8

Transform faults

Transform faults represent one of the three types of plate boundaries. A peculiar aspect of their nature is that they are abruptly transformed into another kind of plate boundary at their termination (Wilson, 1965). Plates glide along the fault and move past each other without destruction of or creation of new crust. Although crust is neither created or destroyed, the transform margin is commonly marked by topographic features like scarps, trenches or ridges.

Transform faults occur as several different geometries; they can connect two segments of growing plate boundaries (R-R transform fault), one growing and one subducting plate boundary (R-T transform fault) or two subducting plate boundaries (T-T transform fault); R stands for mid-ocean ridge, T for deep sea trench (subduction zone). R-R transform faults represent the most common type and are common along all mid-ocean ridges (**Fig. 1.5**).

The length of R-R transform faults remains constant; however, in contrast the length of R-T and T-T transform faults, with one exception, either grows or shrinks (**Fig. 8.1**). Transform faults that connect subducting plate boundaries typically cut through areas of continental crust. Examples include some of the most notorious transform faults, the San Andreas Fault in California (**Fig. 8.7**), the North Anatolian Fault in Turkey (**Fig. 8.10**), the Jordan Fault in the Middle East (**Fig. 8.6**), and the Alpine Fault on the southern island of New Zealand (**Fig. 8.11**).

Oceanic transform faults

Mid-ocean ridges are intercepted by R-R transform faults that normally are perpendicular to the ridge. Thus the ridges are subdivided into segments that mostly have lengths of several tens of kilometers. At the East Pacific Rise west of Mexico, large transform faults occur at distances of several hundred kilometers and smaller ones occur at distances of 10 or 20 km. In each case the fault connects two segments that appear to be dislocated. However, the ridge segments maintain their distance from each other and are not dislocated by the fault; in fact, the fault forms a connecting link of constant length (**Fig. 8.1b**). Although every transform fault is a strike-slip fault, not all large strike-slip faults represent a plate boundary (**Fig. 8.1a**).

Because of the drift of the newly formed oceanic crust away from ridge segments, a relative movement along the faults is induced that corresponds to the spreading velocity on both sides of the ridge. The sense of displacement is contrary to the apparent displacement of the ridge segments (**Fig. 8.1b**). In the example shown, the transform fault is a right-lateral strike-slip fault; if an observer straddles the fault, the right-hand side of the fault moves towards the observer, regardless of which way is faced. Transform faults end abruptly in a point, the transformation point, where the strike-slip movement is transformed into a diverging or converging movement. This property gives this fault its name. In the example of the R-R transform fault, the movement at both ends of the fault is transformed into the diverging plate movement of the mid-ocean ridge. Beyond the transformation point, the crust on both sides of the imaginary prolongation of the fault moves in the same direction with the same velocity. Therefore, no strike-slip movement occurs in the prolongation of the fault beyond the transformation point. The dashed lines in **Figure 8.1b** mark this fissure where younger crust is welded against older crust beyond the the transformation point.

The best confirmation for the mechanism of oceanic transform faults is the earthquake occurrence and the fault-plane solutions of the quakes (Ch. 2). Only the segments of the active transform fault between the ridge segments indicate continuous seismic activity; seismicity ends abruptly at the transformation points, the termination points of the faults. The fault-plane solutions always indicate horizontal displacement parallel to the fault with a sense of displacement which is consistent with the prediction of the theory.

Fracture zones in the ocean floor

In spite of its abrupt end, the prolongation of a transform fault is topographically expressed on the ocean floor. This expression is caused by the different ages of crust across the prolongation. This age difference creates an isostatic imbalance so the crust lies at different depths. Across this prolongation, there is no plate boundary. With respective increasing age and increasing distance to the ridge, the ocean floor subsides (**Fig. 4.11**). Younger crust

