antiformal area (a **rhomb horst** or **push-up**). Positive flower structures are also termed **palm-tree structures**, owing to the convex upward form of the upward-diverging faults.
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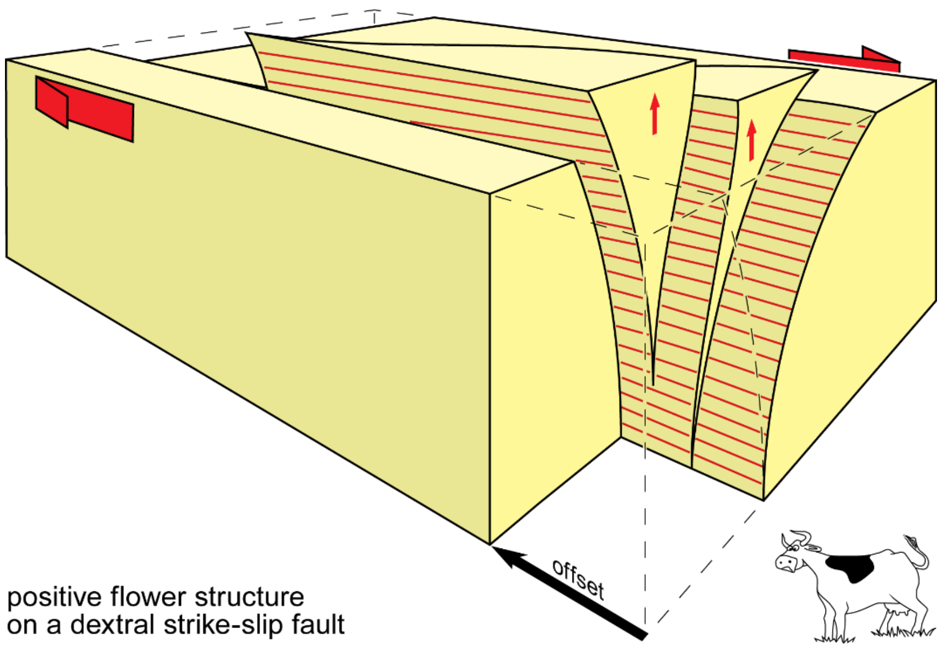
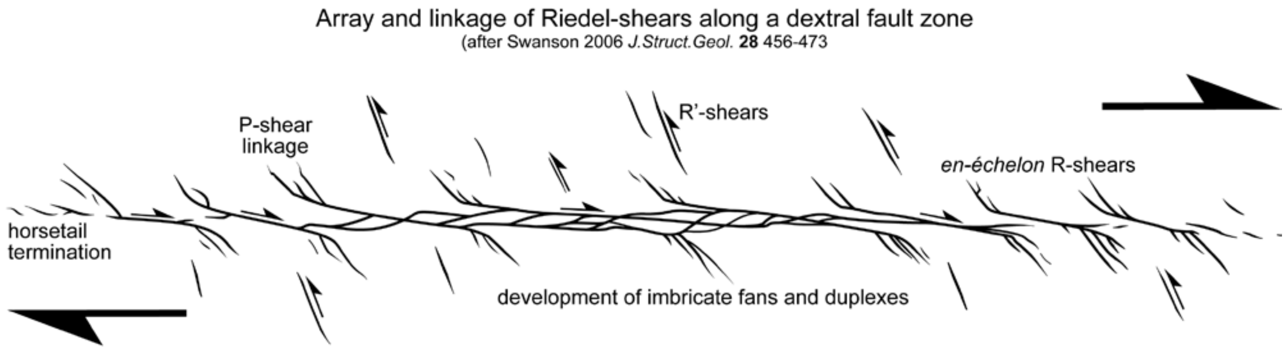


positive flower structure
on a dextral strike-slip fault

Sections of flower structures display strong variations along the same wrench system.

Strike slip faulting

Models using analogue materials such as clay and sand have revealed a fairly consistent faulting sequence in experimental strike-slip fault zones. Fault zones usually begin with a set of relatively short R-shears arranged in *en échelon* arrays and coeval with minor, conjugate R'-shears. With further deformation, R' shears connect propagating and overlapping R-shears while P-shears begin to form. Then, linkage of R-, R'- and P-shears, imbrication and duplexing of the resulting rhomb-shaped blocks combine to give a through-going but irregular fault zone consisting essentially of alternating R-shear and P-shear segments, synthetic to the sense of movement on the major fault. The differences in orientation of these segments relative to the overall slip direction means that the P-shear linkages are in restraining orientations for continued displacements. Further strike slip faulting may involve the modification of these restraining sections through both **abrasive** and **adhesive** Y-shear wears to form a more planar, through-going fault zone.

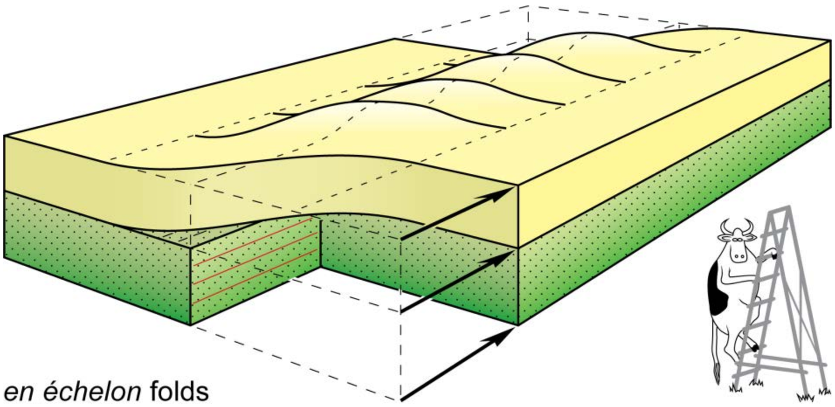


In theory all shear surfaces can occur and slip together but analogue experiments show that they mostly develop in different places at different times. Only some segments or splay faults are active at any one time. Faults can be dormant for considerable periods. This leads to complex and repeated reactivation of faults and fault segments leading to complex structure and stratigraphy.

