

Plate movements and their geometric relationships

Three different types of plate boundaries were introduced in Chapter 1: constructive boundaries (mid-ocean ridges), conservative boundaries (transform faults), and destructive boundaries (subduction zones). We also introduced the concept that describes plate motion on the spherical surface of the Earth as the rotation of a given plate around an axis that passes through the center of the Earth. Therefore, every plate movement or relative movement between two plates can be described by the location of the pole of rotation and the angular velocity of the movement. Although this chapter uses geometry to explain the movement of plates, the major concepts presented here can be followed without using the equations with trigonometric functions.

There are several important rules and concepts of plate motion: (1) Relative movement between two plates is always parallel to transform faults. Though deviation from this rule can occur in nature at certain regions along transform faults, especially where they have a compressional or extensional component (Ch. 8), these can be neglected when considering the theoretical concepts presented below. (2) Although oblique movement is possible, movement along divergent plate margins tends to be perpendicular to the plate boundary because this condition generates maximum stability of the spreading axis. (3) At convergent plate boundaries there is no such preferred orientation; subduction movement ranges from oblique to perpendicular to the plate boundary.

Helpful transform faults

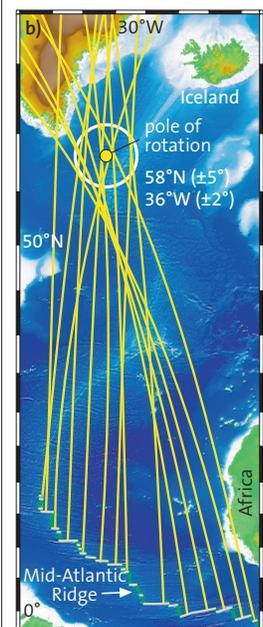
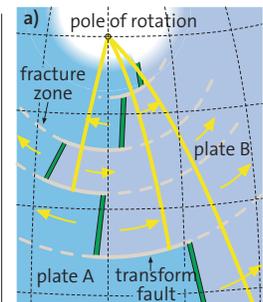
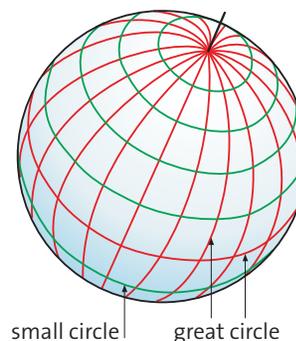
Transform faults are very useful in the construction of plate movements. If a transform fault is precisely oriented, motion is in a pure strike slip sense and has a geometric relationship to the common pole of rotation of the two plates separated by the fault: the fault follows a small circle around the pole. Small circles form when the surface of the Earth's sphere is cut by planes that do not pass through the center of the Earth. In contrast, great circles, which are larger than small circles, are formed when the surface of the Earth's sphere is cut by a plane that passes through the center of the Earth (the largest possible circles on the surface of a sphere and the shortest distance between two points on the surface

of a sphere). These geometries can be illustrated by examining Earth's latitude-longitude grid – all longitudes and the equator are great circles whereas all other latitudes are small circles (Fig. 2.1). Like the arrangement of latitudes with respect to the geographic pole, transform faults are arranged concentrically around the common pole of rotation of two plates. Great circles vertical to transform faults meet in the common pole of rotation, as do the longitudes of the Earth in the geographic pole, i. e., the pole of rotation of the Earth. Following this concept, poles of rotation between two adjacent plates can be constructed (Fig. 2.2).

The correct construction of the pole of rotation can be controlled by the Mercator projection of the Earth's surface. In a Mercator projection the poles are at infinity; therefore, it is not possible to display the polar regions in this projection. The grid is orthogonal, i. e., longitudes and latitudes are linear and vertical to each other. If we use the common pole of two plates as the pole of a Mercator projection, then all transform faults which separate these two plates must be parallel to the equator of this projection (Fig. 2.3). Irregularities cause small deviations from the ideal orientation of the transform faults. Mid-ocean ridges in this projection are exactly orthogonal to the transform faults if the divergence of the ocean floor is vertical to the spreading axes.

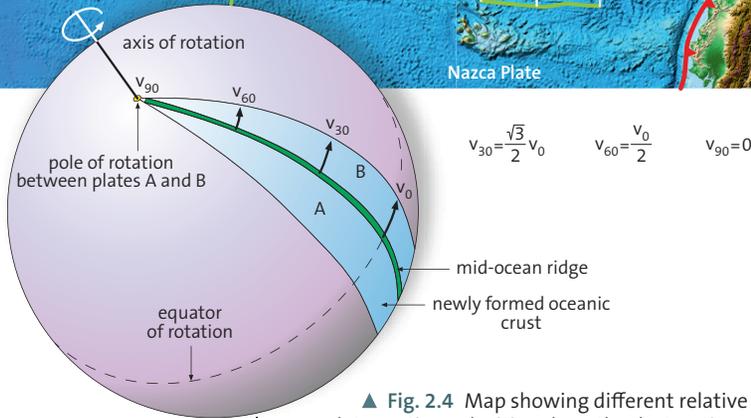
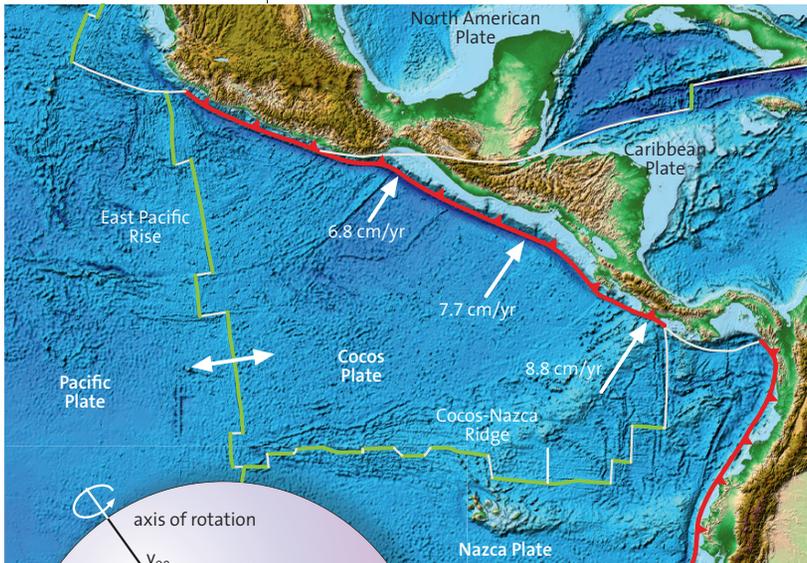
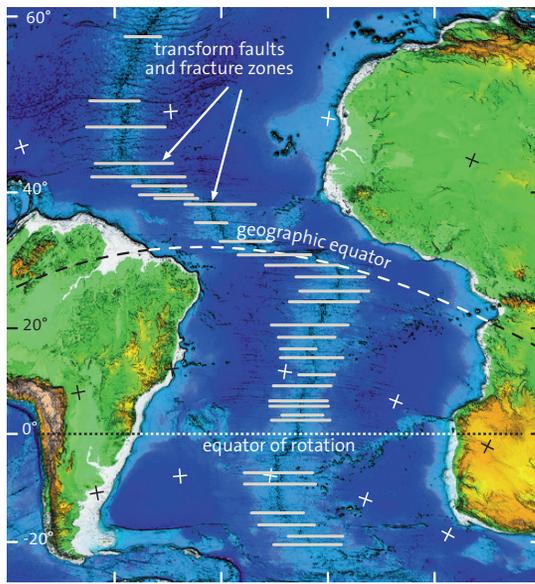
The poles of rotation of the two sides of both the Mid-Atlantic Ridge and the East Pacific Rise are located near the geographic pole (LePichon, 1968). Both ridges are more or less north-south oriented and their transform faults east-west oriented. The preferred north-south orientation of the mid-ocean

► Fig. 2.1 Possible great circles (red) and small circles (green) on the surface of a sphere.