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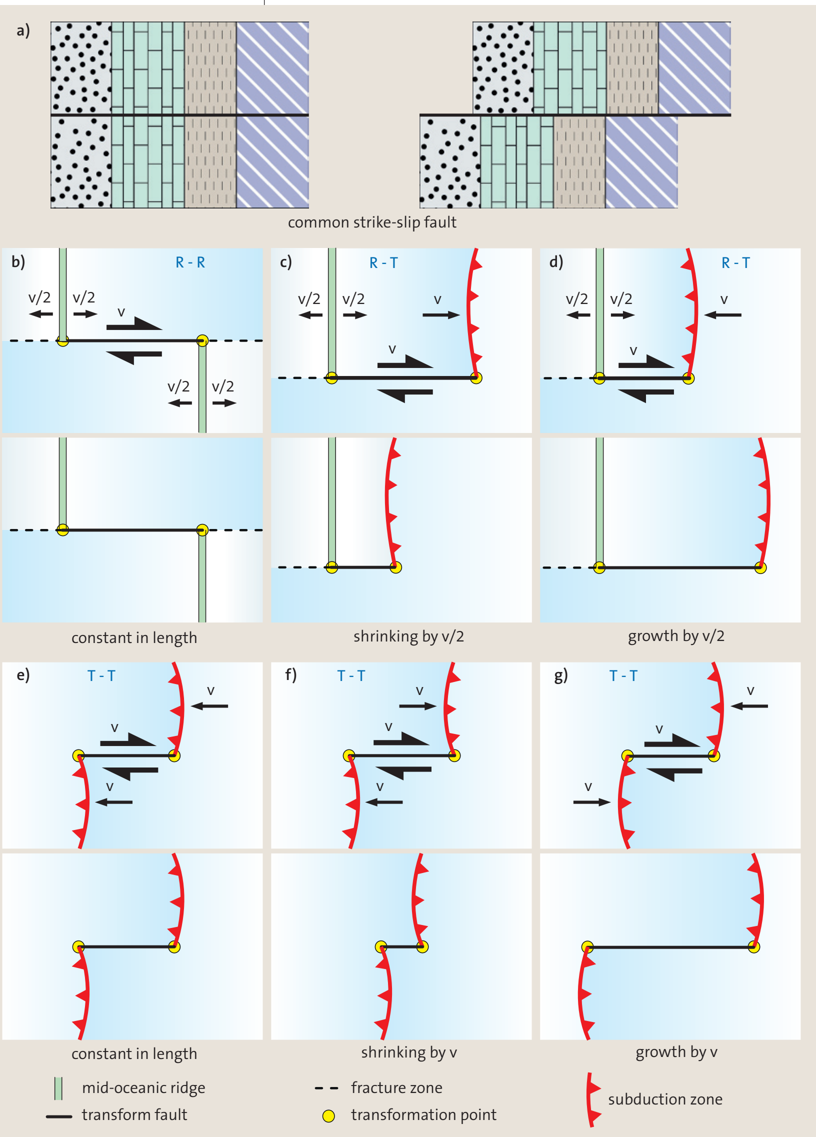
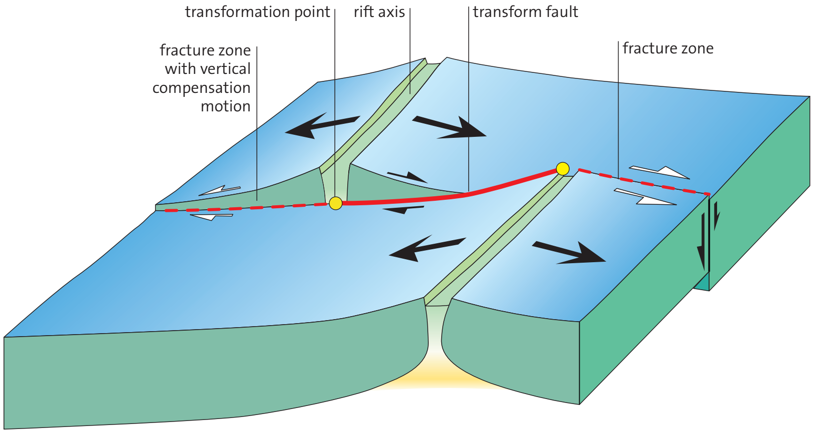


◀ Fig. 8.1 Sketch maps showing possible configurations of transform faults (b-g) compared to the geometry of a common strike-slip fault (a). All examples shown have right-lateral displacements. The movement velocity (v) is the relative movement between the two plates. Each respective lower image indicates the modification to fault geometry over time. R: mid-ocean ridge, T: deep sea trench (subduction zone).

▼ Fig. 8.2 Geometry of transform faults at a mid-ocean ridge. Although the strike-slip movement ends abruptly at the transformation point, a vertical movement occurs in its prolongation ("fracture zone") because the adjacent crustal segments of different ages subside with different rates.



is at the same time subsiding faster than older crust. Because the prolongation of the active part of the transform fault separates crustal segments of different ages, relative vertical movements occur along this fissure (**Fig. 8.2**). Therefore, these fissures are planes of movement, mostly vertical in nature, and are called fracture zones. Beyond a transformation point at a subducting plate boundary, a fracture zone cannot continue because plate segments are not welded together at such a location but rather are split; crust on either side is of the same age (**Fig. 8.1c–g**).

The fracture zones on the ocean floor are clearly visible in submarine digital relief maps. They represent zones of weakness within the oceanic plates and are thus easily reactivated. Prominent examples can be observed in the Eastern Pacific where several significant fracture zones occur. They are spaced at distances of approximately 1000 km and can be traced from the margin of the North American Plate westward into the ocean (**Fig. 8.3**). Also in the Atlantic, especially in the region between Western Africa and Brazil, a number of large fracture zones occur as the prolongation of transform faults. At the fracture zones, the magnetic stripe patterns appear displaced in the same dimension as the mid-ocean ridges (**Fig. 2.12**).

