



20 Transform Plate Boundaries

The remarkable ridges and troughs of the San Andreas fault system of southern California, shown in the panorama above, are one of the great surface expressions of plate tectonics. The long linear valleys mark faults that are part of a plate boundary that cuts through the entire lithosphere to a depth of about 100 km; they are not merely surface features. Over the last 30 million years, horizontal movement along the strike-slip faults of the San Andreas system amounts to several hundred kilometers. Rocks on either side of the fault are on fundamentally different plates. The deformation is produced as the North American plate slips south past a narrow slice of continental crust trapped on the Pacific plate. Carefully examine this panorama, because from it you can begin to develop a more accurate concept of what Earth's tectonic system does.

Transform faults and fracture systems are even more spectacular on the ocean floor (see the inside back cover of this book). They slice through the midocean ridges in hundreds of



places and sweep across the ocean floor for thousands of kilometers, imparting a spectacular fabric to the solid surface of our planet. They form the most prominent and widespread fracture system on Earth.

Although huge oceanic fracture zones are intimately related to transform fault movements, only short segments are active transform plate boundaries. The closely spaced fracture zones of the southern Atlantic Ocean grade southward into a coarser fabric in the southern Indian Ocean. There, the fracture systems have their own distinctive characteristics. In the northern Indian Ocean, fractures are short and closely spaced, whereas those in the southwestern arm of the ridge near Australia are four times as long. Some of the longest and boldest fractures are in the southern Pacific Ocean, but northward, the East Pacific Rise is more subdued and the fracture systems have weaker topographic expression.

Transform faults connect various kinds of plate boundaries. All play an important role in Earth's plate dynamics. Thus, it is clear that transform plate boundaries are ubiquitous and play an important role in global tectonics. Our focus in this chapter is on the processes that occur at these plate boundaries and the features they produce.



MAJOR CONCEPTS

1. Transform plate boundaries are unique in that the plates move horizontally past each other on strike-slip faults. Lithosphere is neither created nor destroyed.
2. The three major types of transform boundaries are: (a) ridge-ridge transforms, (b) ridge-trench transforms, and (c) trench-trench transforms.
3. Transform plate boundaries are shear zones where plates move past each other without diverging or converging. During shearing, secondary features are created, including parallel ridges and valleys, pull-apart basins, and belts of folds. Compression and extension develop in only small areas.
4. Oceanic fracture zones are prominent linear features that trend perpendicular to the oceanic ridge. They may be several kilometers wide and thousands of kilometers long. The structure and topography of oceanic fracture zones depend largely on the temperature (or age) difference across the fracture and on the spreading rate of the oceanic ridge.
5. Continental transform fault zones are similar to oceanic transforms, but they lack fracture zone extensions.
6. Shallow earthquakes are common along transform plate boundaries; they are especially destructive on the continents.
7. Volcanism is rare along transform plate boundaries, but small amounts of basalt erupt locally from leaky transform faults.
8. Metamorphism in transform fault zones creates rocks with strongly sheared fabrics, as well as hydrated crustal and even mantle rocks.

CHARACTERISTICS OF TRANSFORM PLATE BOUNDARIES

Transform plate boundaries are zones of shearing, where two plates slide horizontally past each other. Rocks in the shear zone are strongly deformed, but no new lithosphere is created and none is consumed. Transform boundaries in ocean basins and on the continents are expressed by steep, linear ridges and valleys. The major types of transform plate boundaries are ridge-ridge transforms, ridge-trench transforms, and trench-trench transforms.

Transform boundaries are strike-slip faults along which two separate tectonic plates grind horizontally past each other without forming or consuming lithosphere (Figure 20.1). **Transform faults** are generally vertical and parallel to the direction of movement. They are produced by **shearing**. Most transform faults are intimately related to divergent plate boundaries on the ocean floor and cut across the midocean ridges. Other types of transform faults connect convergent and divergent plate boundaries, and some cut across the continents themselves. Volcanism and deformation are less common at transform boundaries than along other types, but transform faults remain complex structural and topographic features.

Oceanic transform plate boundaries are part of even longer features called **fracture zones** (Figure 20.1). Fracture zones are enormous structures that range up to 10,000 km long and may have a vertical relief of 6 km. They are remarkably narrow—only a few zones are as much as 100 km wide—but all consist of a series of parallel fractures. On regional maps, an oceanic fracture zone may appear to be a fault that offsets an oceanic ridge. However, a fracture zone (gray in Figure 20.1) extends in both directions beyond the active transform fault boundary (red). Compared with the fracture zone, the actively deforming transform plate boundary is much shorter, typically less than a few hundred kilometers. This active zone is marked by steeply dipping faults and complexly deformed oceanic crust.

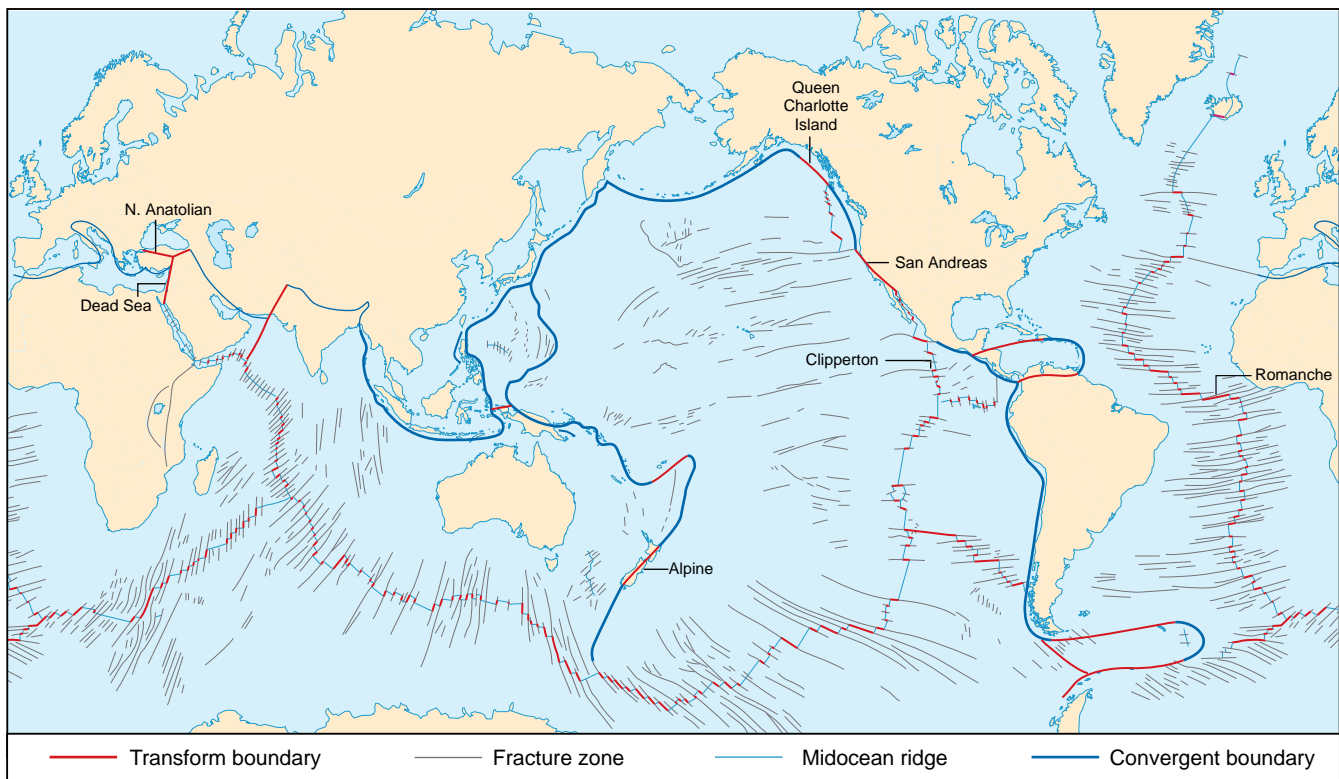


FIGURE 20.1 A map of the major transform plate boundaries and associated oceanic fracture zones shows that most are related to spreading of the oceanic ridge. Also, most curve because they are parallel to small circles around the poles of plate rotation. Other transform boundaries are related to convergent margins in regions of complex plate movement.

Casual examination of maps of oceanic fracture zones, like Figure 20.1, may fail to convey an accurate notion of their size and length. Many are long enough that they would extend across the entire United States as systems of parallel ridges and troughs. (For example, compare the length of several Pacific fracture zones with the United States on the map.) Most of the valley walls are much higher and steeper than the ridges of the Appalachian Mountains or the Front Range of the Rockies. The relief on some fracture zones is comparable to that of the great eastern scarp of California's fault-bounded Sierra Nevada. Without erosion by river systems, the transform fault scarps on the ocean floor are quite unlike any on land. They are neither dissected with stream valleys nor greatly subdued by weathering and erosion. Most erosional modification results from mass movement along the slopes of the escarpment.

On the continents, transform plate boundaries are major strike-slip faults with displacement of hundreds of kilometers, placing rocks of widely different origins and ages side by side. This movement produces the linear cliffs, ridges, and troughs that are common surface expressions of major strike-slip faults. Like oceanic transforms, a continental transform fault is not one plane, but consists of a zone of faults that can be several kilometers wide. Stream erosion of transform faults on continents tends to subdue their topographic expression, but movement on the great Alpine Fault in New Zealand has produced mountains more than 3000 m high. Continental transform faults also pose great hazards because of the abundant earthquakes they produce.

How does a transform fault differ from the associated fracture zone?

Types of Transform Plate Boundaries

By carefully considering the map in Figure 20.1, you can see that a transform plate boundary is a special kind of fault that *transforms* one type of plate motion into another type. For example, the *diverging* motion between plates at an oceanic ridge can be changed along a transform fault to the *converging* motion between plates

at a subduction zone. Transform faults can connect convergent and divergent plate boundaries in three different ways: (1) ridge-ridge transforms connect two segments of a divergent plate boundary; (2) ridge-trench transforms connect a ridge and a trench; and (3) trench-trench transforms couple trenches at two different convergent plate boundaries (Figure 20.2).

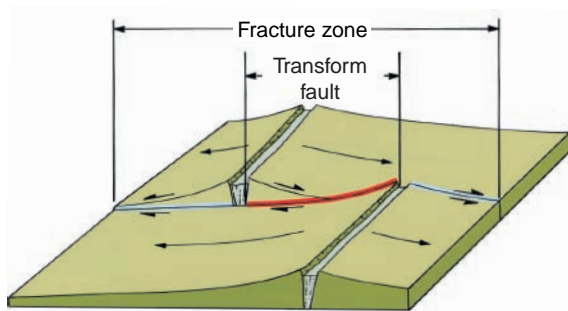
Ridge-ridge transform faults are by far the most abundant. It is therefore important to analyze the movements of these transforms in detail. Keep in mind that active displacement on these faults occurs only *between* the ridge segments, as shown in Figure 20.2A. The figure shows that plate movements are in opposite directions between the ridge crests. No movement occurs along the rest of the fracture zone.

Thus, the transform fault sustains formidable shearing movement. In the upper part of the plate, brittle shearing creates **mylonite** (Chapter 6) and tectonic breccias. Numerous earthquakes are produced by repeated rupturing of the brittle rocks along the upper part of the fault zone. Brittle fracturing grades into ductile deformation in the weak underlying asthenosphere; consequently, seismicity is characteristically shallow along a transform, occurring in the brittle zone. The fault cuts through the entire lithosphere.