▲ Fig. 2.2 Construction of the common pole of rotation of two diverging plates (Morgan, 1968). a) Principle of construction: normals (deep yellow) to the transform faults meet in the pole of rotation; the transform faults follow concentric small circles around the pole of rotation. b) Determination of the common pole of rotation of the South American and African plates using transform faults at the Mid-Atlantic Ridge between Brazil and Western Africa.

► Fig. 2.3 Geometric relationships between the common pole of rotation and transform faults respectively fracture zones in their prolongation in the southern Atlantic (LePichon, 1968). The Mercator projection is related to the common pole of rotation between South American and African plates (58° N, 36° W, see Fig. 2.2). In ideal cases, the transform faults run parallel to the equator of rotation. The mid-ocean ridge tends to be orthogonal to this.



▲ Fig. 2.4 Map showing different relative plate motion velocities along the destructive plate boundary between the Caribbean and Cocos plates. Velocity is dependent on the distance to the common pole of rotation of the two plates which is located northwesterly off the field of the map (DeMets et al., 1990). The sphere schematically indicates how relative plate velocity increases between of two diverging plates with increasing distance from the rotational pole.

ridges is probably a result of a long lasting relation between plate drift and the rotation of the Earth.

Relative movements and triple junctions

Relative movements between two plates are different at different places along their common boundary, only the angular velocity remains the same. Along any given transform fault, the movement is the same because all points along the fault are at the same distance to the common pole of rotation of the two plates. The spreading rate along the boundary between two diverging plates becomes smaller with decreasing distance from the pole of rotation; at the pole itself, it is reduced to zero (Fig. 2.4). Correspondingly the same is valid for rates of convergence between converging plates. The largest movement is at a distance of 90° from the common pole of rotation along the only possible transform fault which represents a great circle: the equator of rotation.

The decrease of velocity of the relative movement from the equator to the common pole of rotation follows the equation

$$v_{\alpha} = v_0 \cos \alpha,$$

where v_{α} represents the velocity of the relative movement at a small circle which is at a distance of the angle α from the equator (Fig. 2.4). If the velocity at the equator of rotation is v_0 , and is, for instance, at a distance of 30° from the equator ($\alpha = 30^{\circ}$)

$$v_{30} = \frac{\sqrt{3}}{2} v_0 \quad \text{or} \quad 0.866 v_0,$$

at a distance of 60° from the equator

$$v_{60} = \frac{1}{2} v_0 \quad \text{or} \quad 0.5 v_0$$

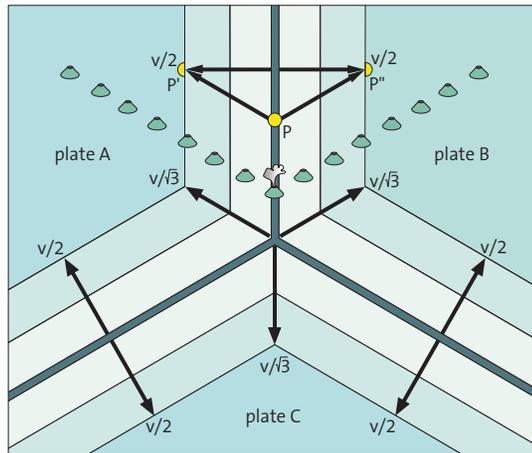
and at the common pole of rotation $v_{90} = 0$.

The geometry of the plates on Earth contain a number of triple junctions, i.e., locations where three plates and three plate boundaries meet in a point. The nature of triple junctions ranges from simple to complex. The simplest case is a triple junction where three oceanic ridges meet; this kind of triple point is called an RRR triple point: R means (mid-ocean) ridge. If the three spreading axes have the same diverging rates, a stage of balance will evolve with three plate boundaries in an angle of 120° to each other (Fig. 2.5). A possible scenario would be a triple junction situated over a uniformly rising mantle diapir unless restraints of other plates cause a distortion.

Assuming that each single plate moves perpendicularly away from the ridge with the same velocity

$v/2$ the geometric relation shown in Fig. 2.5 will be the result. The vectors which are orthogonal to the spreading axes only display the relative movement between two adjacent plates. Looking at the triple junction at a fixed point, plate B moves with the velocity of $v : \sqrt{3}$ towards east-northeast (N60°E). Because the other two plates move in an analogous way, the movement of the two halves of a point (P' und P''), which have been formed as a common point (P) at one of the ridges, appears as a relative movement orthogonal to the ridge. The effectively covered distance, however, is larger than the distance to the ridge.

An example for such a situation exists in the Southern Atlantic, where the hot spot of Tristan da Cunha, located near the mid-ocean ridge, feeds volcanoes. The hot spot produced volcanoes on both the South American Plate and the African Plate as they drifted away from the spreading center on their respective plates (Fig. 2.6). Traces of these hot spots are thus visible in volcano chains oriented towards NW (Rio Grande Ridge) and NE (Walvis Ridge) respectively. If we consider the hot spot in this example to be point P, then volcanoes in a given distance from the hot spot are the points P' und P'', which have the same age. The age of the volcanoes increases with distance from the hot spot. This example shows that the relative plate movement is rather close to east-west, as also indicated by the orientation of the transform faults and their traces.