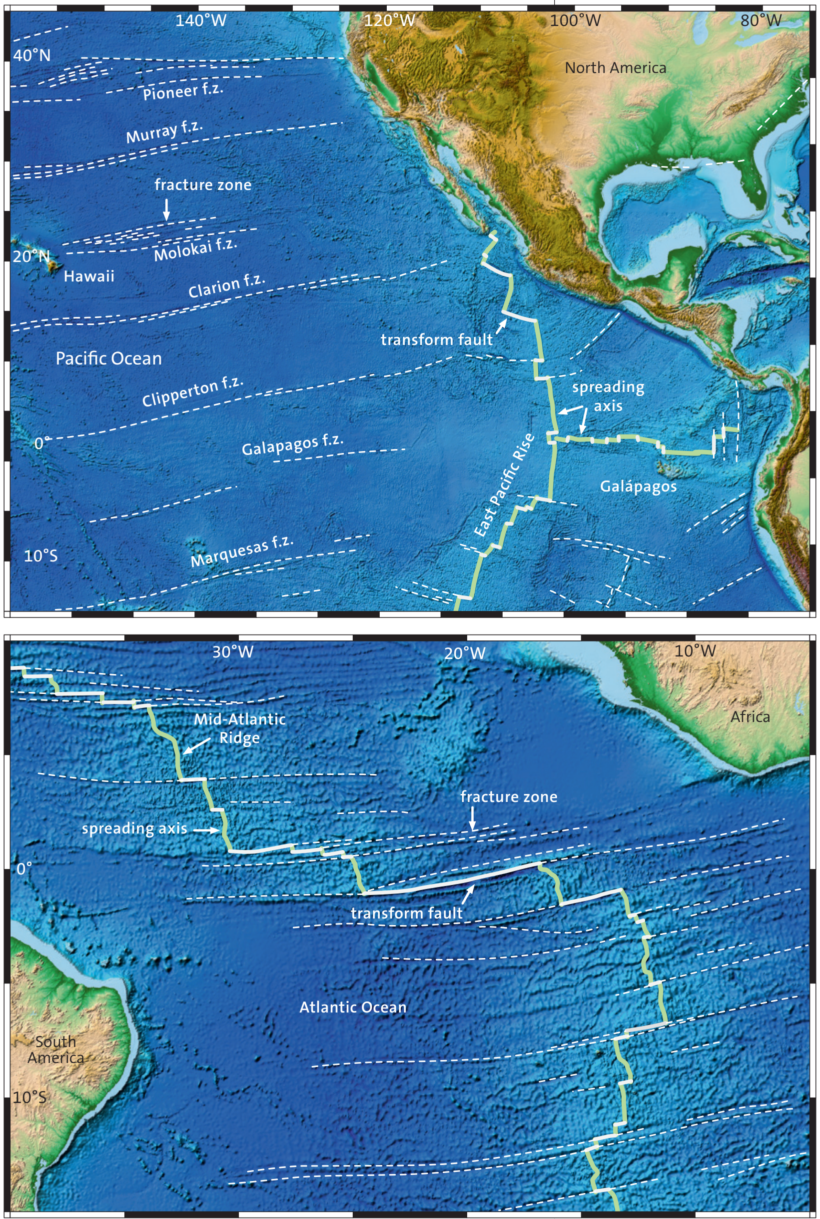
Oceanic transform faults and fracture zones commonly form escarpments, ridges or deep troughs with relief greater than 2000 m. The intervening segments of the mid-ocean ridge appear as dome-shaped bulges (Ch. 5). The Puerto-Rico Trough at the northern edge of the Caribbean Plate is an example of a large depression along a transform fault and its dimensions approach those of a deep-sea trench at a subduction zone (**Fig. 8.4**). It obtains a maximum water depth of 9219 m. Along the Murray fracture zone in the northeastern Pacific (**Fig. 8.3**), a trough with a water depth of more than 6000 m is developed; in contrast, the abyssal plain is 1000 m higher. Also along this fracture zone are elongate ridges that protrude more than 1000 m above the ocean floor.

The occurrence of ridges and troughs along oceanic transform faults is a result of tensional and compressional processes. Tension or compression occurs along the fault when the plate motion direction slightly changes. Commonly, the narrow, elongate stretched plate segments between the transform faults and fracture zones may be locally rotated further complicatig the fault geometry. Tension and compression may alternate at the same location or appear spatially laterally along a fault zone. Tension and compression generate distinct products on the ocean floor; tensional forces generate deep cracks in which sedimentary deposits form and occasionally produce intraplate volcanism whereas compressional forces generate reverse faults or folds, particularly within soft sedimentary deposits of the troughs, and ridges result. These movements along the fracture zones are capable of producing sporadic, small earthquakes.

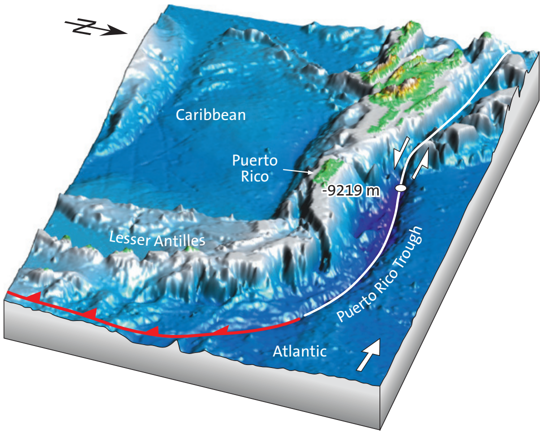
The vertical and lateral movements along oceanic transform faults and fracture zones cause the exposure of various kinds of oceanic rocks; these rocks are commonly strongly deformed and metamorphosed. Sheared fragments derived from the deeper crust, including deformed and metamorphosed gabbros, have been found in various locations. At the Vema fracture zone in the Atlantic, the entire profile of the oceanic crust is exposed by the vertical movements (**Fig. 5.12**). Serpentinites converted from peridotites in the uppermost mantle, can ascend along the zones of weakness to the surface.