Relationship between folds and strike-slip faults

Passive en échelon folds

Folds associated to wrench fault systems are typically non-cylindrical, doubly plunging and relatively short with steeply dipping axial planes. They are arranged spatially such that culminations and depressions in successive folds lie along lines that make an acute angle with the approximately parallel fold axes. Such folds are stepped, consistently overlapping, and said to be arranged *en échelon*. Taking the axial planes as roughly orthogonal to the shortening direction, their distribution permits to decipher the potential strike-slip fault they are related to. Such folds are common above strike slip faults in the basement, which have not broken the cover. The *en échelon* folding reveals the relative sense of movement.

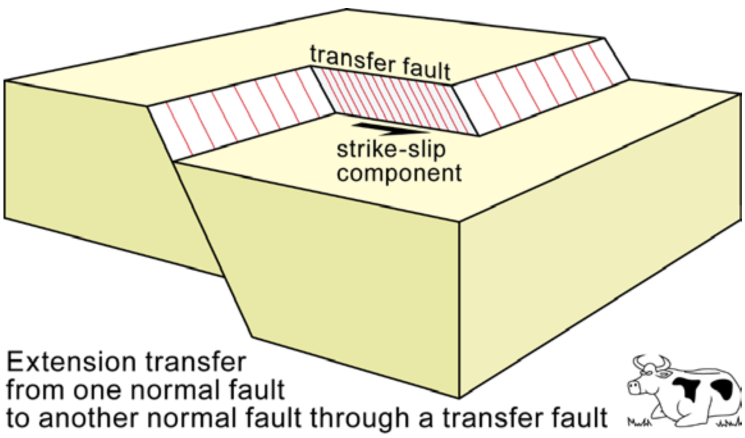


Local strike-slip faults associated with other structures

Local strike-slip faults occur in the hanging wall blocks of low-angle faults and accommodate different amounts of displacement either on different parts of the fault or between the allochthonous and adjacent autochthonous rocks. They are common in deforming regions that are detached from lower levels (e.g. in foreland fold-and-thrust belts). In this case, local strike slip faults die out downwards on a décollement that separates the deformed cover from the underlying basement.

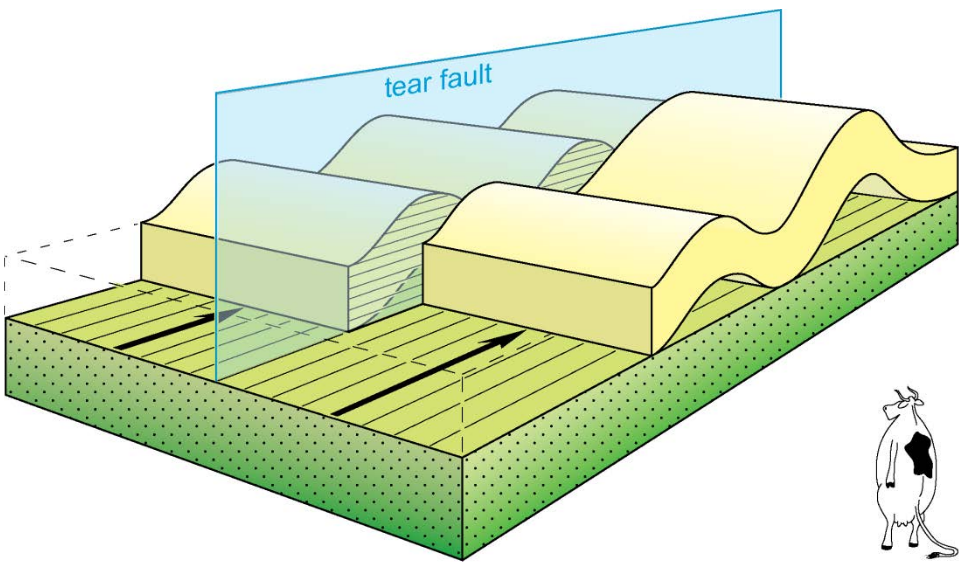
Transfer fault

A **transfer fault** is a strike slip fault that transfers displacement between two similar non-coplanar structures (e.g. in step-overs between two normal or thrust faults). It is striking parallel to the regional direction of extension or compression. The transfer fault terminates on these two other structures and is also known as lateral ramp. It is a local and passive fracture formed in response to active faulting on faults which link with the transfer. Hence, transfer faults can reverse their strike-slip sense in time and space and may show apparent offsets opposite to the true movement sense.



Tear fault

A **tear fault** is a relatively small strike slip fault that runs across the strike of a contractional or extensional belt and accommodates differential displacement between two adjacent segments of the belt. Tear faults are therefore parallel to the movement direction of thrusts or normal faults; they are usually common in hanging walls of low-angle faults. Fold axes, where folding is involved, tend to terminate against tear faults.



LARGE-SCALE ANALYSIS OF STRIKE-SLIP SYSTEMS

Strike-slip tectonics characterises the mature stages of orogenic belts. For example, escape tectonics in Asia occurred only late in the India-Asia collision. Similarly, there was lateral extrusion of Northwest Europe away from the North-African indentor well after the Variscan collision.

General features

Steeply dipping **transcurrent** fault zones and shear zones absorb the mechanical effects of stresses generated during the frictional move. Characteristically, deformed rocks have steep foliations and sub-horizontal lineation.