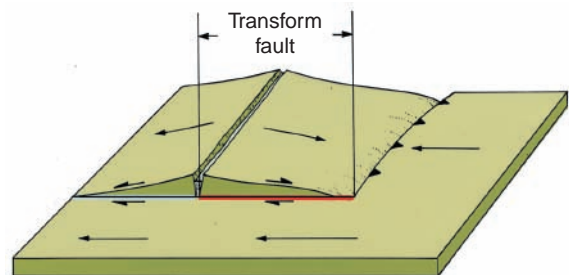
Ridge-trench transforms are much less common (Figure 20.2B). But they form an important connection between spreading and converging plates. The longest transform faults are all of this kind. One type of ridge-trench transform connects a ridge with the overriding side of a convergent boundary, like the one east of the southern tip of South America (Figure 20.1). Here, two long transform faults connect a short ridge with the trench along the Scotia arc. Together, these plate boundaries form a huge hairpin curve. Another type of ridge-trench transform connects a ridge with the subducting side of a trench. An example is the Queen Charlotte Island Fault off the western coast of Canada (Figure 20.1).

Trench-trench transforms (Figure 20.2C) are also rare. Figure 20.1 shows two good examples. One is the Alpine Fault in New Zealand, which appears to connect two trenches in the south Pacific. The direction of subduction changes across the transform fault. Another trench-trench transform fault connects the western Aleutian trench and the Kamchatka trench on the eastern shore of Russia.

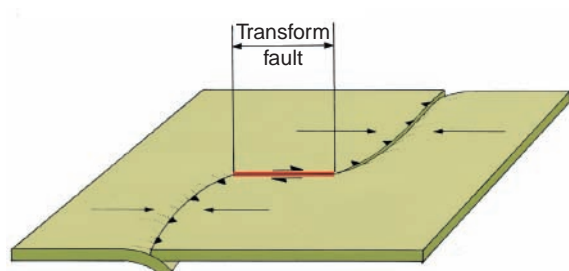
Why are ridge-ridge transform faults more abundant than other types?



(A) Ridge-ridge transform fault.

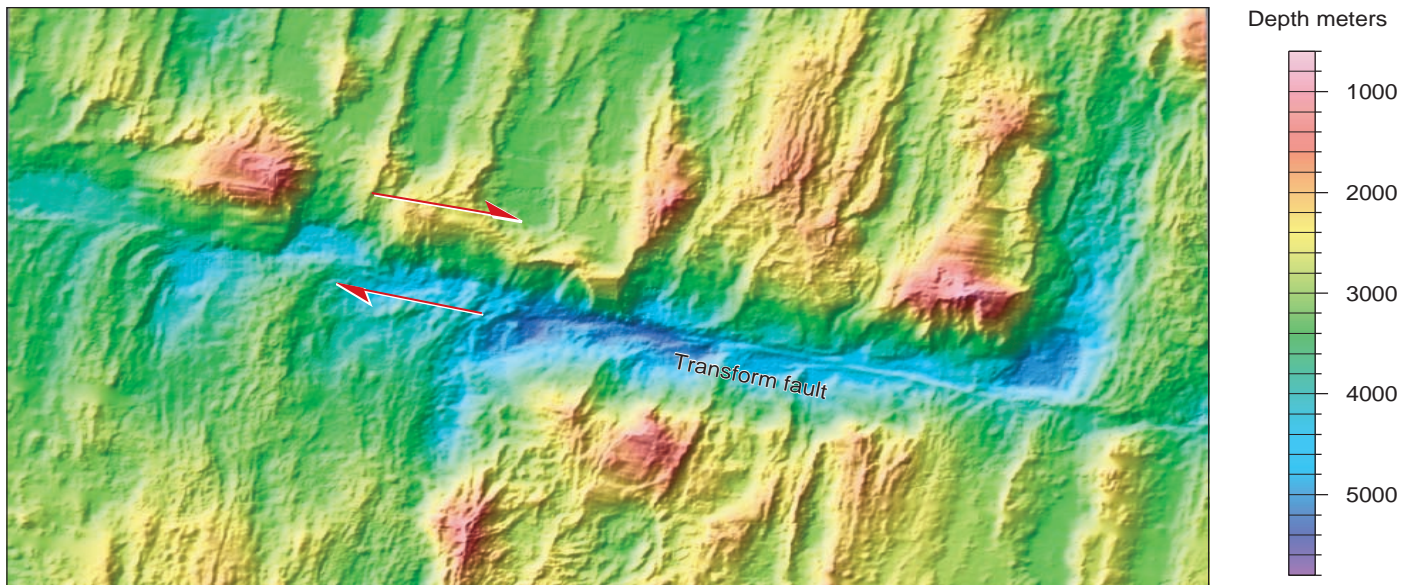


(B) Ridge-trench transform fault.



(C) Trench-trench transform fault.

FIGURE 20.2 Transform faults can connect convergent and divergent plate boundaries in various combinations. (A) shows the common ridge-ridge transform fault. Note that relative motion occurs only along the boundary of the plates between the two segments of the ridge. (B) shows a ridge-trench transform fault. (C) shows a trench-trench transform fault. In all cases, the trend of a transform fault is parallel to the direction of relative motion between plates. This characteristic is helpful in determining the direction of plate motion.



OCEANIC TRANSFORM PLATE BOUNDARIES AND FRACTURE ZONES

Transform plate boundaries in the ocean basins are prominent linear features that are perpendicular to the midocean ridges. They are the short, active parts of fracture zones that may be several kilometers wide and thousands of kilometers long. The characteristics of oceanic fracture zones depend on the age difference between the lithosphere on either side of the fault zone.

The long oceanic fracture zones that slice across the seafloor are not what they first seem to be. The sharp linear surface expression of fracture zones and the apparent offset of an oceanic ridge may suggest that they are simple strike-slip faults, with displacement occurring along their entire length. However, nothing could be farther from reality. To understand oceanic fracture zones, you must keep in mind the relative motion of the plates at a spreading ridge.

Active displacement on the fracture zone occurs only along the line that connects the offset ridge segments (Figure 20.2). This zone is the transform fault, and it is the only place where the fracture zone is a boundary between plates. It is along this zone that earthquakes occur. Beyond this transform zone, the plates on either side of the fracture are moving in the same direction and at the same rate; they are linked together on the same plate. There is thus an active segment of the fracture (a transform fault, which is a plate boundary) and an inactive segment (which is not a plate boundary).

As the plates slide past each other in the transform zone, their boundaries are fractured and broken (Figure 20.3). This fracturing produces parallel ridges and troughs in the fault zone (Figure 20.4). If there is no displacement along faults beyond the transform zone, then how do these valleys and ridges form? It is probably easiest to envision the inactive portion of the fracture zone as a long “thermal scar” in the oceanic crust. Where a ridge segment terminates against a transform fault, the newly formed hot ocean floor lies next to older, colder ocean floor (Figure 20.2A). A steep cliff or scarp is produced if there is a large difference in the age of rocks on either side of the fault zone, as shown in the figure. The younger lithosphere near the oceanic ridge is hotter and expanded, so it stands higher than the colder and contracted lithosphere on the other side of the fracture. The higher side of the transform fault thus may change from one side to the other, as you can see in the figure.

FIGURE 20.3 Intense shearing occurs at transform plate boundaries. This map of the flanks of the mid-Atlantic ridge shows all of the hallmarks of a transform fault. Linear valleys, depressions, and ridges are all aligned along the fault. In addition, the abyssal hills bend to make J-shaped curves as they reach the transform. (Courtesy of D. Blackman)

How long and wide are oceanic fracture zones?

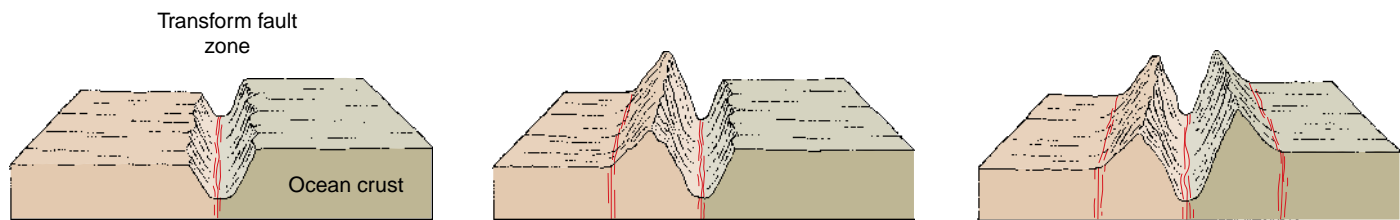


FIGURE 20.4 Various topographic expressions of transform boundaries result from juxtaposition of rock bodies having different temperatures, ages, and internal structure. The simple-to-complex valleys and scarps shown here are common.

As spreading continues, this elevation difference persists, and the scar grows longer and longer. Thus, a fracture zone is a historical recording of the relative plate motions on either side of a spreading ridge. For example, the fracture zones in the North Atlantic trace the movement of North America away from Africa.

Another distinctive characteristic of transform plate boundaries is that no significant amount of lithosphere is formed or consumed. Tremendous shearing, grinding, metamorphism, and deformation occur in these narrow zones. In fact, between 1% and 10% of the oceanic lithosphere has been deformed by processes at a transform fault. There is generally little or no volcanic or intrusive activity, although some volcanism may occur along “leaky” transform systems. Transform plate boundaries play an important structural role in the tectonics of our planet, and considerable movement and adjustment occur along these zones as the plates shift and move about.

Examples of Oceanic Fracture Zones

To become better acquainted with the characteristics of oceanic fracture zones, let us look more closely at three different transform systems.