Continental transform faults

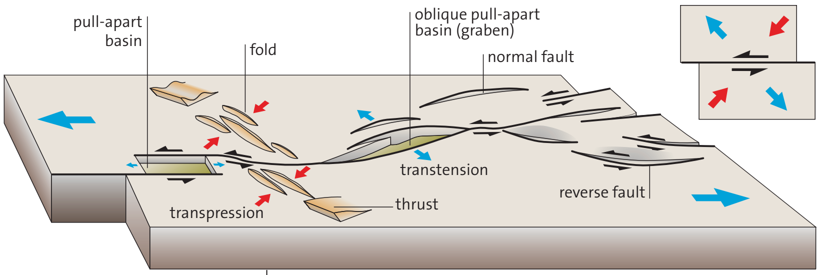
Continental transform faults are considerably more complex than their oceanic counterparts. Their geometry and complexity reflect the easy deformability of continental crust, its variable composition, and the presence of pre-existing structures developed during long periods of crustal evolution. Continental transform faults are generally accompanied by numerous other faults of variable size and type so that broad fault zones or fault systems develop. These fault zones range to several 100 km in width and comprise fragmented rhombic or lenticular blocks of variable dimensions. Some of the blocks are also moved in the vertical direction because of local compression or tension, even though the plate movement and main displacement occurs in the horizontal direction. Some continental transform faults are characterized by 1000 km or more of movement over millions of years. The San Andreas Fault system and its predecessors of California and western Mexico illustrate these points: the right-lateral system is approximately 2500 km long, 30 million years old, several hundred kms wide, has offset segments of continental crust more than 500 km, and consists of blocks that have experienced uplift or subsidence of 5–10 km. The southern half of the system has evolved into the



▲ **Fig. 8.3** Map showing major fracture zones and transform faults in the East Pacific and Central Atlantic.

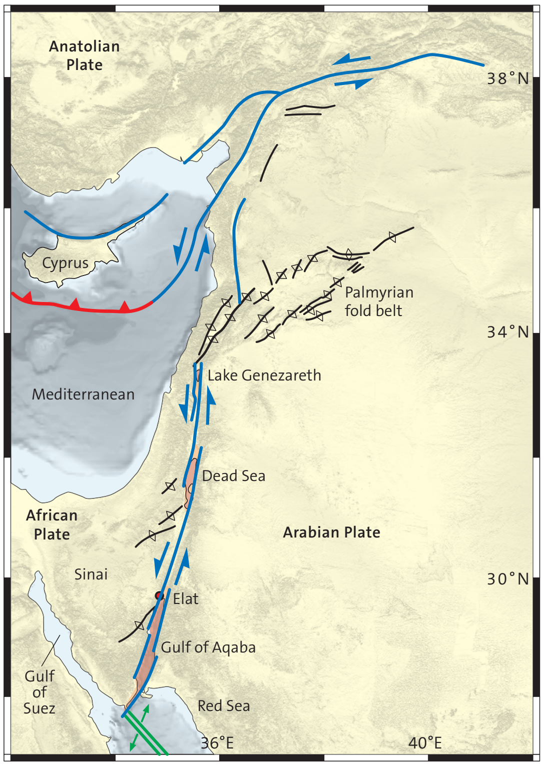


◀ **Fig. 8.4** The transform fault at the northern boundary of the Caribbean Plate forms the Puerto Rico Trough at more than 9000 m below sea level.



▲ **Fig. 8.5** Block diagram showing geometry of a transform fault system with pull-apart basin, oblique pull-apart basin, transpressional structures (folding, reverse faulting) and fan-out of the fault. The insert indicates the principal directions of compression and tension in relation to the main fault.

► **Fig. 8.6** Map of the Jordan structure, a large transform fault system that connects the spreading system of the Red Sea with the subduction zone of Cyprus. Pull-apart basins like the Dead Sea and Lake Genezareth line up along the transform fault. Transpression is responsible for the formation of the Palmyrian fold belt. The relative movement between African and Arabian plates is about 1 cm/yr.



Gulf of California, a transtensional, very recent (ca. 5 Ma) ocean basin.

Earthquake activity at continental transform faults is much stronger than that at oceanic transform faults because of the large thickness and complex structure of continental crust and the length of the faults, up to or more than 1000 km. Along with subduction zone faults, these fault zones produce the most devastating earthquakes. The 1906 San Francisco earthquake yielded displacements of more than 5 m along the San Andreas Fault (see **Fig. 8.9**) and was one of the strongest earthquakes of the 20th century. The North Anatolian Fault of Turkey also produced a dreaded sequence of earthquakes. The last devastating earthquake was that of Izmit in 1999, the strongest earthquake since 1939 along their fault (see **Fig. 8.10**).

The complex structure of continental crust transform faults typically alters the geometry normally defined by the small circle to the pole of rotation (Ch. 2), so consequently, the course of the fault consistently deviates from the theoretical track line. Thus zones of tension and compression develop in the crustal blocks gliding along each other. The complex and variable geometry of continental transform faults is illustrated in Figure 8.5. Transtension occurs where the strike-slip motion is also under tension, and transpression occurs where the motion is also under compression. Graben-like depressions and oblique tensional basins, termed pull-apart basins, are generated under transtension; surrounding uplands supply the rapidly subsiding basins with sediment. Transpression generates reverse faulting and folding in the adjacent crustal blocks. The normally rapid uplift results in high rates of erosion. The Ridge Basin along the San Andreas Fault is a well studied pull-apart basin and the mountains of the Transverse Ranges including the San Gabriel Mountains and San Bernadino Mountains are examples of transpressional uplift.

Pull-apart basins can also form where stepover geometry occurs along transform faults. Here two overlapping segments of the fault system generate a basin as wide as the distance between the segments and as long as the zone of fault overlap (**Fig. 8.5**). The continental crustal basement can become thinned or even dismembered, and in the latter case, new oceanic crust will be formed. The basins have high subsidence rates (up to several mm/yr) and are supplied with abundant sediment from the graben walls along with mixed volcanic rock material. Technically, pull-apart basins represent a growing plate boundary across the transform fault.