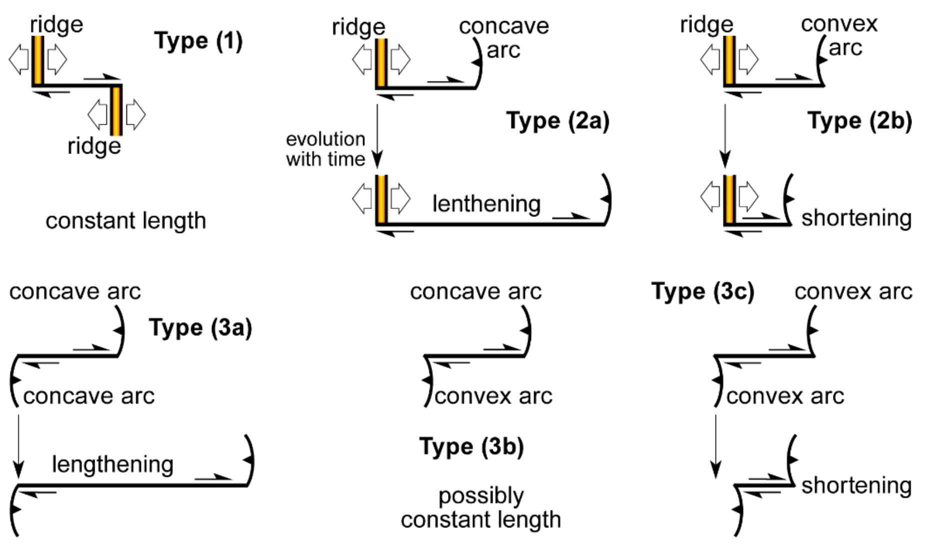
Transform boundaries

Transform faults are strike-slip faults at plate boundaries, parallel to the direction of relative motion of the plates on either side. They include transfer faults along which plates slide past each other, but the kind of motion between plates is changed at the end of the fault. For example, the transform fault may connect convergent and divergent plate boundaries, or trenches to trenches, etc... Such transform faults finish at a point where the strike slip movement is transformed into the corresponding convergence or divergence.

Accordingly, there are three basic types of transform faults that are extended to six more specific types:

Type			Example
(1)	Ridge-	Ridge	Mid-Atlantic
(2a)	Ridge-	overriding trench margin	
(2b)	Ridge-	subducting trench margin	Queen Charlotte Fault
(3a)	Concave trench -	concave trench	
(3b)	Concave trench -	convex trench	Alpine Fault, New Zealand
(3c)	Convex trench -	convex trench	Suliman Fault

This number can be doubled to twelve types if the sense of offset (sinistral or dextral) is considered.



Types of dextral transform faults, after Wilson 1965 *Nature* **207(4995)**, 343-347

Ideal type (1) transform faults are the most common, almost exclusively in oceanic regions. The Ridge-Ridge (R-R) transform are dynamically stable; offsets of the ridge axis correspond to offsets of continental margins and the length of the transform fault remains constant. Other transform types

evolve with time, but possibly (3b). The displacement rate along the transform fault depends on the relative velocities of the linked spreading and subduction zones. Cases (2a) and (3a) will tend to lengthen, in particular if slab roll back imposes trench migration. Conversely, and for the same reason, cases (2b) and (3c) will tend to diminish in length.
One of the best known examples is the San Andreas Fault that forms the plate boundary between the Pacific Plate to the west and the American Plate to the east.

Transform boundaries

Transform faults trend close to the relative motion between two plates. They are oceanic or continental. They have variable dimensions, from few hundred meters long, sometimes transient faults segmenting ridges, up to several hundred kilometres long, eventually oblique-slip faults. Transform faults reflect enormous strike-slip displacements between plates and thus truncate the whole lithosphere.

Ridge–ridge transform faults: strike slip in oceanic setting

No divergent plate boundary has a smooth, continuous trace; all are offset by transform faults. Ridge-Ridge transform faults (**fracture zones**) are prominent features that repeatedly offset the ocean ridges to accommodate differences in the spreading rates of either side of a ridge and/or between neighbouring segments.