Romanche Fracture Zone. The most spectacular fracture in the central Atlantic Ocean is the Romanche fracture system, which lies almost on the equator (Figure 20.5). The fracture zone cuts the slow-spreading Mid-Atlantic ridge and includes a ridge-ridge transform fault between the African plate on the north and the South

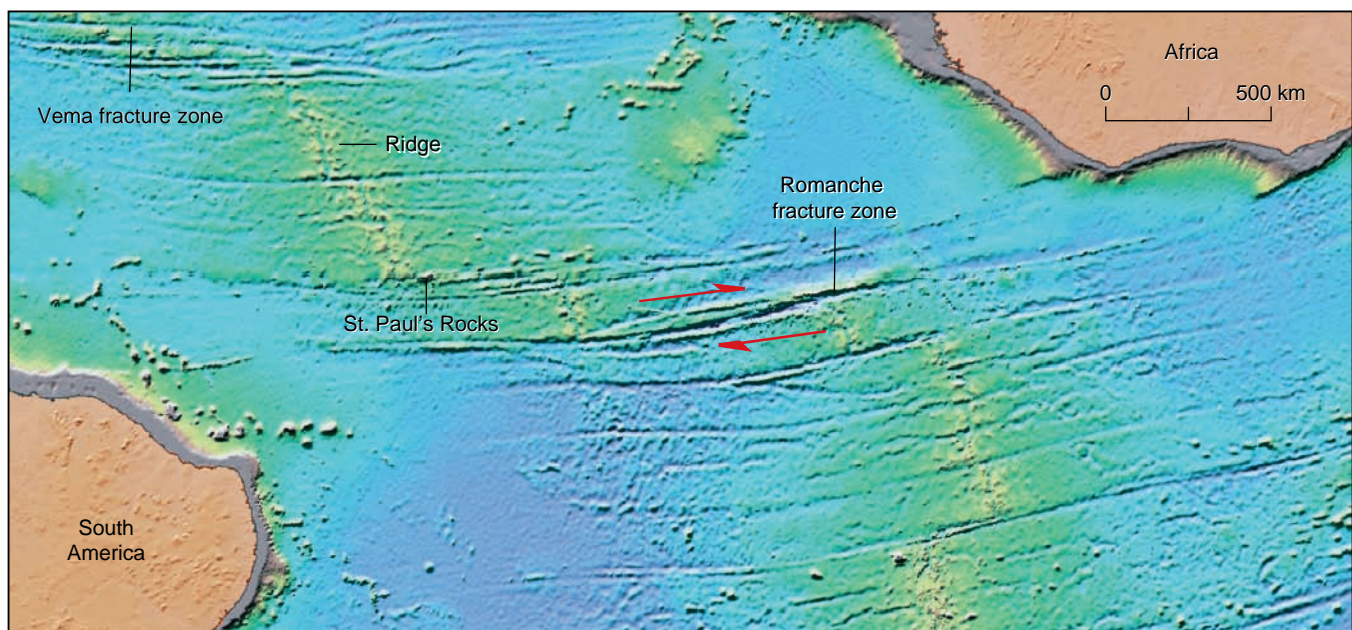


FIGURE 20.5 The Romanche fracture zone extends across most of the Atlantic Ocean, forming a huge ridge and trough system some 5000 km long and almost 100 km wide. The active transform boundary lies between the offset ridge axis. (Courtesy of D. T. Sandwell and W. H. F. Smith, Scripps Institution of Oceanography, University of California at San Diego)

American plate on the south. The fracture zone stretches across the entire Atlantic Ocean; even the active transform is 600 km long. Consequently, the difference in age of the oceanic crust on either side of the fracture is huge, nearly 50 million years (compare with the map on the inside front cover).

The Romanche fracture zone is a series of deep valleys separated by ridges. One narrow ridge rises above sea level to make cluster of small islands—St. Peter and St. Paul's Rocks, one of the few oceanic island groups that did not form by volcanism. The floor of this zone is fractured and grooved and contains the deepest part of the central Atlantic Ocean (7960 m below sea level). This deep gap in the Mid-Atlantic Ridge is significant in circulation of oceanic water in that it permits cold bottom water from the ocean near Antarctica to flow from the western side of the ridge in the southern Atlantic into the deep basins of the northern Atlantic on the east side of the ridge.

The transform fault is not a single plane but a fault system tens of kilometers wide containing many separate vertical faults that branch and crosscut one another. Many slumps from the steep walls of the escarpment cover large parts of the valley floor. These deep cuts expose complete sections through the oceanic crust. Rocks dredged from the floor of the fracture zone include igneous rocks such as basalt, gabbro, and mantle peridotite as well as their deformed or metamorphosed equivalents—mylonite, metabasalt, and serpentinite (hydrated peridotite). Without question, the transform is a zone of intense shearing, manifested by breccias and highly deformed serpentinites. Extensive slumping and landsliding off the steep scarps also have produced coarse talus breccias.

Clipperton Fracture Zone. The Clipperton fracture zone stretches from the coast of Central America to the middle of the Pacific Ocean (Figure 20.1). The active transform boundary, however, is only 85 km long and connects two segments of the East Pacific Rise (Figure 20.6). The lithosphere differs in age across the fracture zone, but only by about 1.5 million years. The spreading rate on this part of the ridge is high, about 10 cm/yr. The transform fault zone is a deep cleft, bounded by high ridges on either side.

The inactive fracture zone beyond offsets magnetic stripes in the oceanic crust, indicating that the entire fracture zone originated as a ridge-ridge transform fault, but the direction of spreading changed slightly about 3 million years ago. On the north side, seismic investigations show no axial magma chamber within 70 km of the ridge-transform intersection. On the other hand, a magma chamber is present on the south side of the Clipperton fracture zone.

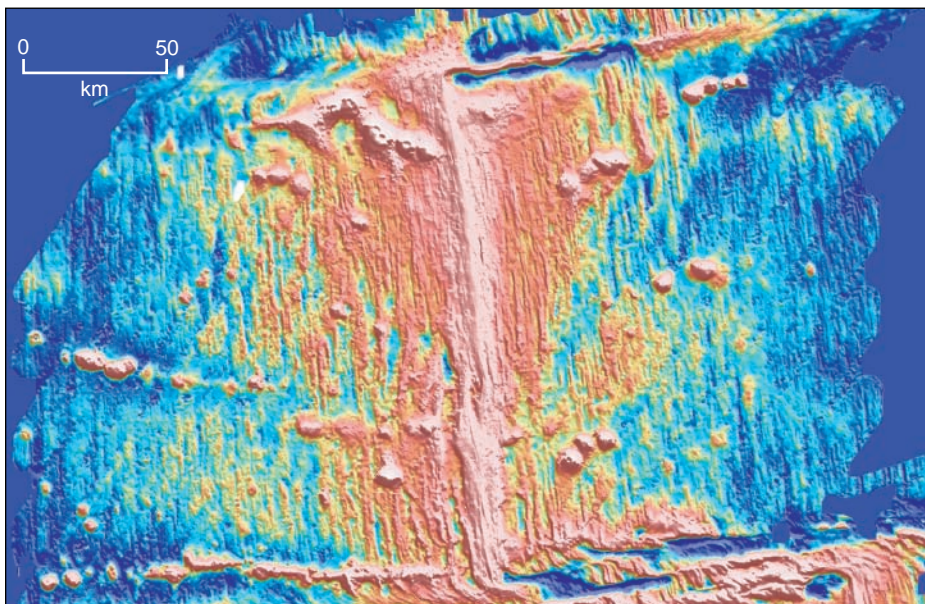
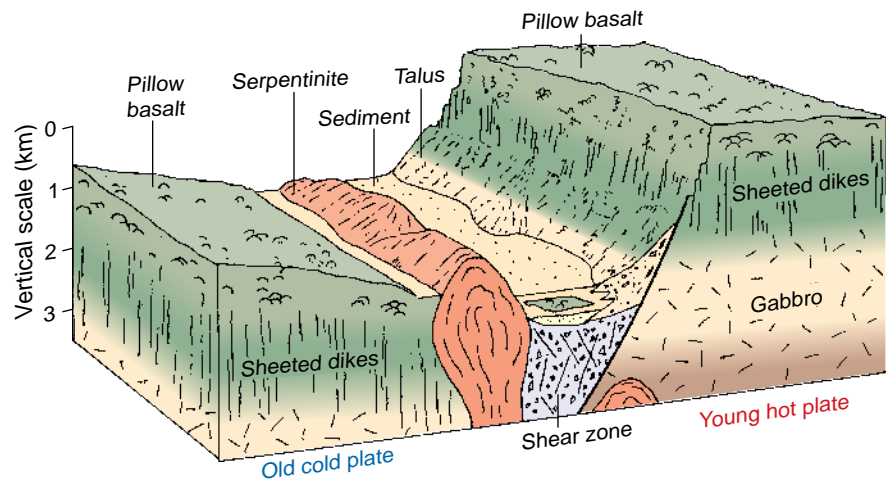


FIGURE 20.6 The Clipperton transform fault cuts the East Pacific Rise, in the northern part of this map. It is just west of the Central American coast. The transform fault forms a series of ridges and troughs connecting two segments of the oceanic ridge. The offset is about 85 km. Note the height of the plate immediately north of the East Pacific Rise and the rugged relief in the fault zone. The fracture system where no shear occurs extends beyond the active transform fault. (Courtesy of K. C. McDonald, University of California at Santa Barbara)



FIGURE 20.7 The structure of a **transform shear** as interpreted from exposures in the Troodos ophiolite complex on Cyprus. The fault zone consists of innumerable vertical faults and is marked by complex breccias made of fragments from basaltic dikes. The large mass of serpentine intruded the fracture zone. Talus breccias are interlayered with sediments and basaltic lava flows, which include pillow basalts that erupted at the transform boundary.



Transform Fault Zones in Ophiolites. Some ophiolites have long, nearly vertical shear zones that slice through the igneous rocks. These zones are probably transform faults formed on the seafloor and then preserved during the thrusting of the ophiolite onto land.

For example, the Troodos ophiolite complex on the Mediterranean island of Cyprus is cut by such a vertical shear zone (Figure 20.7). The shear zone is about 10 km wide and cuts through the rocks of the ophiolite sequence. Dikes in a sheeted dike complex curve toward the major strike-slip fault, just as ridge tips do at a transform fault zone. Outcrops of gabbro and serpentinite lie on the south side of the fault. The large mass of serpentinite is interpreted to have formed when peridotite in the mantle combined with seawater flowing through the highly permeable fracture zone. Because serpentinite is both buoyant and weak, it may have intruded into the fracture zone as a diapir. Talus breccias formed as steep slopes on the seafloor failed. Apparently, high ridges and deep valleys ran parallel to the shear zone. The breccias are interlayered with sediments and basaltic lava flows, which include pillow basalts. Small volumes of lava must have erupted along the shear zone. All of these features reveal that this area of the ophiolite was strongly sheared along a strike-slip fault while it was still at the bottom of the ocean and long before it was thrust onto dry land.

Processes at Transform Plate Boundaries

Transform boundaries strongly influence local tectonic and igneous processes and are responsible for much of the structural and topographic variation of the ocean floor. The examples described above show that most oceanic fracture zones have pronounced topographic relief, with high linear ridges and deep linear troughs, steeply inclined fault scarps, and sheared rocks. Like many strike-slip faults on land, a transform fault zone is not a single plane but a fault zone that can be as much as 100 km wide. The transforms thus contain numerous separate fault planes that branch, merge, and cross one another to make a braided network of strike-slip faults. Volcanism also diminishes near the transform intersection with an oceanic ridge.

To understand why these characteristics develop, let us explore some of the fundamental processes that take place at transform plate boundaries. Their distinctive fabric largely results from the complex interplay of strike-slip faulting, age and temperature contrasts across the transform fault, and shearing rates.

Contraction and Extension in Transform Fault Systems. At many transform fault boundaries, strike-slip displacement occurs along several separate fault planes that curve slightly, merge, and separate again. Horizontal movement within this braided system of curved faults produces local zones of horizontal compression or

Why is Cyprus important for the study of transform faults?

What processes occur along transform faults?