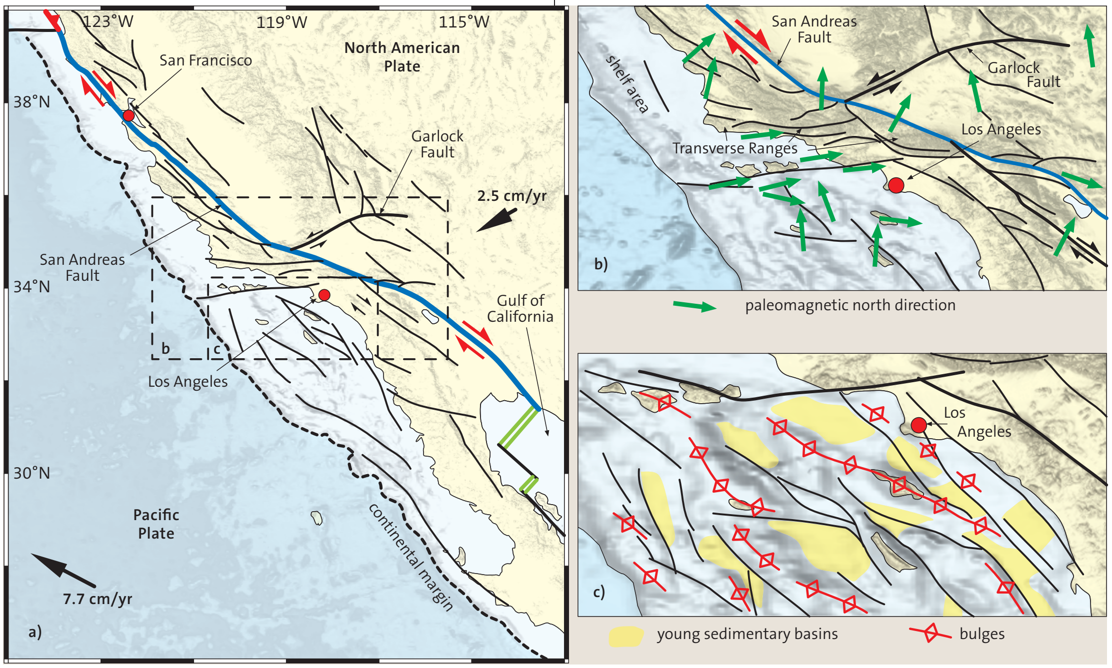
The Dead Sea, a modern pull-apart basin, exists in the Jordan Rift (**Fig. 8.6**). The system initiates in the Gulf of Aqaba, a graben-like transform fault with a left-lateral total displacement of 110 km that extends northward into southeastern Turkey. At several locations the main fault is offset at left-handed stepovers that continue as a parallel fault. A left-lateral displacement with left-hand stepovers generates a pull-apart basin (**Figs. 8.5, 8.6**). The Dead Sea has a basement that has subsided several thousand meters. Sedimentary input by rivers, however, is low due to the desert environment. Therefore, the 6 km-thick sequence of sedimentary material contains thick layers of evaporitic sediments like halite and gypsum. Much of this formed in response to repeated saltwater invasions from the Mediterranean that subsequently deposited evaporite sediment during desiccation. The present low precipitation and high evaporation rates in the Dead Sea mean that subsidence rates exceed sedimentation rates to form the deepest depression on Earth, nearly 400 m below sea level. North of Lake Genezareth, which is another pull-apart basin 200 m below the sea level, the transform fault exhibits a restraining bend with transpression. This bend is partly responsible for the compression that produces the Palmyrian fold belt.

San Andreas – the infamous transform fault of California

The 1100 km-long San Andreas Fault in California is probably the most studied fault on Earth. The San Andreas Fault, which forms the plate boundary between the Pacific and North American plates, has a displacement rate of 6 cm/yr (**Fig. 8.7**). The details of this fault system illustrate the complexity of transform faults in continental areas. The present plate boundary with its intense earthquake activity is one of the most dangerous faults in the world. The San Andreas Fault is part of a complicated, broad fault system accompanied by numerous other faults of various sizes and types. All of the parallel faults, some currently active, some apparently extinct, are right-lateral (dextral) faults. Although a total displacement of 1500 km can be documented on the system since its inception 25–30 million years ago, only 300 km of this displacement has occurred at the present San-Andreas Fault. The remaining 1200 km of displacement has been taken up by the other accompanying faults.

The Garlock Fault (**Fig. 8.7**), a WSW-ENE striking fault with left-lateral (sinistral) displacement, has an orientation perpendicular to the San Andreas system. Dextral and sinistral faults form a conjugate fault system because they belong to the same stress field and were alternately activated during the same period. Because the Garlock Fault is nearly perpendicular to the San Andreas Fault and causes deviation in the course of the latter, a strong transpressive component develops along the plate boundary and the accompanying parallel faults of the San Andreas system.