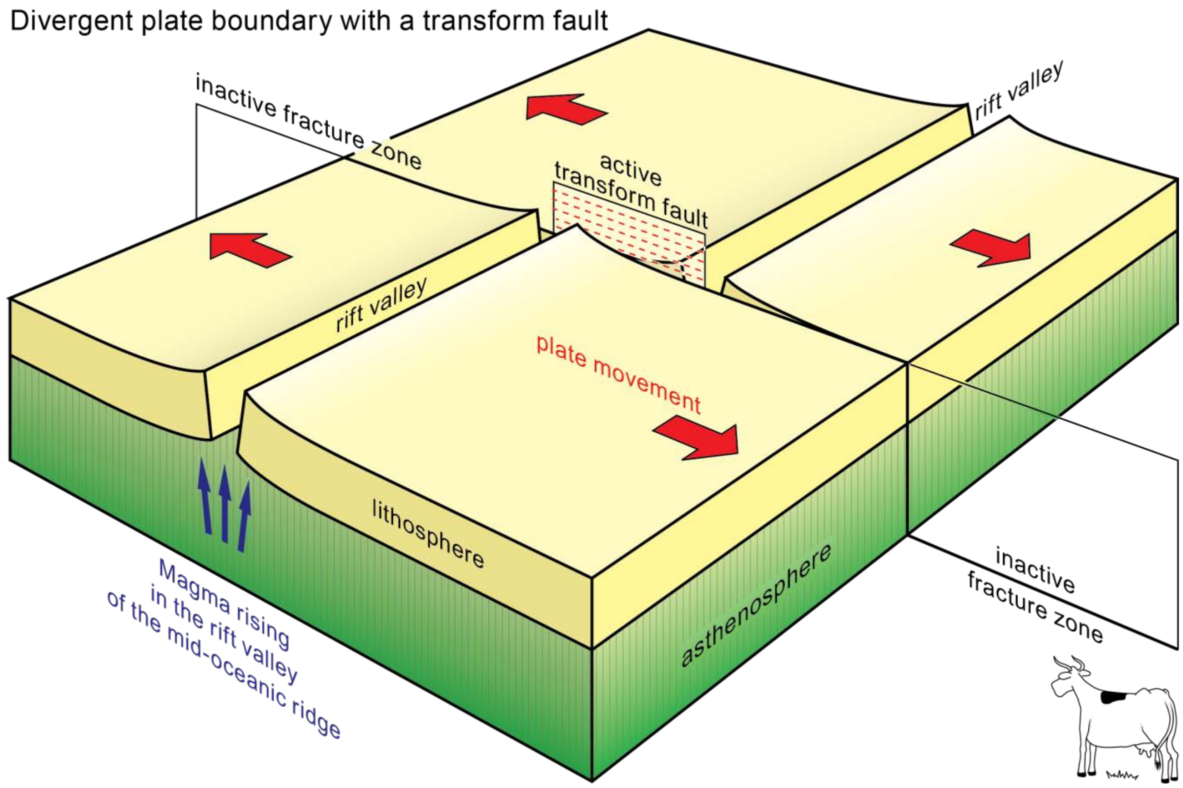
Origin

Major transform faults are often inherited from the continental rifting stage, when **transfer faults** connected two independent rifts or compensated uneven extension, and these faults are continuously propagated from the passive margins oceanward to segment the ridge (e.g. the, Romanche transform zones separating the African and South American plates in the Central Atlantic). Most transform faults form as part of the original plate boundary using old weaknesses and allow orthogonal spreading to proceed.
Assuming transform faults in oceanic crust are pure strike-slip, they normally follow small circles on the earth’s surface. One may use them to find the pole of rotation for divergent plates moving apart on a sphere.

Morphology

Fracture zones are very obvious, long linear bathymetric depressions with a sharp topography.
Ridge-Ridge transform faults have the following characteristics:
(i) They are nearly parallel to the direction of relative motion of the plates on either side, the spreading direction of the ocean ridge. They connect two offset segments of the ridge, which are nearly perpendicular to the spreading direction. The divergent motion away from the ridge is “transformed” to a transcurrent motion along such a fault.
(ii) They terminate the ridges abruptly. They also are plate boundaries and serve as zones of strike-slip accommodation between opposite-travelling domains of seafloor.
(iii) Equal displacement along their length.
(iv) Transform faults can accommodate unlimited amounts of displacement, which may even exceed the length of the fault.
(v) Contrarily to ordinary strike-slip faults, adjacent and parallel transform faults may show opposite senses of relative displacement. Sense of displacement can be opposite to what it seems to be from the apparent offset of the oceanic ridge.
(vi) The transform faults and the ridge are coeval. Earthquake activity is much higher along the transform faults (energy release 100 times greater) than along the ridges. But, because of the relative motion between the plates, the faults are active only between the offset segments of the ridge. Beyond this area, the plates on either side of the fracture are moving in the same direction and at the same rate and may be considered to be linked together. Earthquake activity along the fracture zones beyond the offset ridge segments is rare. It means that the apparent offset of ridges along the transform fault

is not necessarily increasing or decreasing during the activity of the system, whose geometry can persist steady for a long time.



(vii) Rocks along transform faults show greater amounts of shearing and metamorphism than the normal oceanic crust. Large blocks of serpentinite suggest that ultrabasic rocks are intruded along fracture zones. Some alkali basalt volcanism, hydrothermal activity takes place.
(viii) Transform faults juxtapose oceanic crusts of different ages. Because of thermal differences, 2–4 km large vertical offsets may form along oceanic transform faults where oceanic lithospheres of different ages are juxtaposed. The depth of the sea floor is dependent on the square root of the age and thus related to density and cooling. Oceanic crusts of different ages have subsided different amounts. Since thermal contraction continues as the oceanic lithosphere moves away from ridge, some dip-slip movement is expected to occur along the fossilised traces of transform faults, causing some seismicity. Thus it is expected that a scarp would develop across a fault zone with the lower side being the older. This initial scarp may still be preserved after 100Ma and it has been suggested that the two sides become welded together and subside keeping their relative heights.

Associated features

Transverse ridges can be associated with transform faults. Those are isolated mountains with a relief of ca. 6km on either or both sides of the transform fault. They cannot be explained by simple strike-slip or volcanic activity. They require components of compression or tension across the transform faults, for example from episodic small changes in spreading directions. Such ridges can become emergent to form islands such as St Peter-Paul (mantle peridotites).
Leaky transforms: when there is a new component of extension across a transform fault it can adjust its trajectory so as to become parallel to the spreading direction, again by splitting up into segments joined by short lengths of spreading ridges. This is called a leaky transform e.g. Gulf of California, Andaman Sea (transtensive).

Ridge-trench transform

The longest transform faults are connecting spreading to convergent plate boundaries (South America). A subtype would link a ridge to a mountain belt. This is the case for the Middle-East Fault, along which the Red Sea formed which links the Red Sea spreading centre to the N-Syria-E-Turkey collision mountains.