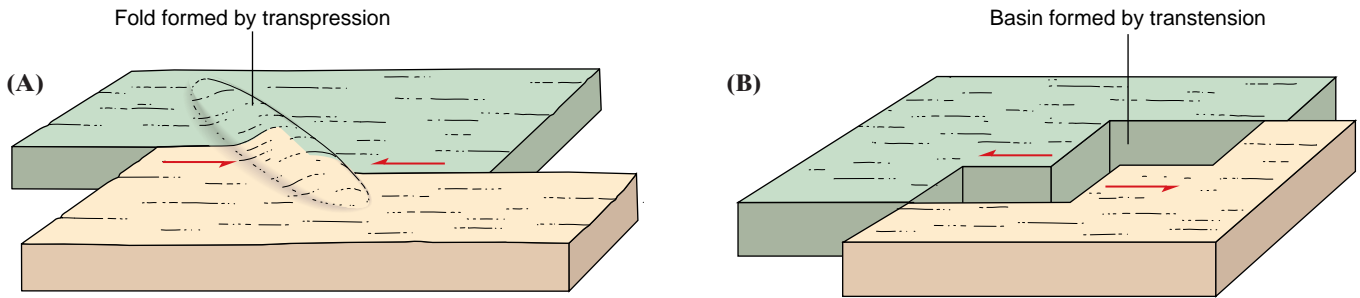


FIGURE 20.8 Secondary compressional and extensional structures are produced by bends or offsets in the transform fault system. Small fold belts mark zones of transpression (A) and pull-apart basins mark transtensional bends (B).

extension (Figure 20.8). Horizontal compression occurs where the bends are oriented so that blocks on either side of the fault are squeezed together (Figure 20.8A). This squeezing creates uplifted regions with small folds and thrust faults that trend perpendicular to the major strike-slip faults. Because this process involves both *transform* and *compression* motion, it is known as **transpression**. This kind of contraction commonly creates long, low ridges, but locally, uplift may be extreme.

Areas of extension can also develop along bends in the strike-slip faults. **Transtension** (*transform plus extension*) produces small fault-bounded troughs known as **pull-apart basins** (Figure 20.8B). This extension results in normal faulting and subsidence of a small block between the two plates. These more or less rectangular basins grow and accumulate sedimentary deposits as strike-slip movement continues. As the troughs grow, the floor may be stretched and thinned so that volcanoes may develop in the central part of the basin.

Thermal Structure and the “Cold Wall.” By their very nature, ridge-ridge transform plate boundaries juxtapose a cold wall of lithosphere against a hot ridge axis. You can see in Figure 20.9 that a relatively thick, cold, and contracted segment of older lithosphere on the flank of a ridge is adjacent to a hot ridge axis where new lithosphere is forming. This may seem at first to be a minor and insignificant characteristic, but it is a major factor in the structural and topographic evolution of the oceanic crust.

In a sense, normal processes that occur along the ridge, such as rifting and the generation of new oceanic crust, come up against this cold wall and stop. Thus, the transform faults at either end of a ridge segment form distinct boundaries to the crust-forming processes, much as the walls of a magma chamber form boundaries to igneous processes in a pluton. The cold wall cools the asthenosphere rising beneath the ridge. This cooling restricts the amount of partial melting and reduces the amount of magma that can separate from the asthenosphere. Consequently, this

What effect does the “cold wall” have on the adjacent oceanic ridge?

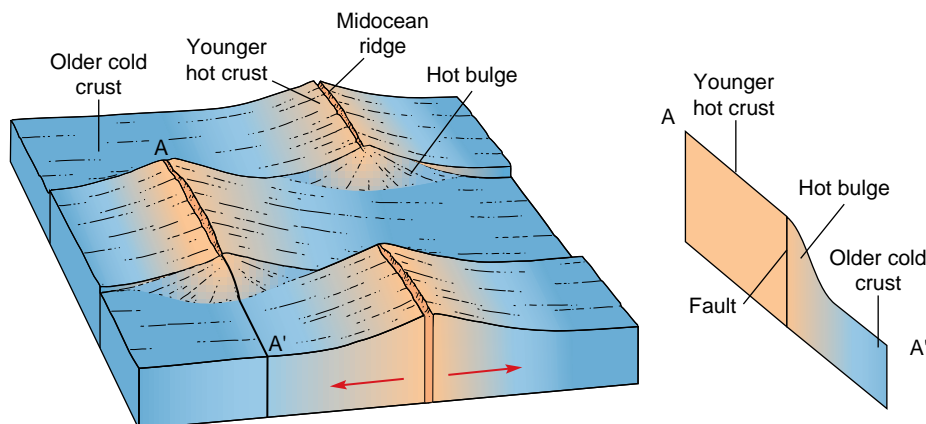


FIGURE 20.9 The thermal structure of a transform boundary is related to differences in age and temperature of the lithosphere across the fault. The cross section along A–A' is parallel to a ridge segment and shows the thermal structure of a ridge-transform boundary. The older, cooler lithosphere creates a “cold wall” that inhibits magmatic processes and concentrates deformation into a narrow zone. The younger, hotter lithosphere stands higher than the older cooler lithosphere. Thus, the scarp alternates from one side of the fracture zone to the other. In addition, a hot bulge forms on the older lithosphere that is adjacent to the hot ridge.

massive cold wall may effectively eliminate development of normal oceanic crust at the adjacent ridge crest. Near transform boundaries the oceanic crust may be very thin.

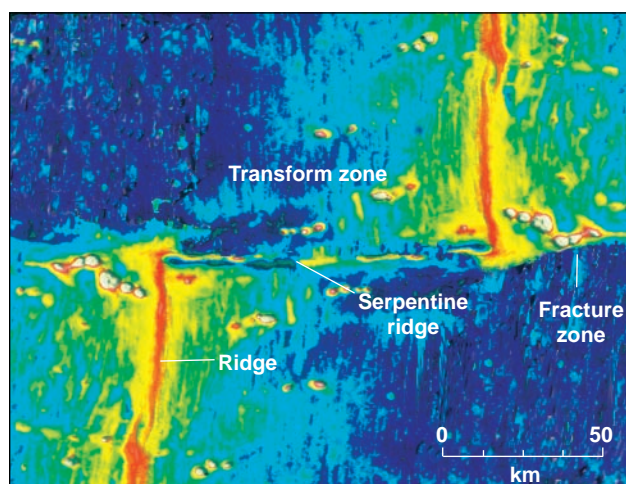
The spreading ridge also affects the cold wall. Intrusion of hot dikes or conductive heating from the hot ridge causes a bulge to develop on the cold side of the fault (Figure 20.9). This bulge is a significant topographic element of the transform. Note the bulge across from the spreading ridge along the Clipperton fracture zone (Figure 20.6).

What is the difference in the structure and topography of long offset versus small offset transform faults?

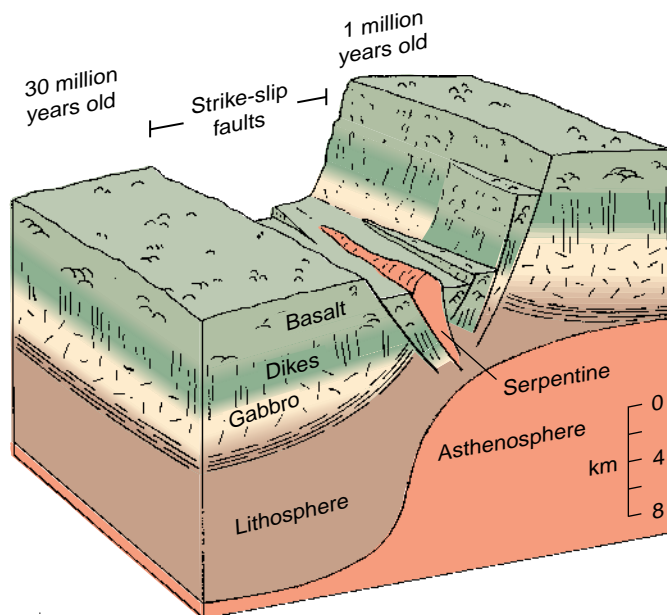
Ridge Offset and Spreading Rate. The structure and topography of ridge-ridge transform plate boundaries vary systematically, depending on the *temperature* of the plates across the transform fault. The amount of *offset of the ridge* and the *spreading rate* control the contrast in temperature. Large ridge offsets juxtapose an old, cold section of lithosphere against a young, hot ridge. Small ridge offsets juxtapose two sections of lithosphere that have almost the same temperature, age, thickness, and strength. (For a given offset distance, ridges that spread quickly will juxtapose plates that are very similar to one another as compared to transform faults on ridges that spread slowly.)

Transforms with *long ridge offsets* (or with slow-shearing rates) have a prominent cold wall (Figure 20.10). On one side of the fault zone, lithosphere is exceptionally thin and weak. Directly across the fault zone, the lithosphere may be 30 million years old and 50 km thick. The striking difference in the thickness of lithosphere keeps the fault zone narrow and prevents the fracture from splitting or migrating. Consequently, the fault zone is well defined, generally less than 1 km wide, and has steep walls. The cold wall also lowers the temperature of magma beneath the ridge and slows volcanism. As a result, the crust that develops here is thin. In addition, seawater penetrates through the thin crust down into the mantle. There it combines with peridotite to form the metamorphic rock serpentinite. Because of its lower density and lower strength, the serpentinite may rise through the crust and make long, narrow **serpentinite ridges** characteristic of transforms at slow-spreading ridges.

As the amount of offset decreases (or rate of shearing increases), the fault zone becomes wider and more complex (Figure 20.11). If the offset is less than about

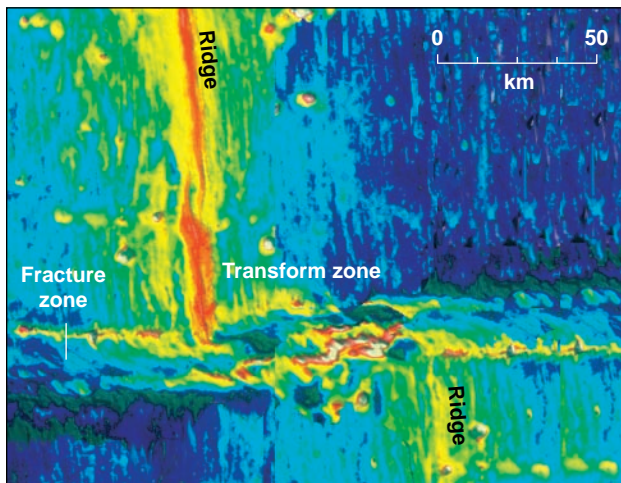


(A) The transform fault is marked by a deep linear valley. Long, narrow, linear ridges commonly parallel the faults. Also, note how the spreading ridge bends into the fault zone. (Courtesy of K. C. Macdonald University of California, Santa Barbara)



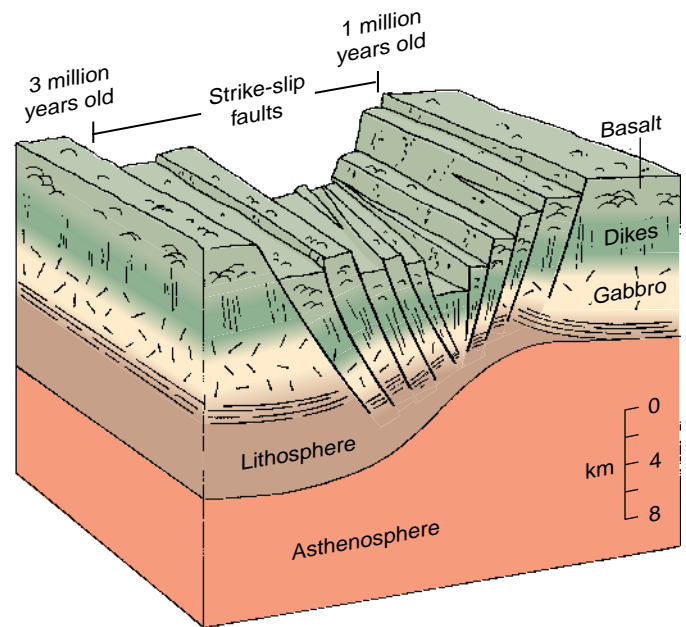
(B) The schematic cross section shows the pronounced contrast in thickness of the lithosphere from the accreting ridge where the lithosphere consists only of hot, new oceanic crust to the much older, colder, and thicker lithosphere on the opposite side.