The complexity of the San Andreas system is clearly documented by the interlocking fault pattern that has produced numerous small crustal blocks that interact with each other. The dextral sense of movement at the plate boundary has rotated some these blocks in ball-bearing fashion (**Fig. 8.7b**). The E-W-trending Transverse Ranges provide the best example. Their odd orientation produces the large E-W offset obvious along the Southern California coast. The up to 120° of rotation over the past 15 m.y. has been determined with the aid of paleomagnetic investigations. The magnetic polarity and direction prevailing at the time of formation is recorded in magmatic rocks during their cooling and in sedimentary rocks during their deposition and diagenesis. If a later rotation of a crustal block occurs the "frozen" magnetic direction does not coincide with the former position of the magnetic pole (magnetic and geographic poles coincide in average). From the difference of the pole directions, the rotation angle of the crustal block can be determined (**Fig. 8.7b**).



◀ **Fig. 8.7** The San Andreas Fault system in California (Christie-Blick and Biddle, 1985) (a). Numerous faults approximately parallel the dextral San-Andreas Fault and have the same sense of movement; the oblique Garlock Fault moves in the opposite direction (sinistral). Green arrows (b) indicate the original north orientation of individual blocks of the Transverse Range. Many of them have rotated clockwise, some as much as 120°. Along the fault, bulges were caused by compression and basins were formed by extension (c).

The geometry of the Transverse Ranges reflects the individual movements of the small blocks and their response to space problems that originate because of their rotation. Collision, transform motion, or separation occurs along their boundaries and, in response, the rocks are deformed or compensated by compressional structures (folds, reverse and thrust faults) or tensional structures (tensional basins, normal faults). In the vicinity of Los Angeles, a number of compressional structures and sedimentary basins exist, each responding to local stress through time (**Fig. 8.7c**). Local relief can be extreme: NE of Los Angeles uplifted blocks tower 3000 m above adjacent basins slightly above sea level; several land-locked basins are actually below sea level. The style and intensity of deformation of the blocks bordered by the faults are highly dependent on their rock composition. Young sedimentary sequences are intensely deformed only where they are compressed between competent basement like granite and high-grade metamorphic rocks. Blocks composed of primarily low-grade metamorphic, especially schistose, rocks have been strongly compressed and folded throughout. Because of such differences, individual ranges of the Transverse Ranges can contrast strongly in their geology and morphology.

The San Andreas Fault and many accompanying faults are characterized by continuous earthquake activity; clearly the system is presently active. The oldest geologic units exposed at the surface show systematically increasing amounts of displacement. Displacement along transform faults is determined by piercing points, any geologic structure or unit that was once adjacent or continuous but is presently offset by the fault movement. Piercing points can include volcanoes, older faults offset by younger faults, folds, distinctive rock bodies, and geomorphic elements such as ridges or stream valleys. The latter two are useful in documenting youngest fault movement and rates. Older piercing points yield an average slip over longer periods of time; for example, an offset Oligocene volcano (ca. 30 Ma) might yield a total offset of 300 km since the formation of the volcano. If the volcano can be shown to be younger than the fault, then the average amount of offset per time can be determined, in this case, 10 km/1 m.y. A Middle Miocene lava flow (ca. 15 Ma) on the same fault segment might yield an offset of 200 km. Note that this rate is somewhat faster, 13.3 km/1 m.y. This would show that later fault movement was more rapid than earlier movement. When measured over very recent periods of time, most faults show episodic movement. Offset streams and stream terraces across the San Andreas Fault clearly document this as do the thousands of stations set up across the fault to measure fault activity. Surprisingly, total offset of the San Andreas Fault is difficult to measure. This is partly due to an absence of precise piercing points, but also due to the fact that fault motion on older faults, some as old as Jurassic, has caused previous offset to the present fault, some of this offset in a sinistral, rather than a dextral sense.

The arrangement of the earthquake epicenters indicate that the San Andreas Fault consists of a more continuous vertical fault plane at depth that fans-out into several shorter fault branches towards the top. Such a branching out towards the top is characteristic of many strike-slip fault systems. This pattern is called a “flower structure” because it resembles a bunch of flowers that fan upwards (**Fig. 8.8**). In case of transpression, crustal wedges fan upwards resulting in a positive flower structure. In case of transtension, the wedges subside like a graben and a negative flower structure develops.

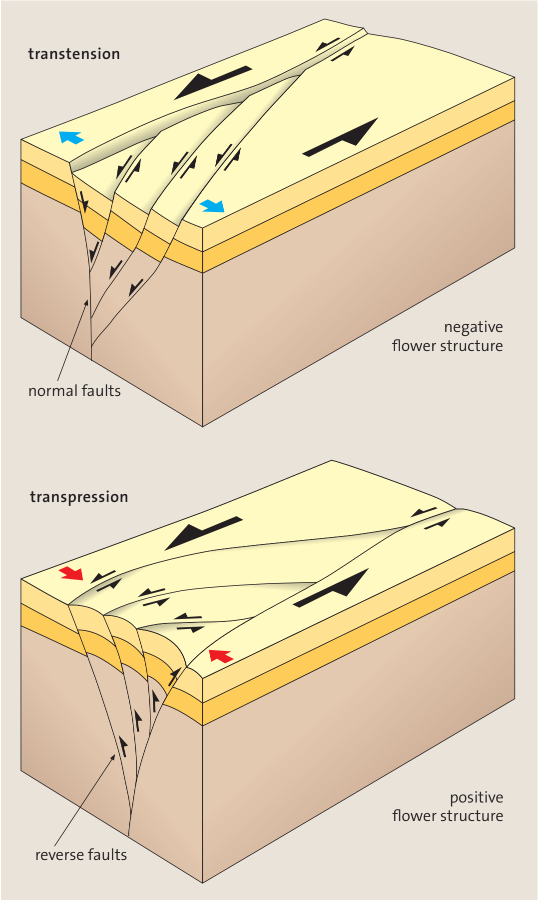
The earthquake epicenters are concentrated in the brittle upper crust that reacts by forming fractures with jerky, episodic movement. In 1978, 7500 earthquakes were registered in southern California alone. Some segments display a somewhat continuous creeping accompanied by very small but frequent earthquakes; this especially occurs where the fault is enclosed by sepentinites of the Franciscan Formation. Other segments, where movement is locked by competent rocks such as granite, gneiss, and quartzite, large stresses accumulate that generate strong earthquakes when the limiting value of rock strength is exceeded. Prehistoric earthquakes on the San Andreas Fault were identified by measuring displacement of Recent sediments that have been dated by radiocarbon methods. In Southern California, during the last 1500 years, eight strong earthquakes have been identified occurring at intervals between 60 and 275 years, most of them with an estimated moment magnitude of 8 or more (Sieh, 1978). This documents the periodicity of large-displacement events.