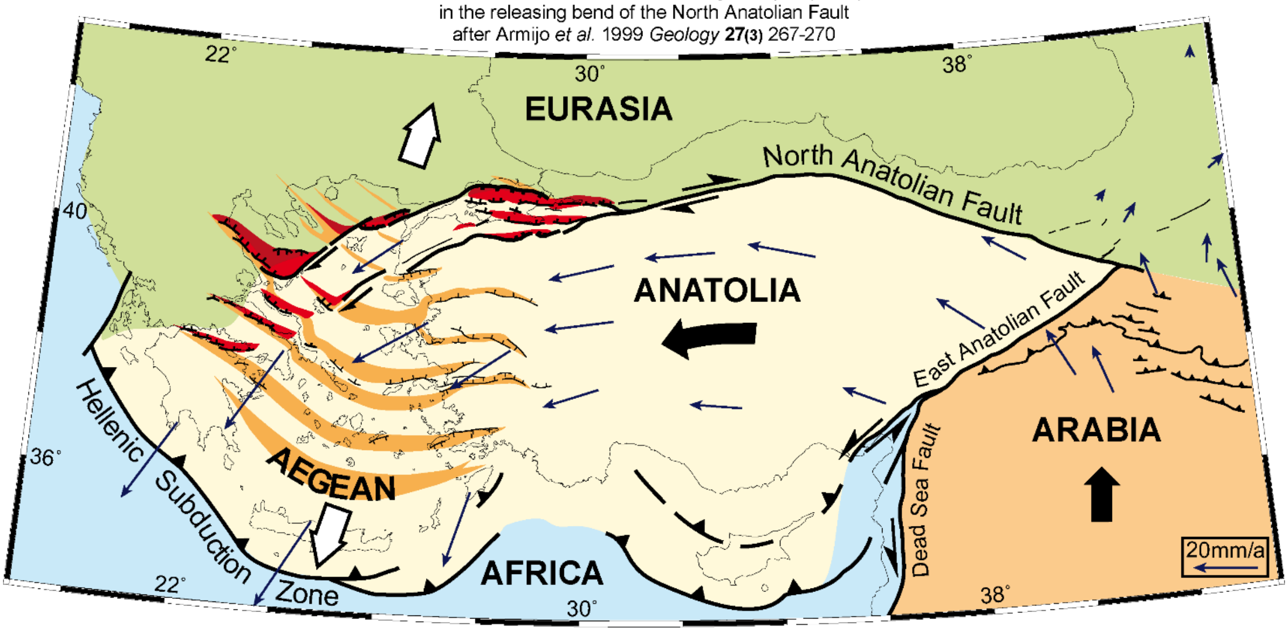
Trench-trench transform

Trench-trench transform faults are rare (Alpine fault in New Zealand). The direction of subduction changes across the transform fault. A subtype of transform faults connecting two convergent plate boundaries occurs on continents, linking two mountain systems. A classic example is the fault system connecting the N-Pakistan Himalayas and the Zagros, in Iran. A subsidiary type links a trench and a mountain (Java Trench - East Himalaya). In any case deformation and metamorphism are more important in continental settings than in oceanic settings. Trench-trench transforms link segments in which converging rates may different. As a consequence, such transform faults may increase in strike length through time.

Continental transform faults

Transform faults that cut through continents are similar to oceanic transform faults. Seismicity is shallow. Best known examples are the Alpine Fault in New Zealand, the Anatolian Fault in Turkey and the Levant Fault Zone that includes the Dead Sea Rift. The Levant Fault Zone, bordering the Arabian and African plates in the Middle East, transforms the spreading motion of the Red Sea into continental collision in eastern Turkey.

Continental extrusion of the Anatolia-Aegean Block between the North and East Anatolian strike slip faults.
Small arrows are current motions from GPS data. Note the losange-shaped pull-apart basin of the Marmara Sea in the releasing bend of the North Anatolian Fault
after Armijo *et al.* 1999 *Geology* **27(3)** 267-270



Oblique subduction

The slip vector oblique to a plate margin, whether in oblique continental collision or subduction, is partitioned into two components: a dip-slip, orthogonal component, responsible for pure underthrusting in the subduction zone; and a strike-slip component responsible for transcurrent motion on strike-slip faults parallel to the margin. Regions of dip-slip and strike-slip faulting commonly occur in different geographic areas, and a correct kinematic model can only be deduced by observing a very large area.

Oblique subduction is quite common. Major strike-slip fault zones paralleling the trench develop in the hanging wall of oblique subduction zones (e.g. the Semangko Fault in Sumatra). An Analysis of the energy balance between obliquity of the movement vector to the margin, dip of slab and friction

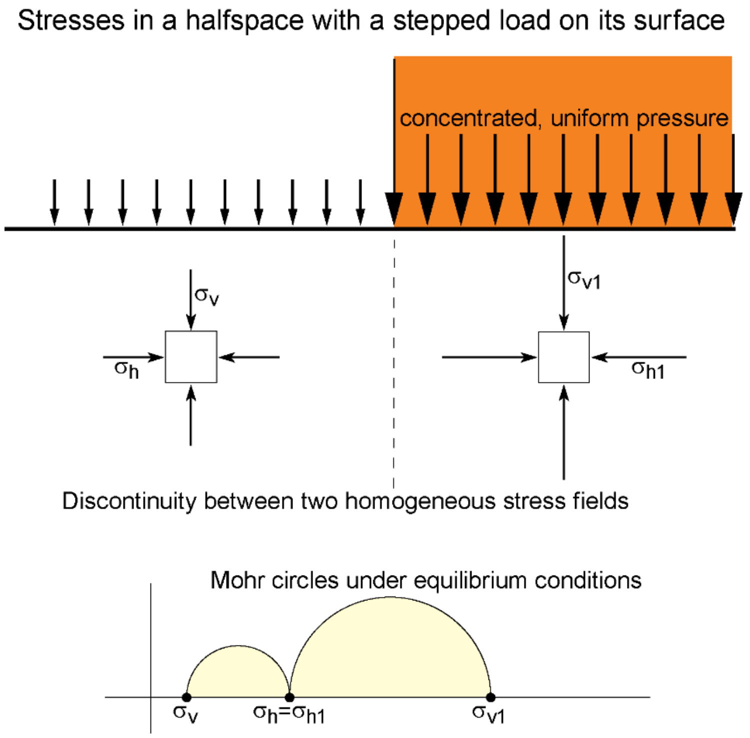
coefficient shows that trench related strike-slip faults should form when the vector-trench angle is less than 35-55° with low slab dips and high friction coefficients.
Partitioning of fault motions is an important mechanism for understanding the lateral tectonic transport of small or large blocks and fore-arc domains.

Tectonic escape

Continued convergence between two collided continents may require more shortening than one mountain system can absorb. Then, deformation propagates into the continents where shortening can be accommodated by **continental extrusion**. This within plate deformation involves large lateral movements (the **escape**) of continental blocks along major strike-slip (**transcurrent**) faults. Such large, solitary transcurrent faults are confined to the upper crust while wrenching is accommodated by diffuse ductile flow in deeper levels. Lateral **extrusion** of crustal blocks along such faults eliminates the need for crustal thickening in a convergent setting.