FIGURE 20.10 A large-offset on a transform fault (or one that has a slow-shearing rate) has a narrow zone of deformation.



(A) The transform fault zone may be tens of kilometers wide. Several shear zones within the transform system form elongate ridges and valleys. They are linked together by extensional pull-apart basins or segments of spreading centers that trend obliquely across the shear zone. Volcanism occurs along these short ridge segments. (Courtesy of K. C. Macdonald University of California, Santa Barbara)

FIGURE 20.11 A small offset transform fault (or one that has a high-shearing rate) has a wide zone of deformation.



(B) This cross section shows that there is little contrast in lithospheric thickness across the transform zone. This relative uniformity permits a wide belt of deformation.

50 km, little variation exists in the temperature, age, or thickness of the lithosphere on either side of the transform. Thus, the boundary is not well constrained by a wall of strong, cold lithosphere. A broad zone of deformation up to 100 km wide develops. The transform contains multiple shear zones and small ridge segments that are oblique to the ridge. In addition, volcanism is more common in the wider shear zones.

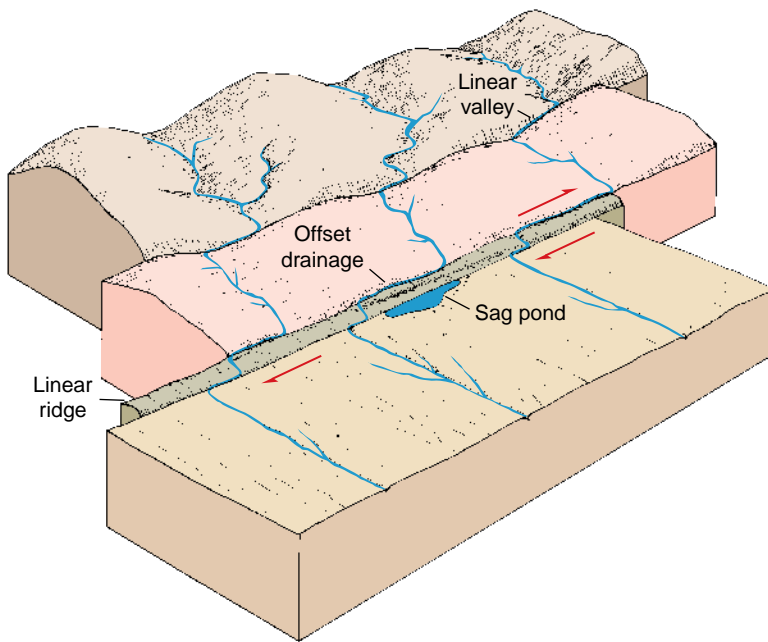
CONTINENTAL TRANSFORM FAULTS

Continental transform faults are similar to oceanic transform faults. They are seismically active and have distinctive topographic features—fault scarps, linear ridges and troughs, and displaced stream channels formed by strike-slip faulting. Pull-apart basins and fold belts develop along bends in the faults.

Transform faults that cut continental crust are not nearly as common as oceanic transforms because most transform faults develop at oceanic ridges. Some inactive transforms are preserved as suture zones in shields or as boundaries to accreted terrains (see Chapter 21). Today's active continental transform faults are important because they help us understand global tectonics and because they are seismic hazards in populated areas.

Continental transform faults are similar to oceanic transforms in that their motion is essentially strike-slip and associated earthquakes are shallow. Like oceanic transforms, continental transform faults penetrate the entire lithosphere and their movement defines a plate boundary. (Most other types of faults involve only the upper part of the crust and die out at relatively shallow depths.) Continental transform faults typically have distinctive linear topographic features (Figure 20.12). These include relatively straight fault scarps, linear ridges and troughs, and streams and valleys that have been beheaded and displaced horizontally. The individual faults in a continental transform system therefore branch, join, bend, and sidestep each other and even establish zones of local contraction or extension.

How are transform faults expressed on continents?



(A) Transform fault zones include strike-slip faults, fault scarps, linear ridges and valleys, offset drainages, and local elongate lakes and ponds.



(B) The San Andreas Fault slices through California, marking the transform boundary between moving tectonic plates. The great scar along the fault line is marked by linear valleys, sharp contrast in landforms, and displaced drainage.

FIGURE 20.12 Continental transform faults produce very distinctive landforms.

Some differences between oceanic and continental lithosphere may be caused by the greater thickness and structural complexity of continental lithosphere. Continental transform faults may follow previous zones of weakness, such as older faults or boundaries between rock types that have contrasting strengths.

Examples of Continental Transform Faults

To appreciate these features and structures, let us consider some details of three well-known continental transform systems.

San Andreas–Gulf of California Transform System. The San Andreas–Gulf of California transform system is 3000 km long, extending from the Mendocino fracture zone off the northern coast of California southward to the tip of Baja California (Figure 20.13). It is a ridge-ridge transform consisting of two main parts: the San Andreas strike-slip zone and the obliquely rifted Gulf of California.

The San Andreas Fault is expressed at the surface by a great scar running through most of California, but it has many subsidiary faults. Thus, the displacement involves a zone more than 100 km wide (see p. 594). These faults are part of the same system that accommodates the motion of the Pacific plate past the North American plate. Undoubtedly, it is the best-known plate boundary in the world. At its southern end, the San Andreas Fault splays out into a series of subparallel strike-slip faults that extend to the head of the Gulf of California. Throughout California, the San Andreas Fault zone is marked by sharp, linear landforms, including straight and narrow valleys, linear ridges, and offset drainage patterns (Figure 20.12B). Local zones of transpression and transtension have developed deep pull-apart basins and zones of intense compression. The rocks in one folded zone have been uplifted about 15 km.

The San Andreas Fault itself is more than 1000 km long, an active boundary between the Pacific plate to the west and the North American plate to the east. The Pacific plate is moving northwestward at about 6 cm/yr relative to the North American plate. As stress builds between the plates, sudden releases cause the

earthquakes for which California is noted. Earthquakes occur along its entire length and as deep as 15 km, but no deeper. The famous San Francisco earthquake of 1906 resulted from movement that produced an offset of as much as 6.4 m.

The San Andreas Fault system began to develop about 30 million years ago (in Oligocene time) and its location on the continent may have been controlled by preexisting fractures in the basement rocks. Horizontal movement along the San Andreas Fault has totaled about 300 km.

The Gulf of California segment of the transform system is a series of long transform faults that connect very short spreading ridges (Figure 20.13). The features of the Gulf of California segment are similar in many ways to those of small-offset oceanic transform systems. Most of the Gulf of California is thinned continental crust, and the floor of the ocean is very shallow. Along the spreading ridges, however, oceanic crust has formed and the bottom of the gulf attains abyssal depths. Opening of the gulf began about 5 million years ago with a spreading rate of 5 cm/yr.

The net result of movement along the San Andreas–Gulf of California transform system has been the opening of the Gulf of California and the displacement of the western block of the San Andreas northward approximately 300 km (Figure 20.13). With continued movement, Baja California and a narrow slice of western California may become an elongate continental fragment surrounded by oceanic crust. The San Andreas–Gulf of California transform system thus provides insight into how some microcontinents are formed, especially where the transforms cut the ridge obliquely, such as in the western Indian Ocean. This mechanism might explain the origin of Madagascar and the Seychelles Islands, which are continental fragments formerly attached to Africa and India.

Dead Sea Transform System. The Dead Sea transform system extends from the spreading ridge of the Red Sea northward to a zone of continent-to-continent collision in the Alpine orogenic belt in southern Turkey (Figure 20.14). The structure, topography, and history of the entire region are magnificent expressions of continental plates moving along a transform system. The transform zone is about 1000 km long and marks the boundary between the western edge of the Arabian plate and the northern part of the African plate. It is a remarkable structure that controls the development of many features in Israel, Lebanon, Syria, and the Sinai Peninsula, as described below.

The main structure is the strike-slip fault zone, which involves several separate fault planes that slice through the entire lithosphere. These faults are not straight but have several angular bends. As a result, large, deep pull-apart basins have formed along the strike-slip fault zone (Figure 20.15). The Gulf of Aqaba (Elat) segment is the widest and deepest. The floor of one of these basins is more than 2000 m below sea level. Farther north, the Dead Sea trough is another pull-apart basin; it is 400 m below sea level, with water depths exceeding 300 m in places. Sediment filling the Dead Sea trough is derived from erosion of the adjacent mountains. It is several kilometers thick and continues to pour into the graben, forming alluvial fans. In a more humid climate, the Dead Sea trough would be a freshwater lake or an extension of the Gulf of Aqaba.

The structural features north and south of the Dead Sea are no less impressive. Note the direction of plate movement illustrated in Figure 20.14. The Arabian plate is moving northward and the African plate southward. Two major bends in the strike-slip fault system occur, one to the north in Lebanon and Syria and the other south of the Dead Sea. As the plates move near these bends, slippage along the fault is inhibited and broad zones of transpression result. This formed compressional folds that branch off the strike-slip fault zone in the Palmyra Mountains to the north (Figure 20.14)

The Dead Sea transform system began about 25 million years ago when Arabia was still part of the African continent. As rifting began to open the Red Sea,

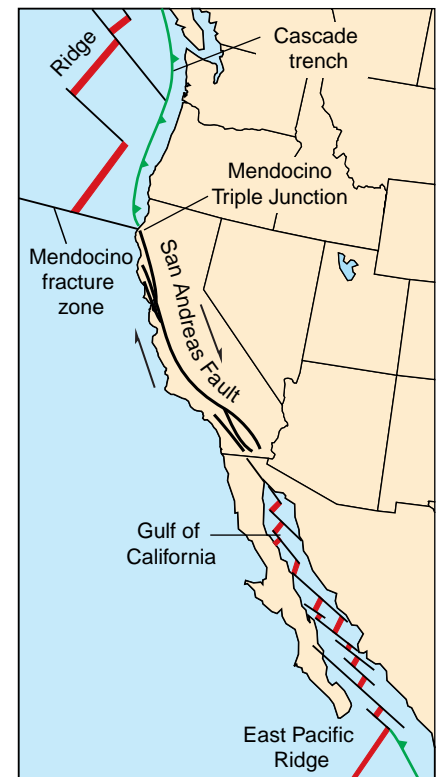


FIGURE 20.13 The San Andreas–Gulf of California transform system extends from northern California to just beyond the end of Baja California. It connects the Mendocino fracture zone, the Cascade trench, and the East Pacific Rise. Where the transform involves continental crust (throughout California), it forms a series of strike-slip faults with intervening pull-apart basins and compressional ridges. In the Gulf of California, where the transform system involves oceanic crust, the fault zone consists of a series of long transform faults connecting short ridge segments.

What structures north and south of the Dead Sea are produced by movement along a transform fault?