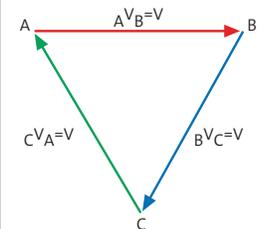
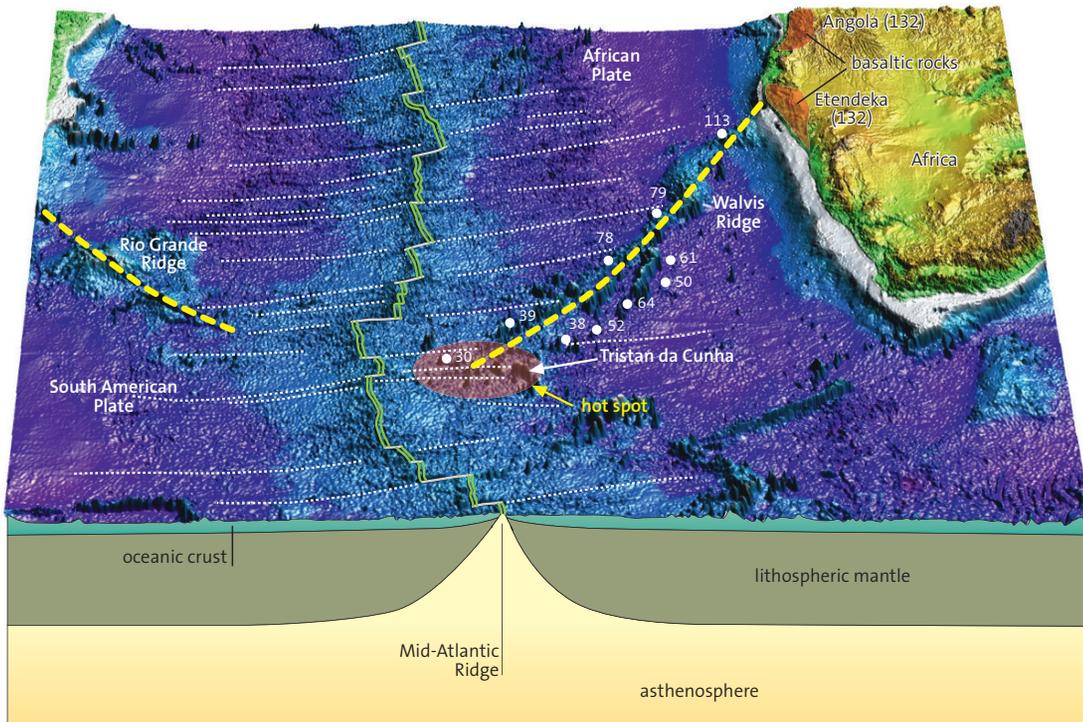


◀ Fig. 2.5 Movement direction and velocity of three plates at an RRR triple junction (three ridge systems meet in a point). The relative movements of two plates against each other do not coincide with the absolute plate movement that is indicated, e. g., by volcano chains formed at a (stationary) hot spot. Stripes of oceanic crust of the same age have the same colors.

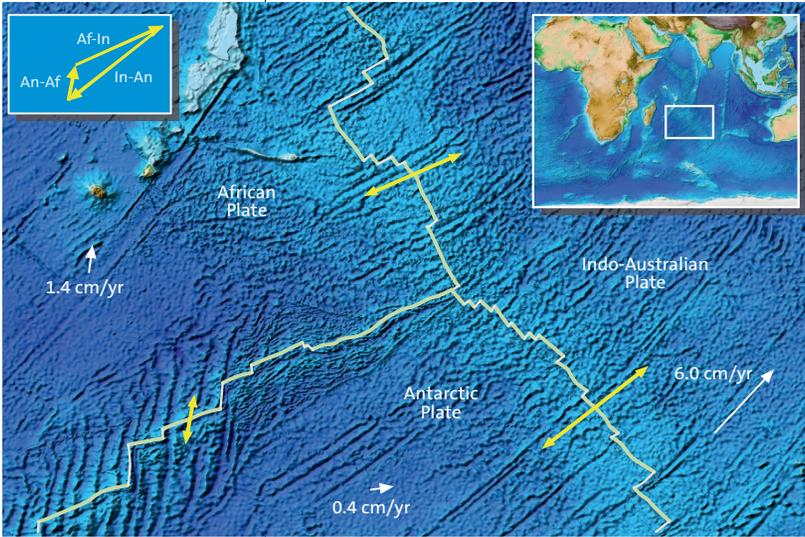
The movement relative to the hot spot, however, is NW directed on the South American Plate and NE directed on the African plate. If the hot spot is stationary, the Rio Grande Ridge and the Walvis Ridge, respectively, indicate the absolute movement of the plate. Today the hot spot is located at a certain distance to the mid-ocean ridge on the African Plate. Therefore, new submarine volcanoes develop only in prolongation of the Walvis Ridge.

Relative movements of plates can be illustrated by vector diagrams. Figure 2.7 follows the method of McKenzie and Parker (1967). If an observer stands on plate A, plate B moves away from him/

◀ Fig. 2.6 Block diagram of a hot spot (Tristan da Cunha) feeding volcanoes near a mid-ocean ridge. The Walvis Ridge is located on the African Plate, the Rio Grande Ridge lies on the South American Plate. The ridges trace the absolute movement of the two plates. Numbers indicate the ages of the volcanic rocks in millions of years.



▲ Fig. 2.7 Vectorial diagram used to determine the relative movement between three plates around a triple junction as illustrated in Fig. 2.5. The vector v_{AB} indicates the movement direction and velocity of plate B relative to plate A.



▲ Fig. 2.8 Map of RRR triple junction between African (Af), Indo-Australian (In), and Antarctic (An) plates in the Indian Ocean. The vectorial diagram describes the different spreading rates and directions.

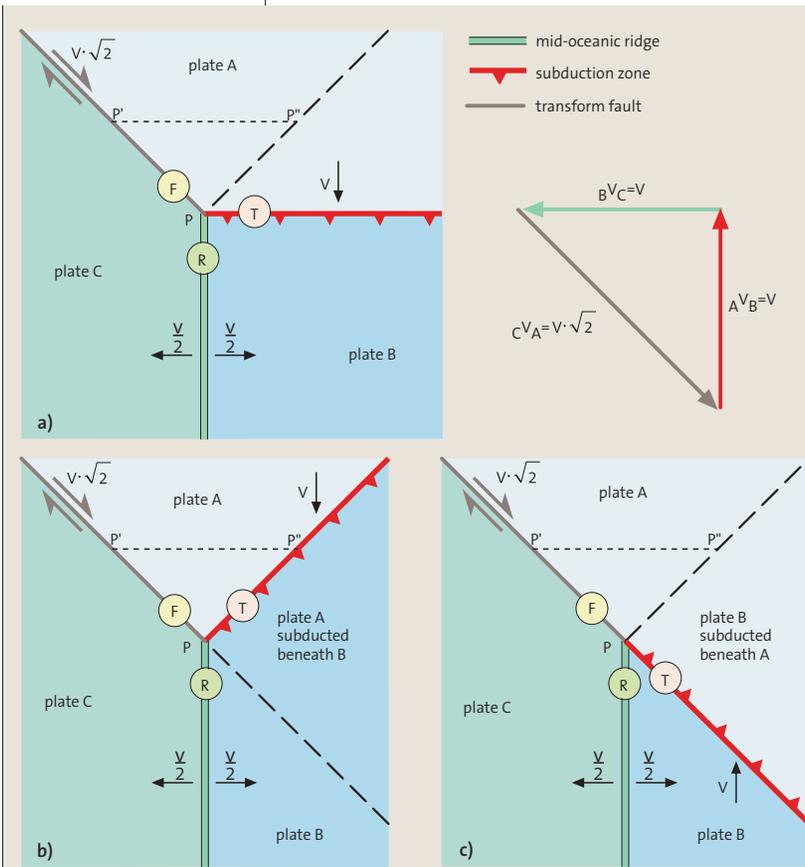
her with velocity v towards the east (${}_A v_B$). If s/he stands on plate B, plate C moves with the same velocity towards the SSW, standing on plate C plate A moves with the same velocity towards the NNW. If the observer returns to the origin, the conditions of the vectorial equation

$${}_A v_B + {}_B v_C + {}_C v_A = 0$$

are fulfilled. Using this diagram, relative movements of three plates around a triple junction can be depicted. If two vectors are known the third results from these.