Concept

The concept of tectonic escape has been developed to interpret active tectonics of Asia. Since collision India has penetrated about 2000 km into Asia and the present day rate of convergence of about 5 cm yr^{-1}. To understand this amount of shortening of the Asian continental plate, an analogy was derived from the theory of **indentation** developed by geotechnical engineers to determine the stability of foundations, cuts, embankments and tunnels. Lithospheric plates are here considered to be thin layers suffering negligible, i.e. no vertical strain. The theory predicts mathematically, for simple shapes of both, plastic medium and die (the indentor), the configuration of lines of failure developed on indentation in two dimensions (i.e plane strain), the **slip lines**.



The problem of India, which has a limited width, pushing against the vast Asia is idealized and compared to the action of a wall on the ground. The horizontal ground and underground (Asia) is a homogeneous halfspace in which the stress field consists of three regions of homogeneous stress states:

- The weight of the wall applies a uniform stress over the width of the wall on the horizontal surface;

- On both sides of the wall the uniform stress applied on this horizontal surface is zero (in reality, the weight of air).

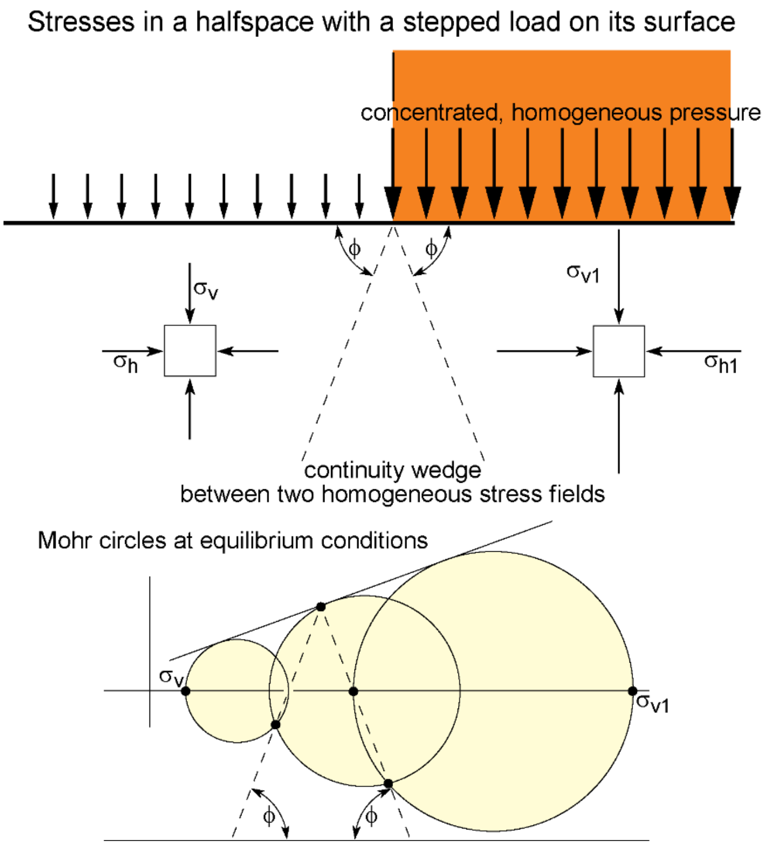
The vertical components of stress in the three regions increase together with depth z according to $\rho g z$, with ρ the density of the ground. The two vertical lines projected from the wall sides down into the half-space represent discontinuities of vertical stress components.

The horizontal components of stress, however, must be equal in the three regions in order to preserve horizontal equilibrium.

How can a stress field have continuous horizontal stress components and a jump in the vertical stress components?

The half-space behaves according to the Mohr-Coulomb shear criteria. In this configuration, the vertical and horizontal components are principal stresses. The yield conditions may be discussed with two Mohr circles, each representing the homogeneous stress states discussed above. Continuity is expressed provided the two circles are tangent at one common principal stress, and failure will occur when the Mohr circles reach the failure envelope.

The stress field is more complicated because the limits of the wall on the surface are stepped edges. In that case the discontinuity lines are symmetrical wedges opening downward from the wall boundaries at a defined angle with the horizontal. In order to preserve equilibrium, the normal and shear stress components along the wedge boundaries must be continuous from one domain to the next. Using the Mohr representation on which on plots the orientation of the wedge boundaries gives the points where the normal and shear stresses are equal for two adjacent domains if the two neighbouring Mohr circles pass through this point. The states of stress in the three adjacent regions are thus determined when the three circles are tangential to the Coulomb envelope, and the procedure is symmetrical for both sides of the wall.

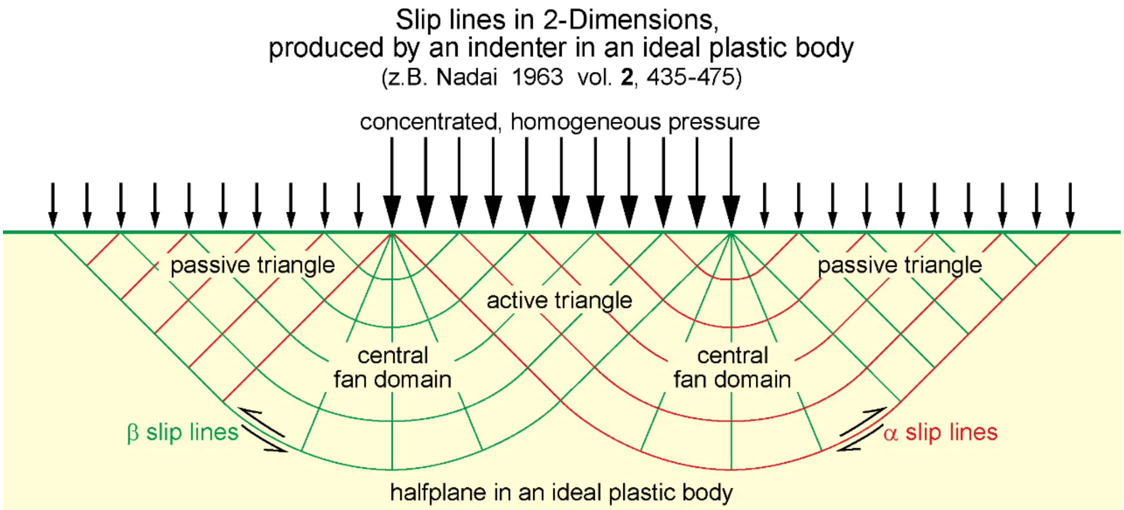


Note that principal stress directions in the intermediate wedges are not horizontal or vertical.