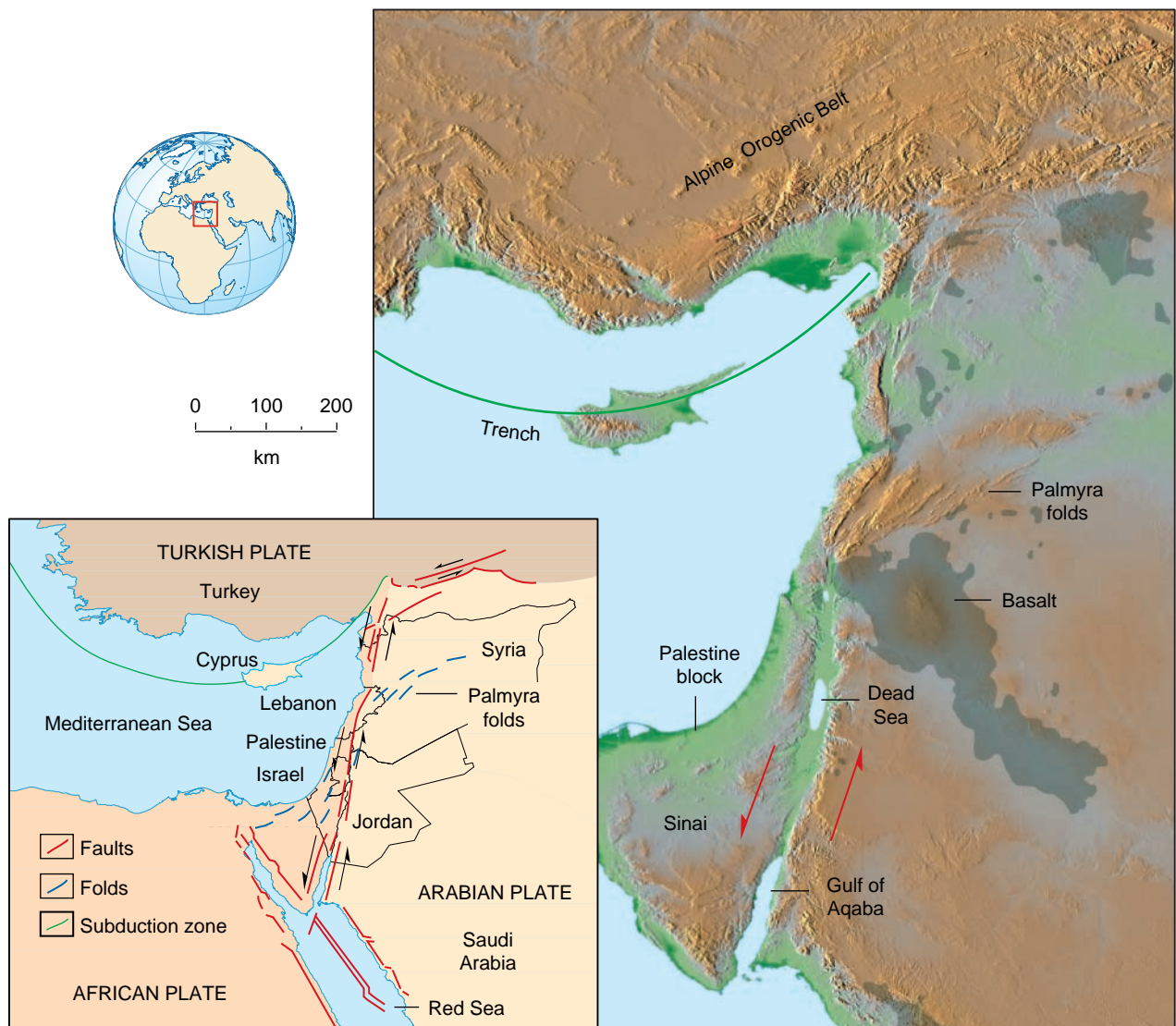


FIGURE 20.14 The Dead Sea transform system connects the Red Sea spreading ridge with the Alpine convergent belt. The movement along the transform zone has produced the long, deep, narrow pull-apart basins of the Gulf of Aqaba and the Dead Sea as well as the contractional folds of the northern Sinai and the Palmyra Mountains of Lebanon and Syria. Small eruptions of basalt occurred near the pull-apart basins. (Courtesy of Ken Perry, Chalk Butte, Inc.)

the Arabian plate split from Africa and began to move northward. The Dead Sea transform was initiated by this movement, and vigorous tectonic activity has continued ever since. Total offset along the southern extent is at least 100 km, but to the north displacement is less, suggesting that part of the plate movement has been taken up by folding in the Palmyra fold belt. Intermittent volcanism along the transform system has occurred since Mesozoic time, and Pleistocene basaltic lava flows and cinder cones are especially obvious (Figure 20.14).

Alpine Transform System of New Zealand. The Alpine Fault is a trench-trench transform system connecting the west-dipping Tonga-Kermadec Trench in the north with the east-dipping Macquarie Trench in the south. As seen in Figure 20.16, the Pacific plate is being consumed in the Tonga-Kermadec Trench east of the north island, and the Australian plate is being subducted south of the south island. Thus, the Alpine transform is a trench-trench transform that traverses a large segment of a continental fragment, shearing New Zealand down the middle. Consequently, this type of transform can be studied from direct observation on land.

What is the offset along the Alpine Fault?

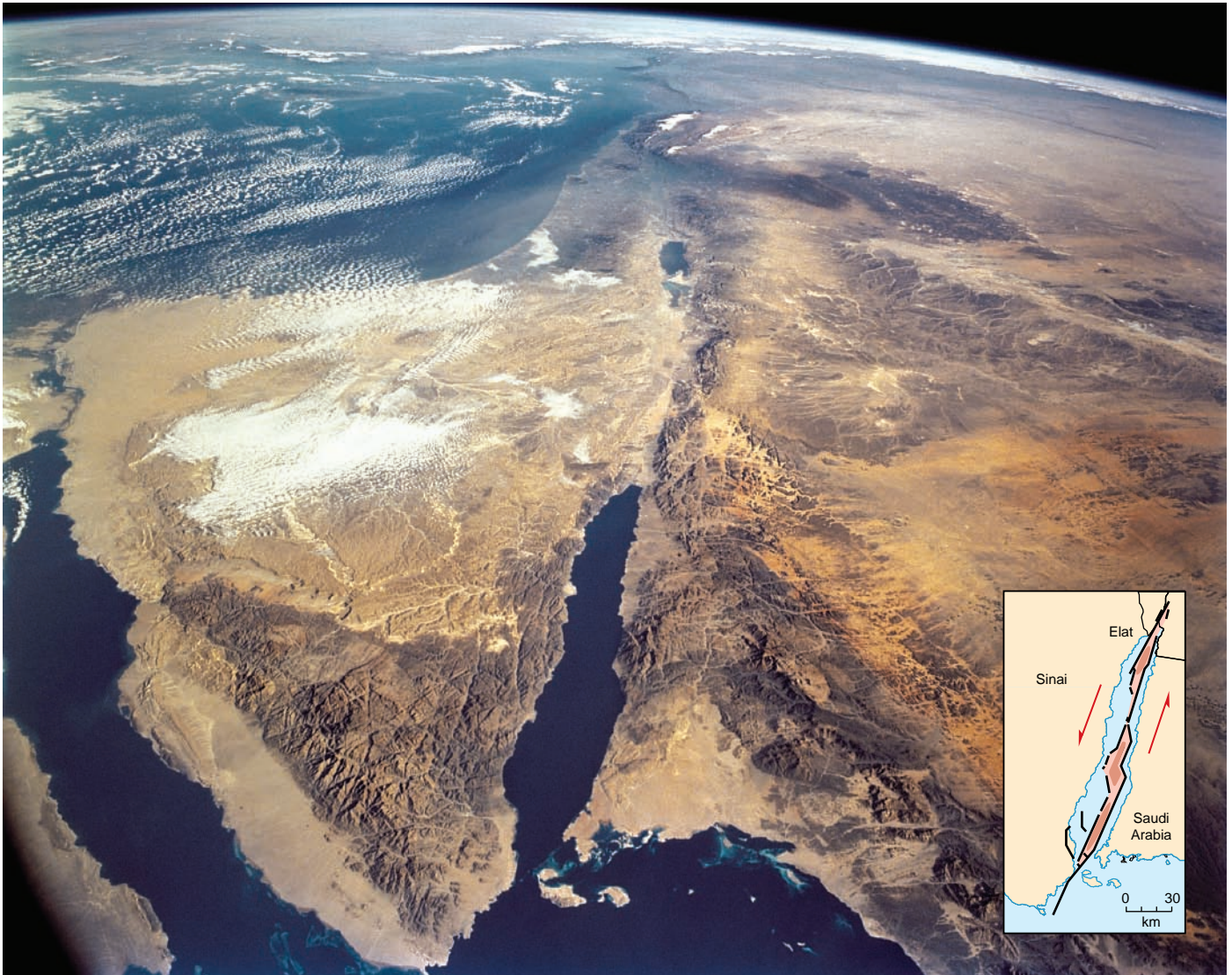
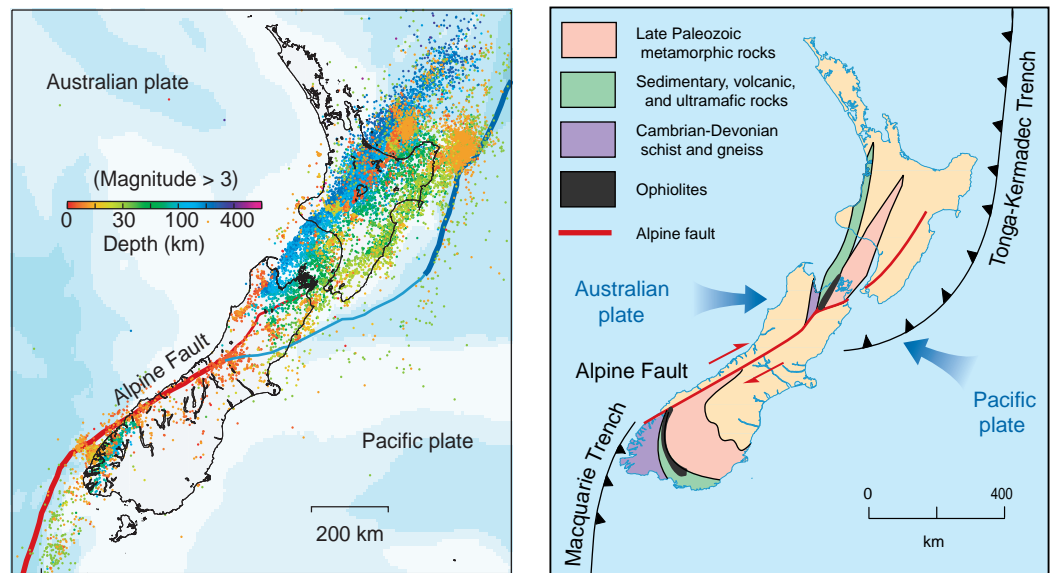


FIGURE 20.15 Pull-apart basins in the Gulf of Aqaba and the Dead Sea dominate this photograph taken by astronauts aboard the Space Shuttle. Such basins are caused by movement on strike-slip faults that have sharp bends and offsets of the major faults (inset). These form three deep basins along the floor of the Gulf of Aqaba and the Dead Sea basin that lies below sea level.

Like the San Andreas Fault, the Alpine transform was well known as a strike-slip fault long before plate tectonic theory developed. Correlation of distinctive rock types near the ends of the fault zone indicates a huge displacement of about 480 km (note the displacement of the late Paleozoic metamorphic rocks on the map). The north and south islands of New Zealand are currently being drawn apart along the Alpine transform system. Throughout much of its length, the Alpine Fault is defined by the abrupt truncation of mountain spurs against the adjacent plains.