An *RRR triple junction* exists in the Indian Ocean between African, Indo-Australian, and Antarctic plates (Fig. 2.8). Drifting of plates does not coincide with the symmetrical model presented above, but the geometric relationships are fulfilled as can be demonstrated by the vectorial diagram.

Numerous other possible triple-junction geometries exist, including where three subduction zones meet, as can be observed in the western



▲ Fig. 2.9 RTF triple junction and its related vectorial diagram (McKenzie and Parker, 1967). a) Unstable situation. b) Stable constellation of the triple junction if plate A subducts beneath plate B. c) Stable constellation if plate B subducts beneath plate A.

Two RTF triple junctions off North America

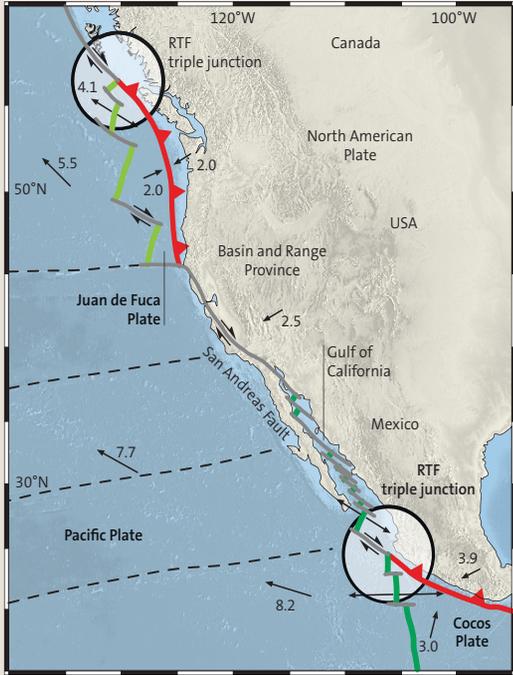
An RTF triple junction is a rather complex situation where a constructive (R stands for ridge), a destructive (T stands for trench), and a conservative plate boundary (F stands for [transform] fault) meet. Figure 2.9a represents a theoretical case proposed by McKenzie and Parker (1967). Plate A is being subducted towards the south beneath plate B with the velocity v (teeth along the subducting plate boundary always point at the overriding plate). Plate C moves away from B towards west with $2 \cdot v/2 = v$. The result is a dextral strike slip movement with the velocity of $v \cdot \sqrt{2}$ along the transform fault (dextral means that if an observer stands on one of the two plates and looks towards the other plate across the fault, then this plate moves towards the right).

The geometric relation illustrated in Figure 2.9a; however, is not stable and thus can only exist for a short time. New oceanic crust formed at the spreading axis between plates B and C at the triple junction (point P) must shift towards the NW parallel to the transform fault (P') if it belongs to plate C. Otherwise a gap would develop at this location. In order to move away in an eastward direction perpendicular to the common spreading axis (looking from the NW-ward moving point P'), the other half of P (P'') must move

by exactly the same amount towards the NE. Since plate B is not being subducted, P'' remains at the surface controlling the course of the plate boundary along the subduction zone. The plate

boundary A/B thus takes a SW-NE orientation. In this manner, the triple junction may remain stable over a longer period. Subduction proceeds in an angle of 45° oblique to the plate boundary A/B (Fig. 2.9b).

A different plate geometry develops when plate B subducts beneath plate A (Fig. 2.9c). P'' is being subducted beneath plate A immediately after its formation. Since plate A dislocates towards the SE with respect to the triple junction, the plate boundary A/B realigns towards the SE and results in a prolonged course (NW-SE) of the plate boundaries A/C and A/B. This geometry occurs in two places along the western coast of North America (Fig. 2.10). The East-Pacific Rise (R), the Central American subduction zone (T), and an equivalent of the San-Andreas transform fault (F) meet at the entrance of the Gulf of California in a complex triple junction. Further north, off the Canadian Pacific coast, this geometry is repeated by the North American, the Pacific, and the mostly subducted Juan de Fuca plates.



◀ Fig. 2.10 Map of plate tectonic setting along the western coast of North America showing two RTF triple junctions. Both triple junction situations are in accordance with that of Fig. 2.9c. Motion velocities in cm/yr.

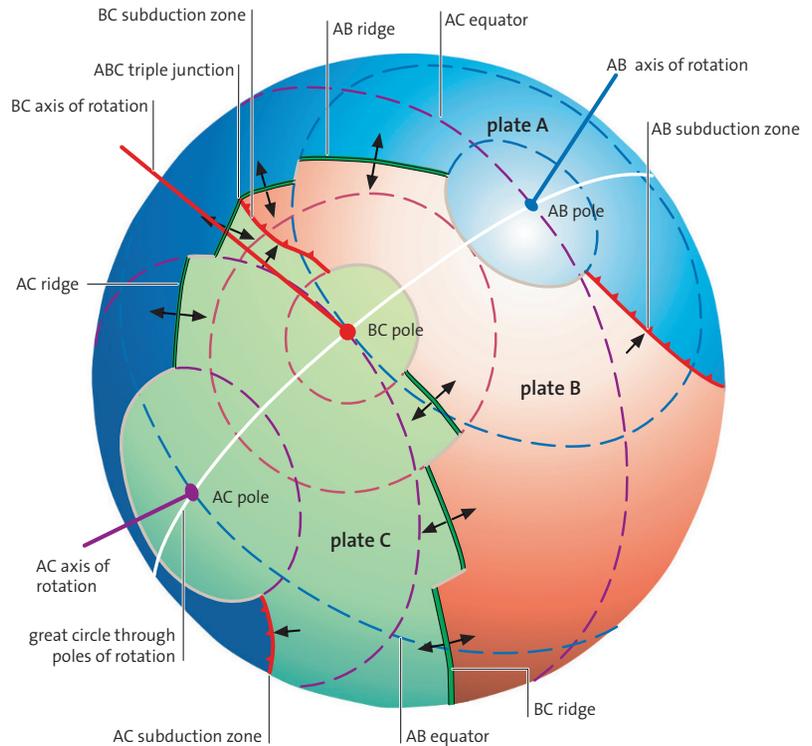
Pacific, where the Eurasian, the Pacific, and the Philippine Sea plates join at a single point (Fig. 1.2). However, not all theoretical triple-junction geometries are possible; for example, three converging transform faults are geometrically impossible.