The two wedges below each side of the wall delimit a rigid, head-down triangle whose top basis is as wide as the wall; this non-deformable triangle tends to move vertically downward due to the pressure exerted by the wall. On both sides of this triangle, and in mirror symmetry about the center line, two zones tend to diverge horizontally to make way for the down-moving, rigid triangle while parts of the ground on both sides of the wall will tend to move upward, to make way to the horizontally displaced zones. These lateral and upward expulsions occur along shear surfaces.

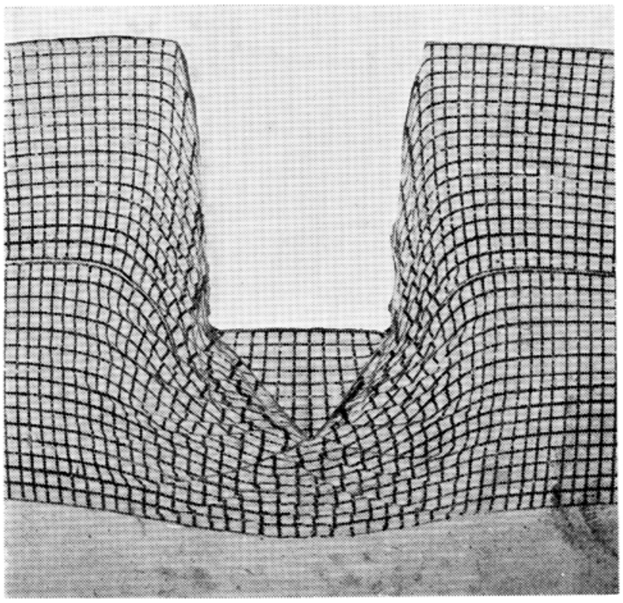
Slip lines

The mathematical solution defines two families of usually curved slip lines conventionally termed α- and β-lines. They form an orthogonal network in perfectly plastic solids with no frictional strength. In that case, the direction of the greatest principal stress bisects the right angle between the α- and β-directions. α- and β-lines coincide with the trajectories of maximum shear stress, and as such can be expressed in geological terms as lines (faults) with dextral and sinistral strike-slip motion, respectively. In materials that have a non-zero friction ϕ, the α- and β-lines are no longer orthogonal but must intersect at an angle of $\left[(\pi/2)-\phi\right]$.



Application

The concept has been further established by analogue modeling. The device includes a block of plasticine deformed by a rigid indenter advancing at a constant rate. Faults on α- and β slip lines guide the sideways translation and rotation of **extruded** blocks. The size of the blocks depends on the indenter width and on the width of the indented block.
In plane indentation experiments confined on one side only, deformation is asymmetric.
The geometrical correspondence between prediction from slip line models and Asian tectonic features suggest that faulting may be the dominant mode of distributed deformation of the continental lithosphere. Fault propagation as a response to indentation on a plate boundary reconciles intracontinental deformation and plate tectonics.



Indentation experiment with lateral escape in silicone
after Johnson, Sowerby & Haddow 1970, Arnold (Publishers) Ltd, London, 176 s.

Tectonic escape shows the following characteristics:

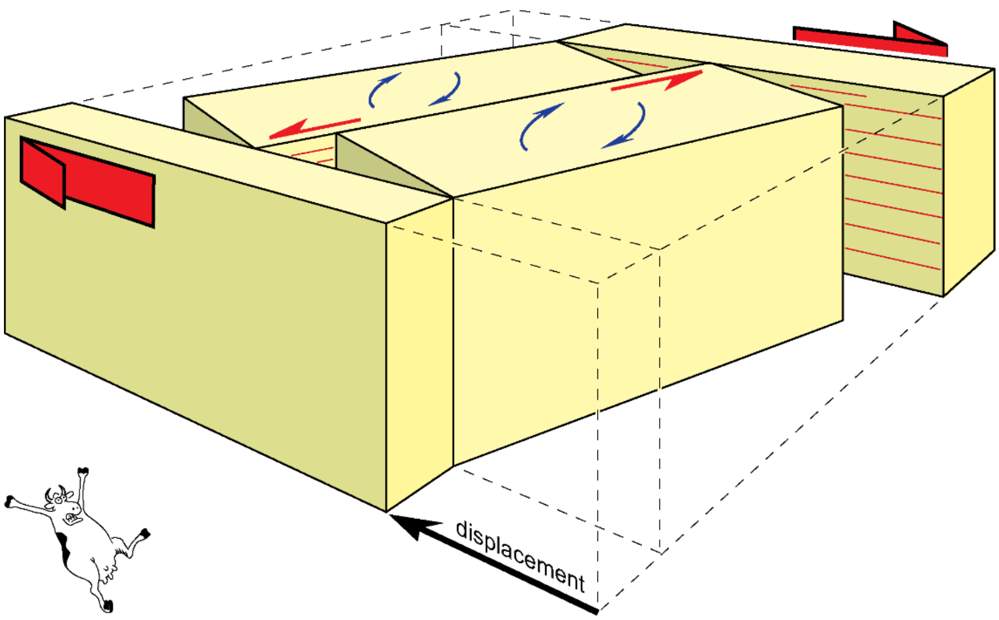
- The "escaping" blocks are bounded by two dominant strike-slip systems, which have the same or opposite sense of movement.
- The movement increases in the direction of escape.

The process can happen on a large scale, or on a small scale along uneven continental margins colliding with indenting promontories.

Block rotation

Measurements of paleomagnetic declinations have shown that crustal blocks in wrench systems have commonly rotated, along with the bounding faults. The rotation axis is essentially vertical. Block rotation takes place in accordance with the bulk sense of shear, as in the domino model of normal faults clockwise in dextral and anticlockwise in sinistral wrench zones.