Movement along the Alpine Fault has been largely horizontal throughout most of its 40-million-year history (at a rate of up to 1 cm/yr). However, significant vertical movements associated with transpression and thrusting along the fault zone have also occurred. For example, a change in plate motions about 6 to 7 million years ago initiated horizontal compression across the fault zone. This compression caused the southern Alps to rise to their present height of over 3500 m (Figure 20.17).

FIGURE 20.16 The transform system of the **Alpine Fault, New Zealand**, connects the west-dipping Tonga-Kermadec subduction zone to the east-dipping Macquarie subduction zone. Note the tremendous displacement of major rock units on the Alpine Fault. The northern subduction zone dips east and the southern subduction zone dips west, as shown by the pattern of progressively deeper earthquakes. (Courtesy of the New Zealand GeoNet Project)



EARTHQUAKES AT TRANSFORM BOUNDARIES

Earthquakes at transform plate boundaries are especially abundant. The seismicity is shallow and shows strike-slip characteristics.

Earthquakes are especially common on transform plate boundaries (Figure 20.18). In fact, most of the earthquakes along the oceanic ridge system are actually on transform offsets to the ridge, rather than on the ridge itself. The energy released by these earthquakes is about 100 times greater than that released from earthquakes along the ridge crest. The abundance of earthquakes is related to the lithosphere temperature along the cooler transform as compared with the hotter ridge. In the relatively cold lithosphere along a transform fault, brittle fracture is

FIGURE 20.17 The **Alpine Fault, New Zealand**, is a strike-slip fault that connects two plate boundaries. The valley in this view was created by differential erosion along the long linear fault. Deformation along the fault created the high Alps of the southern islands. (Courtesy of New Zealand Institute of Geological and Nuclear Sciences)



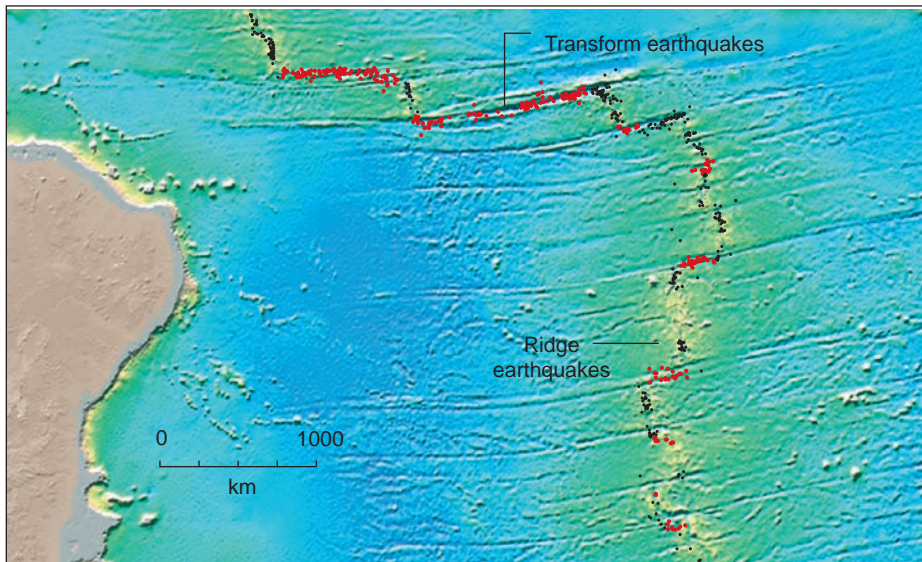


FIGURE 20.18 Shallow earthquakes on a midocean ridge are more frequent on the transform faults, where the crust is cooler, thicker, and more brittle, than on the spreading ridge itself. The region directly beneath the ridge is too hot and ductile to produce many earthquakes. Strike-slip earthquakes (blue) form on transform faults and earthquakes on normal faults (red) are common on ridges. (Courtesy of D. T. Sandwell and W. H. F. Smith, Scripps Institution of Oceanography, University of California at San Diego)

common. Deformation by ductile flow is more common in the hotter rocks right at the ridge, and earthquakes are consequently less common.

Earthquakes along oceanic transform faults are shallow—most are less than 10 km deep—and small compared with those occurring at convergent plate margins (as deep as 650 km) and along continental transform faults (as deep as 20 km). Moreover, shallow earthquakes along the transforms are rarely related to magma intrusion or volcanism as are earthquakes at the ridge crest.

In the 1960s, identification of earthquake patterns along oceanic fracture zones was fundamental to establishing our present understanding of transform fault motion. Early workers found that most of the earthquakes along transform faults are related to *strike-slip* movement on faults perpendicular to the ridge crest. In contrast, earthquakes along the ridge axis occur on *normal* faults parallel to the ridge. As predicted by the plate tectonic theory, earthquakes only occur on the active transform fault zone—typically the area between two ridge axes—and few occur along the inactive part of the fracture zone (Figures 20.2 and 20.18).

Earthquakes are also abundant along continental transform faults. The tremors that plague much of western California occur along the San Andreas transform system (Figure 20.19). One of the most famous earthquakes in history was the 1906 San Francisco event. This shallow earthquake lasted only a minute but had a magnitude of 8.2. The shaking ruptured gas lines, and the fire that followed caused most of the destruction (an estimated \$400 million in damage—a great value at that time—and a reported loss of 700 lives). Horizontal displacement of up to 7 m occurred over a distance of about 400 km, offsetting roads, fences, and buildings.

MAGMATISM AND METAMORPHISM AT TRANSFORM PLATE BOUNDARIES

Volcanoes rarely develop on transform faults, but small volumes of basalt may erupt in pull-apart basins. Metamorphism along transform fault zones creates deformation fabrics, seafloor metamorphism, and serpentinite.

At transforms that juxtapose old crust against an active spreading ridge, the generation and emplacement of basaltic magma is modified because of the cooler temperatures induced by the adjacent thick, cold lithosphere. The temperature becomes lower along the ridge axis as it approaches a transform fault (Figure 20.9). The cooler temperatures diminish volcanic activity because it disrupts the

Knowing your location accurately is vital in almost all geologic studies. It is important for research ships at sea, for oil drilling rigs on land, and even for geologists collecting an individual specimen from a rock outcrop. Traditionally, geologists have determined their locations in the field by consulting a topographic map or aerial photograph and using distinctive landmarks to approximate their position. These locations were usually accurate to within a few meters. If more precise locations were needed, laborious measurements with surveying equipment, a transit, or a steel tape could be used.

Ancient people used the stars to navigate. Stars and constellations could be found in predictable places in the sky. By knowing their own position relative to the stars, early navigators could calculate a good fix on their location on the globe. Today, the *Global Positioning System* (commonly abbreviated as GPS) uses radio signals (instead of light) from a constellation of 24 satellites (instead of stars) to find the location of a spot on the surface. In effect, GPS uses these “artificial stars” as reference points to calculate positions that can be accurate to within a few millimeters. The satellites are launched and maintained by the U.S. Department of Defense. GPS receivers are small enough to carry in the field.

A GPS unit measures the distance from your location on Earth to four or more satellites in orbit and then it calculates each distance by accurately measuring how long it takes radio signals from the satellite to reach the receiver. Using a method similar to that used to find earthquake epicenters (Figure 18.4), four “distance spheres” are formed and their mutual intersection gives your location on Earth.

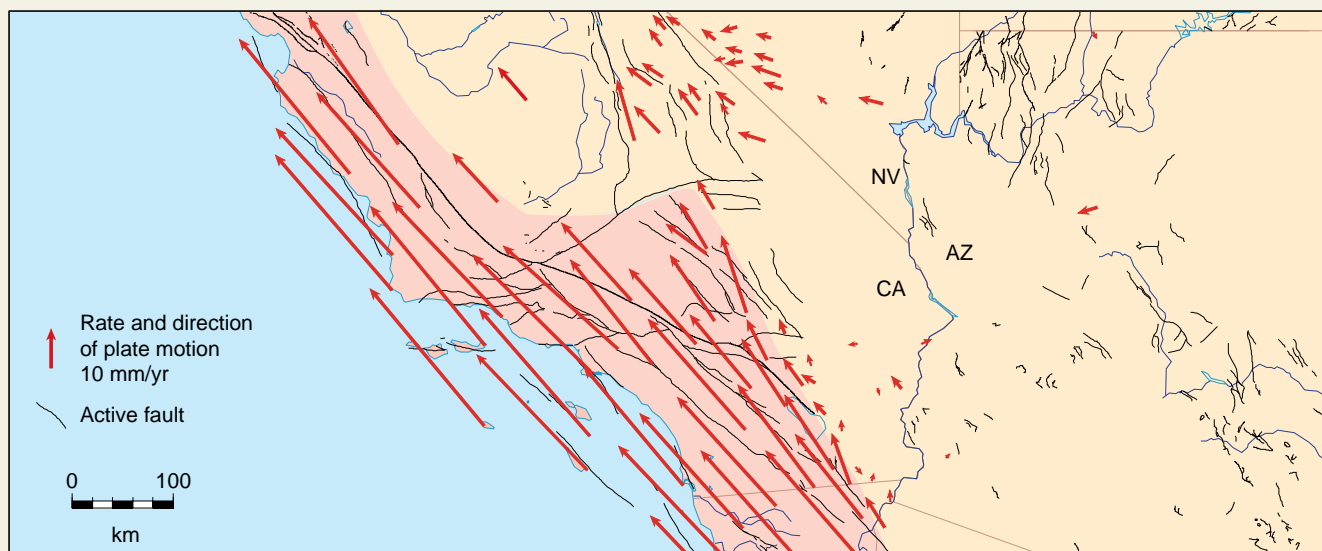
Obviously, the accuracy of the location depends on the accuracy of the distance measurements. One way to improve the accuracy is to stay in the same place for a long time and allow many readings to be averaged. For precise measurements, like those described below, a GPS receiver may need to remain in the same place for an entire day.



(Courtesy of A. Johnson/National Air and Space Museum/Smithsonian Institution)

Once a location is known, say, for a sample collection site, a geologist may be satisfied and never return to this location. But others interested in plate motion may come back to the same site again and again to measure the changing position of that spot. Remember, most plates move a few centimeters each year, a distance well within the capabilities of a precise GPS survey. Since the frame of reference (the satellite) is off the planet, an absolute direction and amount of motion can be found by comparing successive measurements.

The map below shows the power of repeated GPS surveying. The arrows are vectors showing the speed and direction of movement of each surveyed spot. It is immediately apparent that parts of coastal California are “quickly” sliding to the northwest at a rate of about 5 cm/yr. The rapidly moving region is on the western side of the San Andreas fault system (Figure 20.13). These velocity estimates are very similar to those found by measuring offset features on the fault and constitute a powerful affirmation of the role played by moving plates over millions of years.