The rotational poles of three plate pairs whose boundaries meet in a triple junction have a common geometric relationship. If we know the orientation and the angular velocities of two rotational axes, the orientation and angular velocity of the third axis can be calculated using a vectorial equation. The angular velocities ω of the three pairs of plates have the following relation:

$${}_A\omega_B + {}_B\omega_C + {}_C\omega_A = 0.$$

The rotational poles of all three plate pairs are located on a common great circle (Fig. 2.11).

▶ Fig. 2.11 Geometric relationship of three plates around a triple junction (Dewey, 1972). The common poles of rotation of the three pairs of plates are all located on one great circle (white line).



Relative plate velocities – past and present

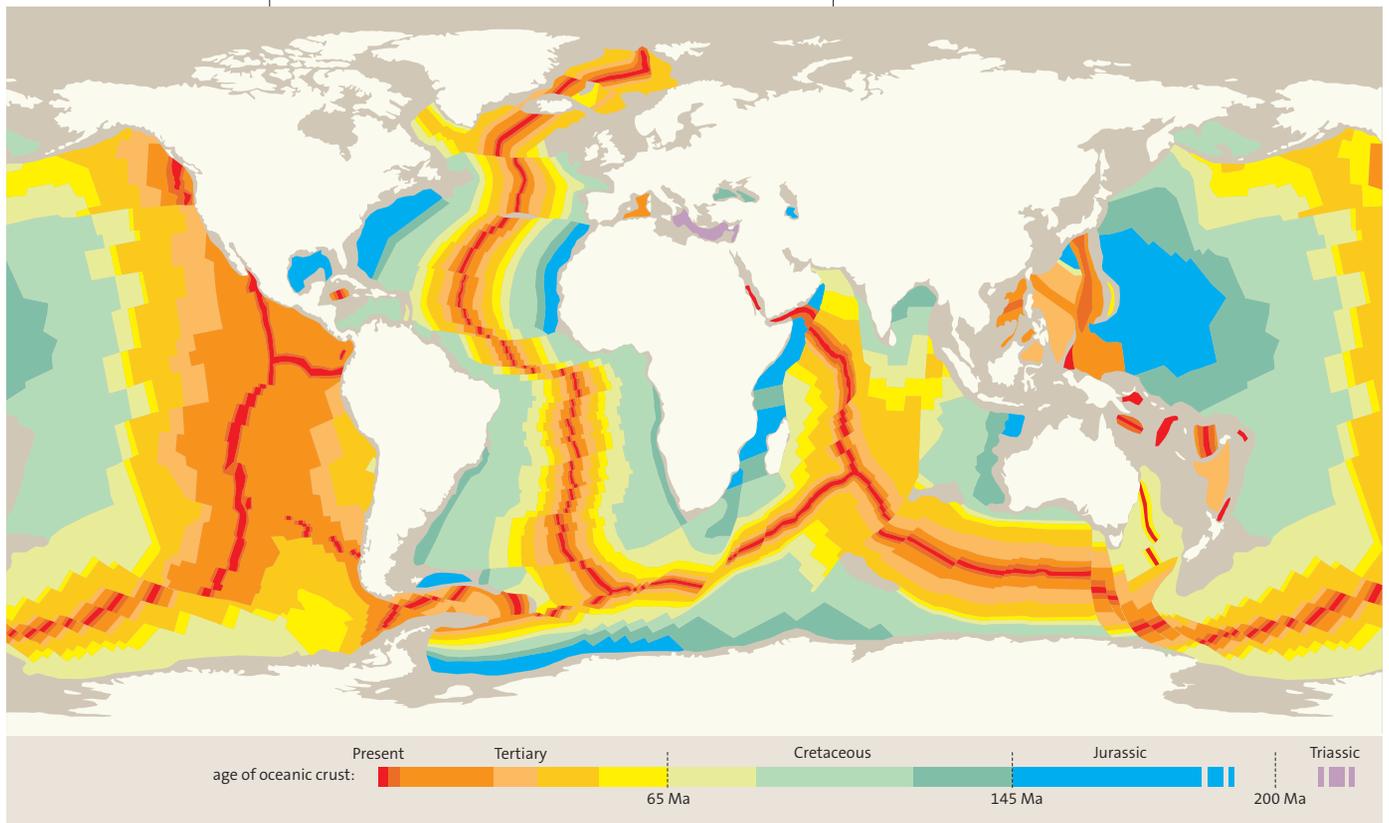
Relative plate movements from the geologic past can be calculated by two methods: (1) by using the magnetic stripes on both sides of a mid-ocean ridge and (2) by tracking the patterns and ages of volcanic chains on a given plate that moved over a hot spot (Ch. 1). From the magnetic stripe pattern, the width of a stripe of oceanic crust formed within a given time span can be measured (Fig. 2.12). This can be used to calculate the average spreading rate of the ocean floor for the given time span. However, it is necessary to know the age or respectively the time span of the magnetic stripes (Fig. 1.6). The age data can be deduced from a comparison of the stripe pattern with the dated magnetic time scale or by the determination of fossil remains of micro-organisms from sediments resting directly above the ocean floor. Stripes located at two plates which are connected at the mid-ocean ridge become narrower towards the common pole of rotation (Fig. 2.12) thus reflecting the above mentioned relation between the velocity of the plate movement and the distance to the common rotational pole of two plates.

The age of volcanoes formed above a hot spot may be determined using various age dating methods. The age difference and the distance between

a given volcano and the presently active hot spot or the distance between two different volcanoes of the volcano chain may be used to calculate the average drifting rate of a plate for the given time span. For instance, the conspicuous kink in the volcanic chain formed by the Hawaiian hot spot (see Fig. 1.5) is 3300 km from Hawaii. The age difference between the volcanoes at the kink and those at Hawaii equals 43 m. y. This results in an average movement of 7.7 cm/yr of the Pacific Plate in relation to the hot spot.

Present velocities are calculated from young time intervals. The model NUVEL (Northwestern University VELOCITY model, established by the Northwestern University in Evanston, Illinois) uses average values of the last 3 million years as the best approximation for the present plate movements. In most cases, fairly good results are obtained. The Atlantic Ocean, currently the ocean with the slowest production of new crust, is spreading (measuring the total separation on both plates) at 2 cm/yr south of Iceland, and 4.5 cm/yr at the point of maximum spreading in the Southern Atlantic (LePichon, 1968; DeMets et al., 1990). Along the East-Pacific Rise, velocities as great as 15 cm/yr are achieved (Fig. 1.2); these are actually the greatest spreading rates between two plates on Earth. Spreading rates

▼ Fig. 2.12 Map showing distribution of ages of oceanic crust. The oldest oceanic crust is of Jurassic age and is located in the NW Pacific (ca. 185 Ma) and near the edges of the Central Atlantic (ca. 175 Ma). Small fragments of older oceanic crust are captured between continental blocks in the Mediterranean Sea..



in the Indian Ocean approach 7.5 cm/yr. Velocities at subduction zones and transform faults have been calculated using the plate movement pattern derived from spreading rates and hot spot activities. Subduction rates approaching nearly 10 cm/yr have been calculated in the western Pacific and movement along the San-Andreas transform fault achieves a total movement of nearly 6 cm/yr.