The San Andreas Fault has various topographic expressions. Erosion of crushed and highly fractured rocks along the fault zone creates long stretches of trenches and valleys. In places where competent rocks occur on either side of the fault, topographic expression is locally suppressed. In places where competent rocks abut young, poorly cemented sandstone and mudstone or older incompetent rocks, a sharp scarp is developed, locally with 3000 m of relief. Rivers running perpendicular across the fault are commonly offset a given distance by recent fault movement. In similar fashion, topographic ridges are offset by the fault. Some of the ridges are a result of transpression that led to the uplift of young, easily deformable sedimentary layers. There are places along the San Andreas Fault, where sedimentary rocks as young as Pliocene stand on end! The strong San Francisco earthquake of 1906 created displacements of several meters along discrete fracture lines (**Fig. 8.9**).

Some basins along the San Andreas Fault yield large petroleum deposits. For example, the Ventura Basin 120 km NW of Los Angeles formed along the fault where the Transverse Range blocks were rotated. The thick Miocene Monterey Formation and related units originated as mostly deep marine deposits formed in waters rich in organics and later folded into complex anticlines that trapped the petroleum. The high organic content resulted from nutrient-rich upwelling of cold water along the Pacific Ocean. A high geothermal gradient (up to 55 °C/km) caused the formation of petroleum at a shallow depth.

The North Anatolian Fault in Asia Minor and the Alpine Fault in New Zealand

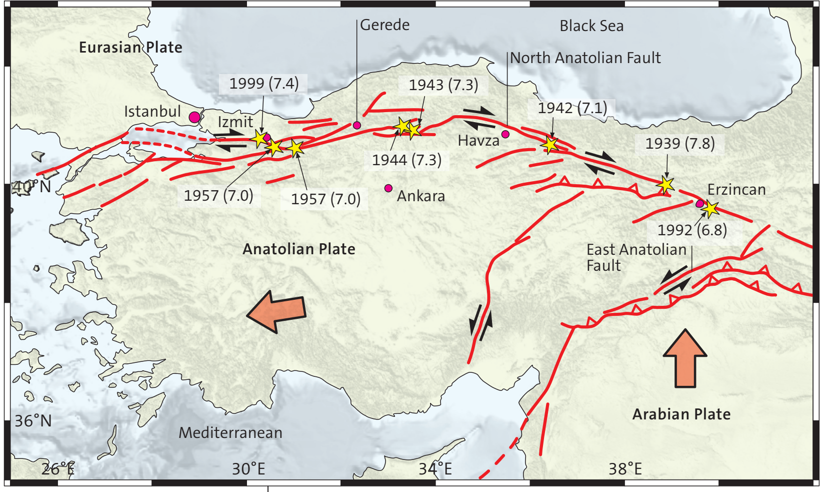
The 1200 km-long North Anatolian Fault forms the plate boundary between the Anatolian Plate and the Eurasian Plate (**Fig. 8.10**). With a calculated dextral displacement of 2.5 cm/yr, it displays a clear northward convex bending which is best explained by the proximal location of the common pole of rotation of the two plates located near the north coast of Sinai (Stein et al., 1997). From 1939 to 1944 a series of four large earthquakes (moment magnitudes between 7.1 and 7.8) occurred along a 600 km-long fault segment; they migrated from east to west. Three more earthquakes (magnitudes between 7.0 and 7.4) occurred between 1957 and 1999, continued the pattern of westward migration, and moved an additional 300 km.



◀ **Fig. 8.8** Block diagrams showing negative and positive flower structures typical of large fault zones that are caused by transtension and transpression, respectively.