(Modified from R. A. Bennett, J. L. Davis, and B. P. Wernicke)

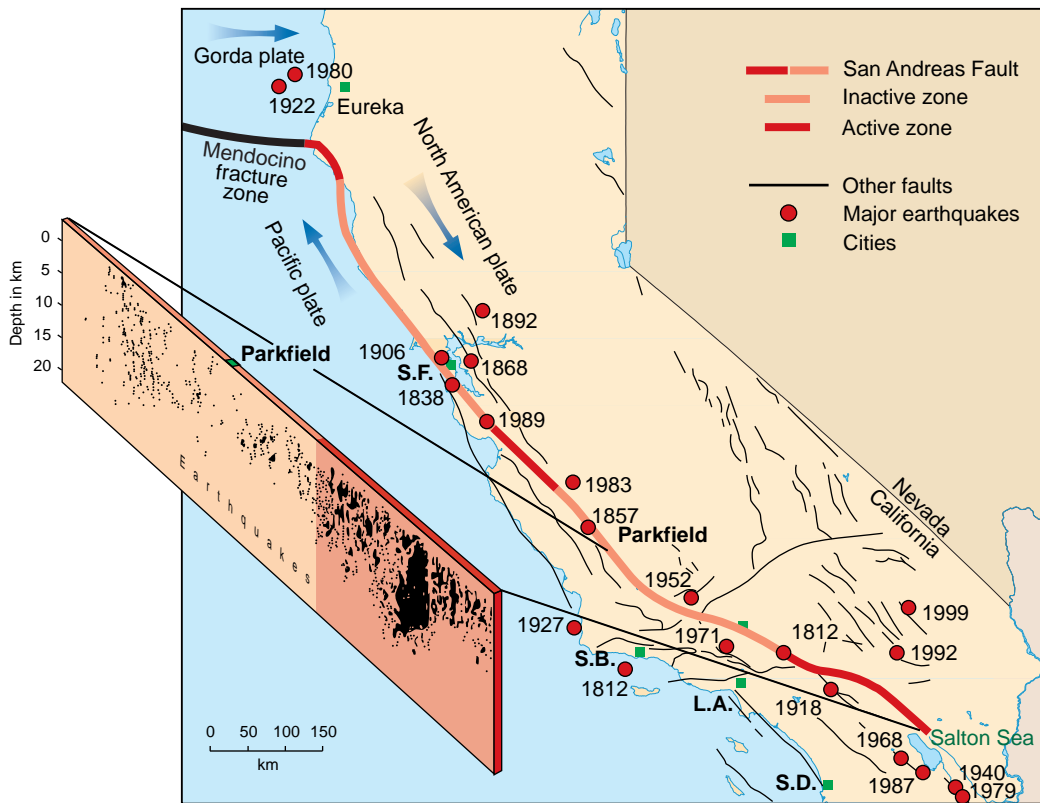


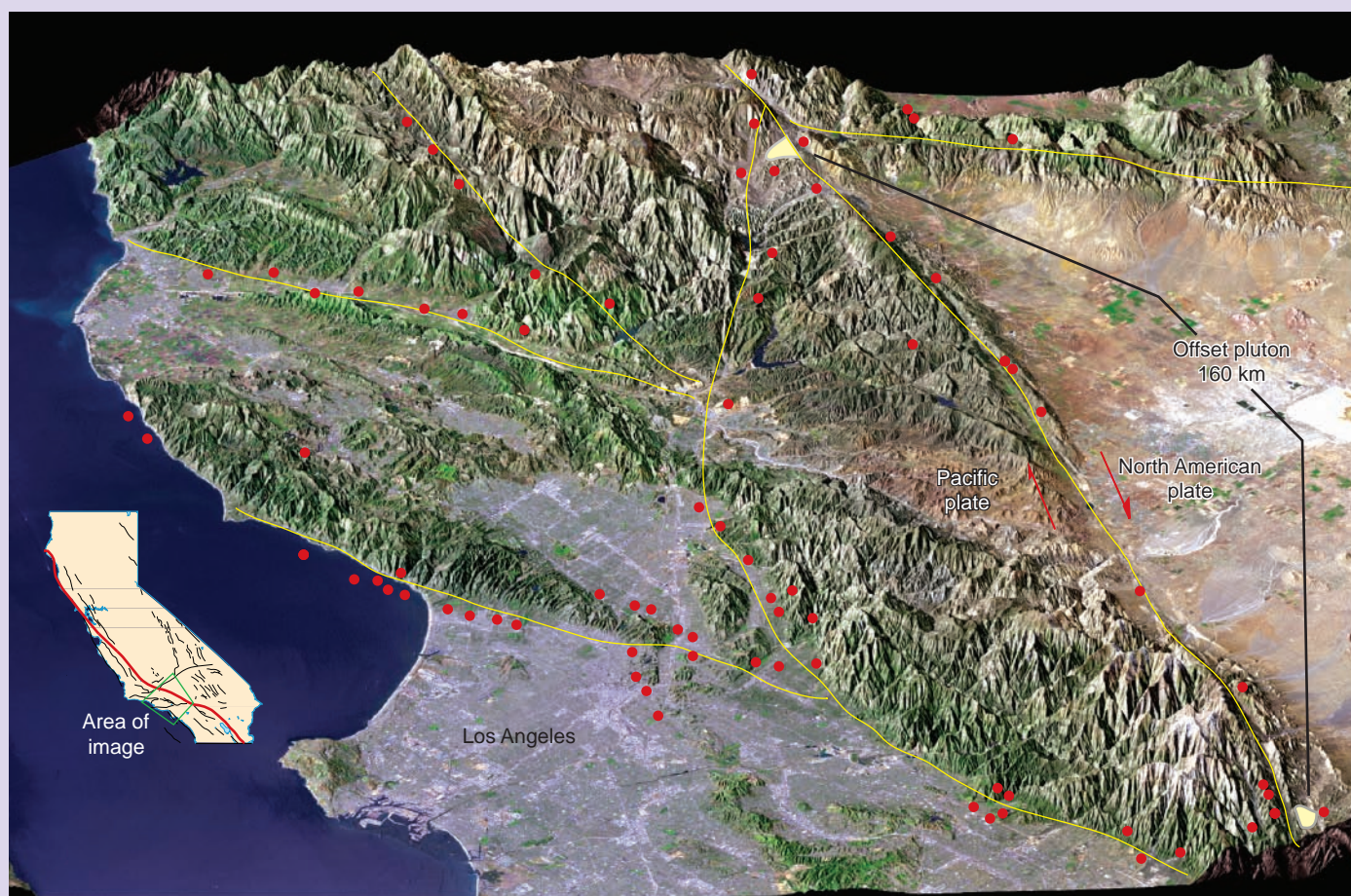
FIGURE 20.19 Earthquakes on the San Andreas continental transform system are concentrated along the fault and its branching subsidiaries. Almost all of the earthquakes occur at depths less than 15 km. The southern part of the fault has had many historic earthquakes while the northern segment has not. Perhaps strain is building toward a large earthquake on the northern strand. (Modified from A. Robinson)

migration of the hot upwelling asthenosphere and lessens the volume of basaltic melt generated. As a result, the amount of magma supplied to the shallow magma chamber decreases as the transform boundary is approached. Consequently, the crust becomes thinner near the transform.

Some continental transform faults are locally associated with basaltic volcanism. Such “leaky” transforms usually have pull-apart basins, where small volumes of basalt erupt as lava flows and cinder cones. The lavas along the Dead Sea transform (Figure 20.14) and those near southern California’s Salton Sea are good examples of this type of volcanism. Partial melting in the mantle occurs when it rises to fill the small voids created by the pull-apart basins.

The most characteristic type of metamorphism that occurs at transform plate boundaries is caused by the horizontal shearing motion. As the two plates grind against one another, fault breccias and fine-grained mylonite are created; at higher temperatures, ductile deformation textures develop. Where a transform fault meets an active ridge crest, metamorphic recrystallization of basaltic lava flows and dikes is also aided by the influx of seawater into hot crust exposed by faulting in the fracture zone.

Why are earthquakes limited to shallow depths along transform faults?



This dramatic view of southern California is a hybrid between a map, a photograph, and a three-dimensional sculpture based on remote sensing and innumerable measurements of elevation. Clearly displayed are the features that led geologists to conclude that a transform fault system has shaped the terrain.

Observations

1. Note first of all, the sharp, nearly straight lines that separate the mountains from the basins.
2. A pronounced linear fabric in the mountains parallels these lines.
3. Geologists working on the ground find horizontal displacement and breccias along these zones showing that each one is a strike-slip fault.
4. Thus, the San Andreas is not a single fault, but a system of many faults (yellow lines).
5. A pluton is sliced and offset by one of the vertical faults in this system. Each part of the Triassic pluton is now separated by 160 km.
6. Earthquakes make this motion tragically obvious; each year 2 or 3 large earthquakes rock the San Andreas fault system causing horizontal displacements of several meters at a time.

7. Earthquake epicenters (red dots for selected earthquakes with magnitudes greater than about 4) clearly delineate the patches of broken ground found by field geologists and revealed here by satellite photography.

Interpretations

These observations clearly show that the lineaments seen on the satellite map were created by movement on a series of strike-slip faults that cut across California. As one block slides past another, strain builds up until the rocks break and release the energy during an earthquake. Repeated earthquakes along the faults, break, crush, and pulverize rocks along the fault plane. These brecciated zones are more susceptible to weathering and erosion. The linear fabric of the mountains was carved by weathering and erosion along these zones of weakness. Long term movement on the San Andreas fault is shown by the offsets of many geological features which imply that the rate of displacement along this strand of the fault is 2 to 3 cm/y. These interpretations led to the conclusion that the San Andreas fault system is a transform plate boundary that separates the North American plate from the Pacific plate.

(Courtesy of NASA/JPL/NIMA)

KEY TERMS

fracture zone (p. 576)	ridge-ridge transform (p. 578)	transform boundary (p. 576)	trench-trench transform (p. 578)
leaky transform (p. 580)	ridge-trench transform (p. 578)	transform fault (p. 576)	
mylonite (p. 578)	serpentine ridges (p. 584)	transpression (p. 583)	
pull-apart basin (p. 583)	shearing (p. 576)	transtension (p. 583)	

REVIEW QUESTIONS

1. Contrast the movement of plates at a transform boundary with that at divergent and convergent boundaries.
2. How does a transform fault differ from a simple strike-slip fault?
3. What are the three main types of transform plate boundaries?
4. Draw a simple line map of the Romanche fracture zone (Figure 20.4). Show midocean ridges, inactive fracture zones, the active fault zone, and the older colder side of the transform fault zone.
5. List two examples of each of the three main types of transform faults.
6. Why is there a steep cliff along one side of an oceanic fracture zone?
7. Compare the features of the Clipperton (small offset) with the Romanche (large offset) transform zones.
8. What are the effects of the cold wall of lithosphere where an oceanic spreading ridge meets a transform fault?
9. What geologic features mark the surface expression of a continental transform fault?
10. Outline the development of a pull-apart basin along a continental transform fault.
11. How can a compressional fold belt form along a transform plate boundary?
12. Where do you think oil might form in connection with a transform fault system such as the San Andreas Fault?
13. Why is seismicity common on a transform fault between two midocean ridge segments but rare on the long fracture zone that extends beyond the ridge?
14. Why is volcanism rare along transform plate boundaries?
15. What kinds of metamorphic rocks would you expect to find along an oceanic transform fault zone?

ADDITIONAL READINGS

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MULTIMEDIA TOOLS



Earth's Dynamic Systems Website

The Companion Website at www.prenhall.com/hamblin provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources



Earth's Dynamic Systems CD

Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Animations of transform fault motion
- Simulated flights down an oceanic transform fault
- Slides showing deformation along transform faults
- A direct link to the Companion Website