Direct measurement of plate movements

Since the 1970s several attempts have been made to measure plate movements directly using Satellite-Laser-Radar (SLR) technology and Very-Long-Baseline-Interferometry (VLBI). SLR sends out radar pulses which are reflected by satellites and then detected. Distances can be measured with this method to an accuracy of centimeters. The VLBI method uses cosmic radio signals as the characteristic patterns of signals produced by quasars (very far away luminaries which constitute “quasi-stellar radio sources” – quasar is an acronym) that can be detected at several stations on Earth. From the difference of the arrival times of the same signals it is possible to determine the distance of the stations to an accuracy of millimeters if the measurements are made over time spans of several years. These techniques have been replaced during the last 10–15 years by measurements with the Global Positioning System (GPS).

Measurements using GPS have an accuracy of less than 1 mm. The current GPS is based on 24 satellites. In principle it is the measurement of waves and their Doppler effect as the satellite moves in relation to the gauging station at the surface. Each measurement occurs simultaneous with at least three satellites, more if possible. Exact synchronisation of the measurement cycles is essential. The GPS receivers measure with two frequencies of waves to enhance the accuracy. To minimize errors, the measurements of two or more simultaneously working receivers are merged (method of interferometry). The course of the satellites must be known with an accuracy of a decimeter and time measurement is achieved to within an accuracy of one part in a billion (during this time span light covers a distance of 30 cm). Moreover, the parameters of the Earth’s rotation must be determined constantly with high precision. The location of the pole is known to within an error of less than 10 mm.

Following installation of the global reference system, it was possible after a period of only two years to determine plate movements to within an accuracy of millimeters (Reigber and Gendt, 1996). To determine the movement of a plate, at least three gauging stations must be installed on

that plate. However, changes in the distance between two stations located on different plates can be determined directly. Comparing the relative movements between stations at Hawaii (Kokee Bay) and in the Bavarian Forest in Germany (near Wettzell) and with a number of gauging stations on other plates, an amazingly good accordance is achieved with values calculated using the NUVEL model. However, some significant deviations do exist (Fig. 2.13a).

For instance, the deviations are significant when examining the values between Hawaii and stations at the western boundary of the North American Plate. This is a tectonically complex area along the boundary between the Pacific and North American plates where young compressive and tensional deformation becomes manifest in folding and basin formation. This generates individual movements of small blocks that do not coincide with the movements of the larger plate to which they belong (see Ch. 8).

Three points located on the Pacific Plate (Hawaii and Tahiti in the open Pacific Ocean, California west of the San Andreas fault) should not have any relative movement amongst each other following the strict definition of plates (NUVEL values: 0 mm; Fig. 2.13a). Nevertheless, Tahiti and California move away from Hawaii by an amount of several millimeters per year. As stated in Chapter 1, this suggests that the plates may be subject to a certain internal deformation related to earthquake activity. However, amounts of movement of this “intraplate tectonics” are at least an order of magnitude smaller than those at the plate boundaries. Such intraplate movements were also detected east of the Atlantic. The Bohemian massif, which encompasses the station at Wettzell, moves closer to Scandinavia by an amount of approximately 3 mm/yr although both regions belong to the Eurasian Plate. Convergence should be expected between Wettzell and southern Africa, because the Alpine-Mediterranean mountain range is still under compression (calculation with NUVEL indicates a convergence of 8 mm/yr); however, GPS data show a slight drifting apart of the two points. This indicates extensional movements within the Mediterranean and/or the African continent.

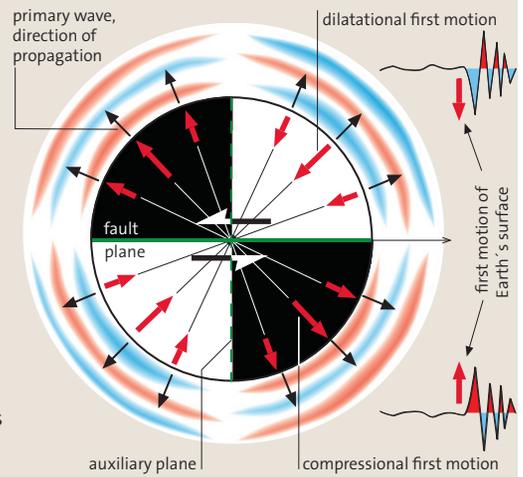
To measure *absolute plate motions*, a stationary coordinate system is required that is centered in the Earth’s center of gravity and defined by the geographic pole (z axis) and the spring point of the ecliptic (x axis). Directly compared absolute plate motions calculated by GPS and with NUVEL show a rather extensive agreement (Fig. 2.13b). Arrows indicating the movement of plates demonstrate the NW and NE drift of the continents at both sides

Fault-plane-solutions of earthquakes

The orientation of planes of movement at plate boundaries can be deduced from earthquake data. In the case of an earthquake triggered at a fault plane, the two blocks move by creating an instantaneous offset up to several meters. This results in the generation of the two types of seismic body waves. Primary (P-) waves oscillate in the longitudinal direction of propagation. They are faster than secondary (S-) waves that oscillate transversally. If all of the seismic data from a given earthquake collected around the Earth are put into a diagram, the quadrants and the two separating planes can be determined with their spatial orientation (Fig. 2.14). In the two quadrants that are in the direction of movement of each block, the first motion of the primary waves is away from the earthquake focus and an observer on the Earth's surface first receives a push; the wave starts with a compressive movement (compressive first motion shown as black quadrants in Fig. 2.14). First motion in the other two quadrants, shown in white, is in the opposite direction; it starts with a tension and is dilatational. Each of these motions is registered by the seismograph.

Using the principles discussed above, the quadrants and the two separating planes can be determined with their spatial orientation (Fig. 2.14). One of these planes represents the slip plane generated by the earthquake; the other one is an aiding plane that has no use in nature. However, initially it is not possible to decide which one of these two planes was the slip plane. Commonly this can be deduced from geological observations if the approximate orientation of a fracture zone is known. On the other hand, careful analysis of seismic data generated by the aftershock activity following every large earthquake provides the opportunity to identify

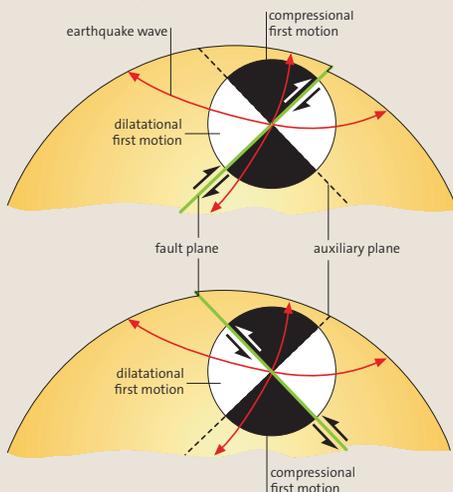
► Fig. 2.14 Principle of fault-plane-solutions of an earthquake hypocenter. The fault plane of the earthquake (orthogonal to the paper plane) and an orthogonal virtual aiding plane define four quadrants. First motions of the primary waves oscillating in the propagation direction and expressed by vertical motions in the soil indicate the sense of movement of the blocks displaced during the earthquake. Seismograms subdivide two quadrants with compressive and two quadrants with dilatative first motion.