Clockwise block rotation in a dextral wrench zone

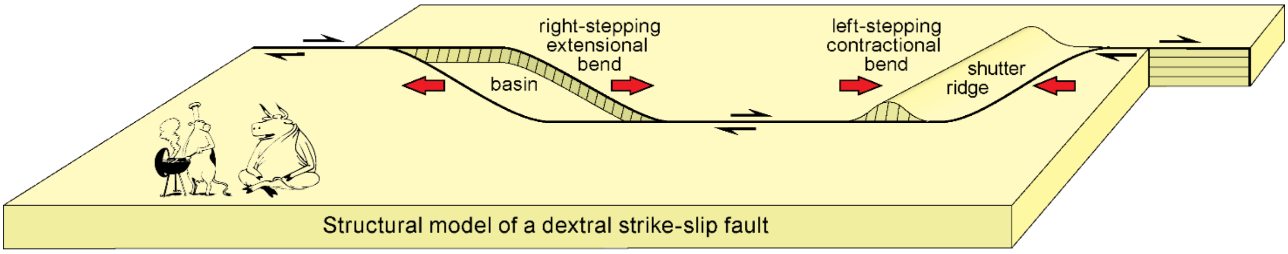


Strike slip faulting and sedimentation

Sedimentary basins developed in strike-slip settings are usually rhomb-shaped, fault bounded pull-apart depressions formed in transtension settings.

Pull-apart basins

Extension in pull-apart basins records the amount of strike slip displacement that formed them. Once established, they subside very quickly and accumulate large thickness of alluvial and or lake deposits. These are coarse-grained terrigenous sediments in large delta or alluvial fans near the fault scarps of marginal half-grabens and basin deposits in the center. A well-known example is the Dead Sea.



Pull-apart basins may eventually lead to plate separation along a system of side-stepping spreading centers. This occurs in the Gulf of California, which has been becoming an oceanic embayment. The thermal evolution of pull-apart basins depends on whether the mantle is involved or not i.e. whether the controlling strike-slip faults cut through the whole crust / lithosphere.
If the mantle is involved then the basin will have a thermal or cooling phase; if not then it will simply be a deep fault controlled basin.

Porpoising subsidence

Repeated cycles of basin uplift and submergence associated with the evolution of steps and bends along wrench systems give rise to multiple unconformities in strike-slip basins. This syntectonic sedimentation style controlled by alternating, multiple basin inversion, suggests that crustal slices “porpoise” along multiple restraining and releasing bends, thus shifting from transpression to transtension zones. Volcanism can occur in such basins when transtension is largely dominant.

Conclusion

Clearly identifiable evidence for strike-slip systems is:

- Riedel fracture patterns of different scale
- *En échelon* folds and strike-slip faults
- Horizontal lineations on originally subvertical foliations.

Basement-involved faulting generally drives strike-slip tectonics. When basement faults are reactivated a zone of **rotational bulk strain** develops in the sedimentary overburden. The strain is accommodated by a variety of *en-échelon* structures including Riedel shears, normal faults, thrusts and folds. However, in basement-detached tectonics (e.g. above a salt layer), a symmetric, conjugate pair of strike-slip faults will develop accommodating irrotational bulk strain. In basement rooted **wrench** faulting, the first structures to appear are *en-échelon* Riedel shears. Riedel shears are important kinematic indicators, e.g. left-stepping faults indicate a right lateral component of displacement. The surface strike orientations of the early Riedel shears, their dips and lengths vary according to the initial stress state, the horizontal layering of the overburden and the complexity of the basement fault configuration. With increasing displacement, short-lived **splay faults** develop at the tips of the Riedel shears, followed by the development of **low angle Riedel shears** and P-shears which link and interfere with the Riedel shears. In cross-section, the most commonly observed fault pattern is a flower structure.

In transtension and transpression, the sense of vertical displacement and the geometry of **oblique-slip** faults are indicative of the tectonic regime; **partitioning** of fault motions is favoured by the presence of a ductile layer at depth. Movements along laterally offset basement faults generate pop-up structures and pull-apart grabens in restraining and releasing bends, respectively. In these cases, the ratio of the length of basement-fault offset to the thickness of the sedimentary cover is the main parameter controlling the geometry of the fault pattern.

Recommended literature

Harding T.P. - 1985. Seismic characteristics and identification of negative flower structures, positive flower structures, and positive structural inversion. *Bulletin of the American Association of Petroleum Geologists* **69 (4)**, 582-600.

Kearey P., Klepeis K.A. & Vine F.J. - 2009. *Global tectonics*, third ed. Wiley-Blackwell, Oxford, 482 p.

Mann P., Hempton M.R., Bradley D.C. & Burke K. - 1983. Development of pull-apart basins. *Journal of Geology* **91 (5)**, 529-554.

Moores E.M. & Twiss R.J. - 1995. *Tectonics*. W.H. Freeman and Company, New York, 415 p.

Park R.G. - 1993. *Geological structures and moving plates*, 2nd ed. Chapman & Hall, Glasgow, 337 p.

Scholz C.H. - 1977. Transform fault systems of California and New Zealand: similarities in their tectonic and seismic styles. *Journal of the Geological Society of London* **133 (3)**, 215-229.

Stein R.S., Barka A.A. & Dieterich J.H. - 1997. Progressive failure on the North Anatolian fault since 1939 by earthquake stress triggering. *Geophysical Journal International* **128 (3)**, 594-604.

Sylvester A.G. - 1988. Strike-slip faults. *Geological Society of America Bulletin* **100 (11)**, 1666-1703.

Twiss R.J. & Moores E.M. - 1992. *Structural geology*. W.H. Freeman & Company, New York, 532 p.

Woodcock N.H. - 1986. The role of strike-slip fault systems at plate boundaries. *Philosophical Transactions of the Royal Society of London* **A317**, 13-29.

Woodcock N.H. & Fischer M. - 1986. Strike-slip duplexes. *Journal of Structural Geology* **8 (7)**, 725-735.