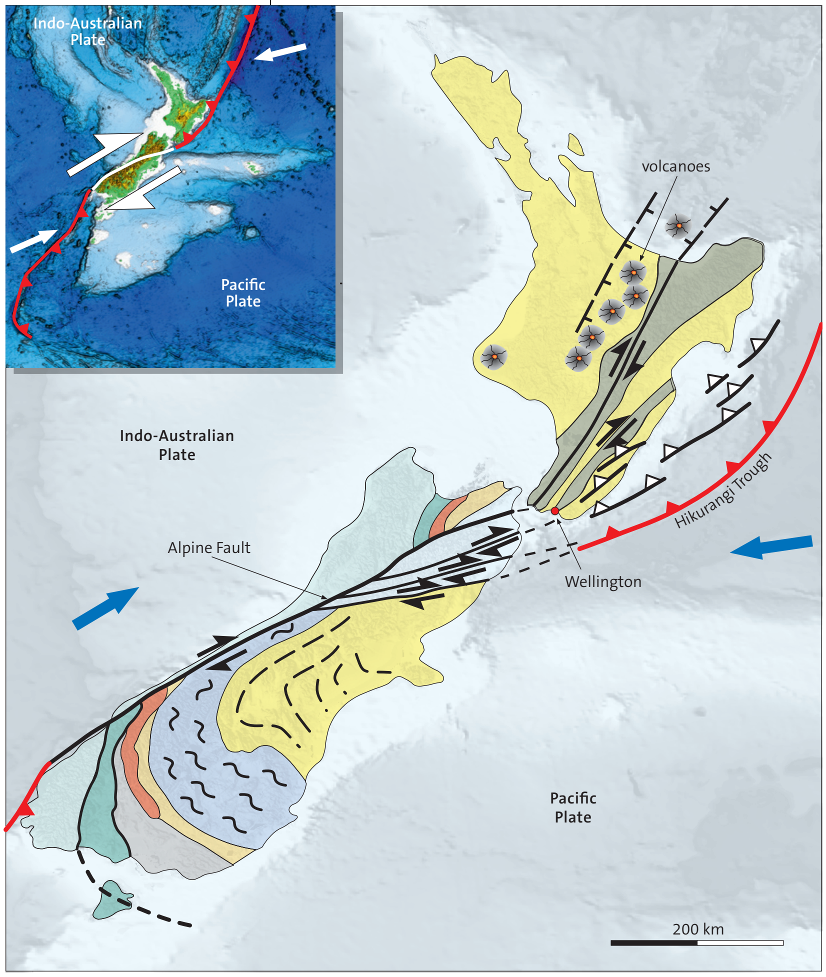
Time and location of the tremors in this earthquake series give insights to understanding the pattern and mechanisms of earthquakes. At each individual fault segment where an earthquake occurs, a spontaneous stress release is generated. Because the block motion occurs over a limited distance, new stress accumulates near the end of the active part of the fault. At this location of new stress, the next earthquake will form and so on. A large fault cannot have motion along its total length during any one event because the friction resistance is too strong. Therefore, the rupture always occurs in sections; for example, during the earthquake of Izmit in 1999, movement occurred over a length of 130 km. The progress of fault activity in stages is thus a normal process and another indication that movement in the upper brittle crust generally happens in an episodic, jerky way. Stages of quiescence at a given location between two large earthquakes may last for several decades or centuries. Along the North Anatolian Fault, evidence near Gerede (**Fig. 8.10**) documented that eight large earthquakes occurred during the last 2000 years. This indicates a periodicity of 200–300 years. Near

▼ **Fig. 8.9** Dextral displacement of a fence along a discrete fracture formed during the 1906 earthquake in San Francisco.



◀ **Fig. 8.10** The dextral North Anatolian Fault forms the plate boundary between the Anatolian and Eurasian plates; stars show epicenters of large earthquakes between 1939 and 1999 (Okomura et al., 1993). The numbers in brackets indicate the moment magnitudes of the earthquakes. The conjugated East Anatolian Fault has opposite sense of movement (sinistral). In the wedge between both faults the Anatolian Plate is pushed westwards ("tectonic escape").

▼ **Fig. 8.11** The Alpine Fault in New Zealand is a dextral transform fault that connects two subducting plate boundaries (see insert for larger field of view). Along this fault the geological units (various colored symbols) are displaced by several hundred kilometers.



Erzincan, five large earthquakes during the last 1000 years yield a recurrence time of 200–250 years (Okomura et al., 1993).

The SW-NE striking sinistral East Anatolian Fault and the E-W striking dextral North Anatolian Fault form a conjugated system. Anatolia moves along these two faults towards the west relative to the neighboring plates. This westward movement is provoked by the Arabian Plate pushing from the south (**Fig. 8.10**). The Anatolian Plate is pressed towards the west in similar fashion to one squeezing a stone from a plum between two fingers. Such a process is called "continental escape" or tectonic escape of blocks (see Ch. 13).

The Alpine Fault in the Southern Alps of New Zealand is a transform fault that connects two subduction zones, each with different polarity. North of the fault the Pacific Plate subducts beneath the Indo-Australian Plate; south of the fault subduction is the opposite (**Fig. 8.11**). Thus the fault lengthens over time (**Fig. 8.1g**). The relative movement between the two plates is not exactly parallel to the fault, but rather oriented slightly oblique. This induces a transpressional component along the fault that is manifested by sharp local uplift along a complex bundle of faults.

At the end of the Oligocene, ca. 25 Ma, two directly opposed subduction zones developed. This unstable situation inevitably led to the formation of the dextral transform fault. Since that time, the fault has increased to a total length of 750 km, the length of the entire southern island of New Zealand. This yields an average growth of 3 cm/yr, the calculated average convergence rate between the two plates. At present, this rate has slowed down slightly. The transpression is responsible for the thrusting of the Pacific Plate onto the Indo-Australian Plate, which occurs at an angle of about 40° and generates uplift of 1 cm/yr. The movement at the Alpine Fault is also irregular. During the last millennium, four large earthquakes occurred with estimated magnitudes of approximately 8 and with displacements of up to 8 m. Three were located near the northern end of the fault with recurrence times of 120 and 350 years. The next large earthquake is overdue as 380 years have passed since the last one.