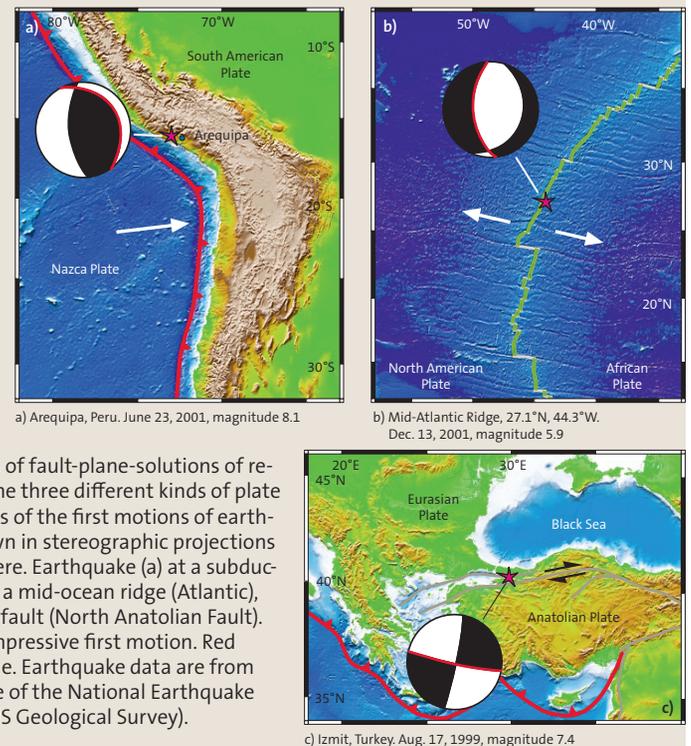
the slip plane because of the shift of the seismic centers. If the slip plane is known, the sense of movement is easily detected (Fig. 2.15). Direction of movement in the slip plane is orthogonal to the aiding plane. A process similar to that used for analyzing P-waves can also be used for the analysis of S-waves that oscillate orthogonal to the direction of propagation.

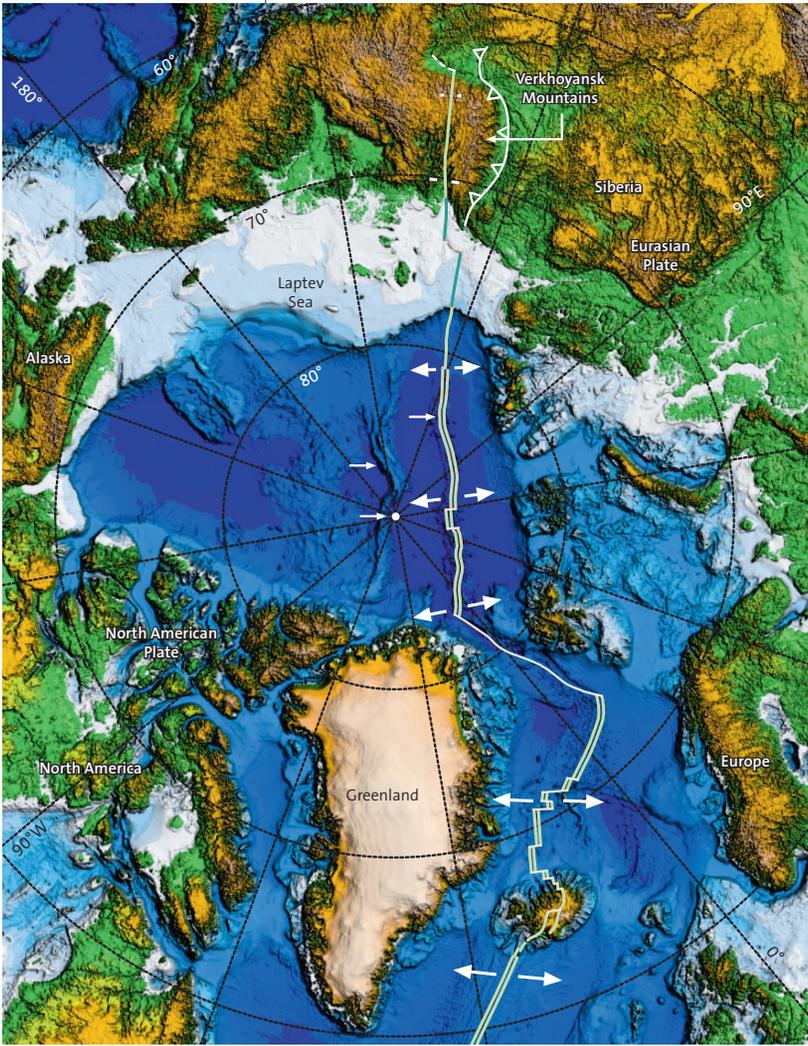
Using this method, which is called fault-plane-solution, the orientation of a slip plane and the sense of movement can be determined with high accuracy. Fault-plane-solutions allow for a reconstruction of plate boundaries and their movement patterns (Fig. 2.16). The analysis of earthquake first motion data impressively confirmed the concept of three different types of plate boundaries (Sykes, 1967).

▼ Fig. 2.15 Ambiguity of fault-plane-solutions illustrated by an earthquake that produces an overthrust. Illustration is a schematic vertical section through the Earth.



► Fig. 2.16 Examples of fault-plane-solutions of recent earthquakes at the three different kinds of plate boundaries. Quadrants of the first motions of earthquake waves are shown in stereographic projections of the lower hemisphere. Earthquake (a) at a subduction zone (Peru), (b) at a mid-ocean ridge (Atlantic), and (c) at a transform fault (North Anatolian Fault). Black quadrants – compressive first motion. Red line – active fault plane. Earthquake data are from the internet catalogue of the National Earthquake Information Center (US Geological Survey).



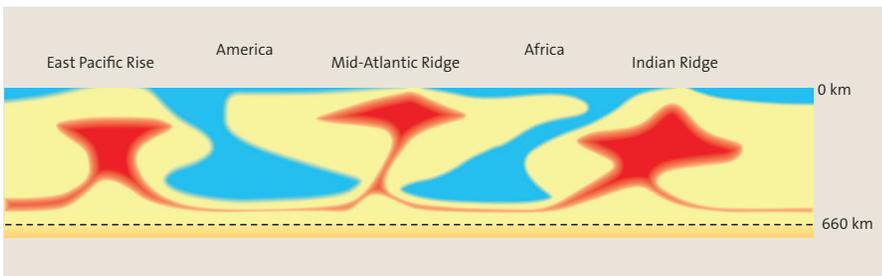


▲ Fig. 2.17 Polar map view showing geometry of the Laurusian Plate as defined in the text. The plate boundary between the Eurasian and North American plates acts like a tear as the spreading center passes through the Arctic Ocean and opens into the Atlantic Ocean. Above the Gakkel Ridge, the two plates behave as one as they merge without a definable boundary across the Russian Arctic region into the Verkhoyansk Mountains of Siberia.

in the Arctic Ocean is compensated by a similar small convergent movement in central Japan and along the eastern coast of northern Japan (about

0.9 cm/yr). The Laurusian Plate (Fig. 1.2) consists of a large plate that comprises most parts of Eurasia and Laurentia (= North America; the name is derived from the latinized word for the St. Lawrence River); the two continents are connected in the area of the Verkhoyansk mountains. Consequently, we propose the term Laurusian Plate because of the problem of unclear boundaries in Northeast Asia. The Laurusian Plate thus defined is subdivided into the Eurasian and North American plate components (Fig. 2.17).

The African Plate has also been considered to be problematic. This plate is surrounded on three sides, west, south and east, by mid-ocean ridges (Fig. 1.5), and consequently has enlarged on these three sides for millions of years. When viewed from the perspective of the mid-ocean ridges, which were once thought to be stationary because they are fed by rising currents from the Earth's mantle, a space problem evolves. However, it is currently known from the technique of seismic tomography (see box) that convectonal currents are extremely complicated and that hot uprising and cool descending branches of currents are commonly oblique and sinuous. It is even possible that mid-ocean ridges are fed by horizontal currents that emit magma along a zone of weakness to the surface. Therefore, the geometry around the African Plate suggests that not all mid-ocean ridges are fed by vertically rising convectonal currents. It is clear that the Mid-Atlantic and the northwestern Indian Ridge move away from each other. GPS data (Fig. 2.13) indicate that the Mid-Atlantic Ridge moves very slowly eastward since the eastward-directed component of the African Plate is larger than the westward-directed one of the South American Plate. Therefore, the Indian Ridge must migrate faster towards the east at several centimeters per year. This is confirmed by the seismic tomography: A hot uprising zone in the upper mantle under the Mid-Atlantic Ridge is steeply inclined towards the west; under the Indian Ridge, a similar situation occurs albeit the westward inclination is at a shallower angle. This indicates a faster eastward migration of the ridge (Fig. 2.18).



◀ Fig. 2.18 Schematic E-W cross-section through the upper mantle to a depth of 660 km that shows mantle currents in the Pacific, Atlantic, and Indian oceans (Anderson and Dziewonski, 1984). Hot anomalies (red) indicate rising mantle currents that are expressed at the Earth's surface by mid-ocean ridges. Cool, descending mantle currents (blue) are characterized by high-velocity seismic waves. Because the Indian Ridge is drifting eastward from Africa, no subduction zone has developed on the east coast of Africa.

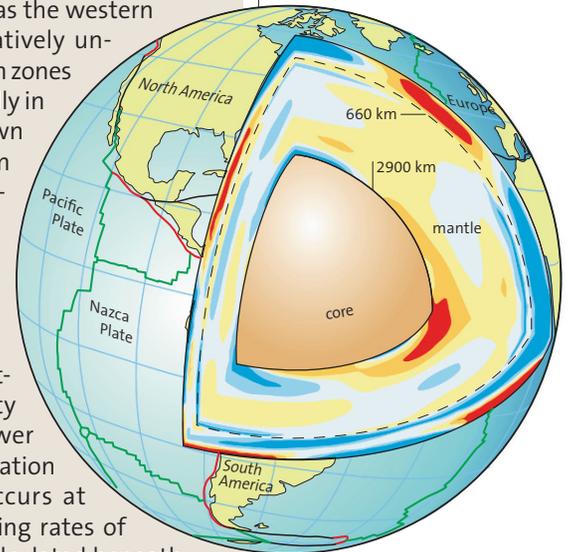
Seismic tomography

The method of seismic tomography analyzes vast amounts of seismic wave data that have passed through the three-dimensional space of the Earth's mantle. This data allows seismologists to determine whether a particular zone of the mantle is slightly warmer or cooler than its surroundings (Anderson and Dziewonski, 1984). Travel times measured in kilometers per second (km/s), are compared from waves that have different paths but propagate across similar areas within the mantle. The comparison allows researchers to determine whether the waves have the expected velocity in the area considered or whether they are accelerated or decelerated. If the rock is hotter, seismic waves decelerate; if it is cooler, they accelerate (Fig. 2.19). Seismic tomography uses different types of waves in the analysis. The differences between the velocities vary and depend upon the type of wave. Cooler regions of the mantle can be correlated with descending currents, hotter ones with rising currents. In this manner, a three-dimensional picture of the currents in the Earth's mantle is generated.

This pattern generated by these currents is extremely complicated (Fig. 2.20). However, in regions where long-lasting subduction has occurred such as the western parts of North and South America and the Alpine-Himalayan Mountain Belt, cold regions plunging obliquely into the

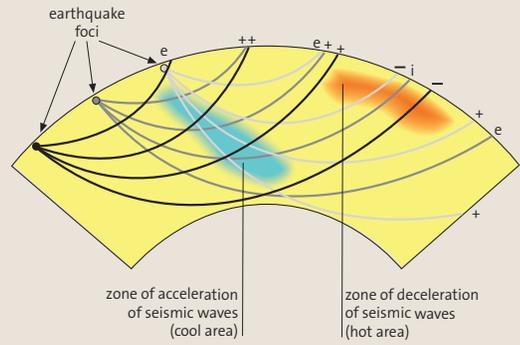
lower mantle (Fig. 2.21) to the core/mantle boundary can be detected (Fig. 2.22). However in complex regions such as the western Pacific, patterns are relatively unclear. Although subduction zones can be detected seismically in the upper mantle only down to approximately 660 km depth, the cold, down-plunging currents induce cold patterns into the lower mantle. The subducted plates are partly absorbed into the upper mantle, but more resistant parts with high density can penetrate to the lower mantle. However, penetration of the lower mantle occurs at far lower velocities; sinking rates of 1–1.5 cm/yr have been calculated beneath South America (Grand et al., 1997). The high resistance of the lower mantle leads to compression and deformation of the remains of the subducted plates (Fig. 2.22).

Below the mid-ocean ridges, hot currents cannot be traced to great depths because the ridges are fed only by the upper part of the upper mantle. At 350 km below the East-Pacific Rise, the distribution of temperatures is irregular (Fig. 2.21 top); at this depth, temperatures would be expected to be higher. Below the

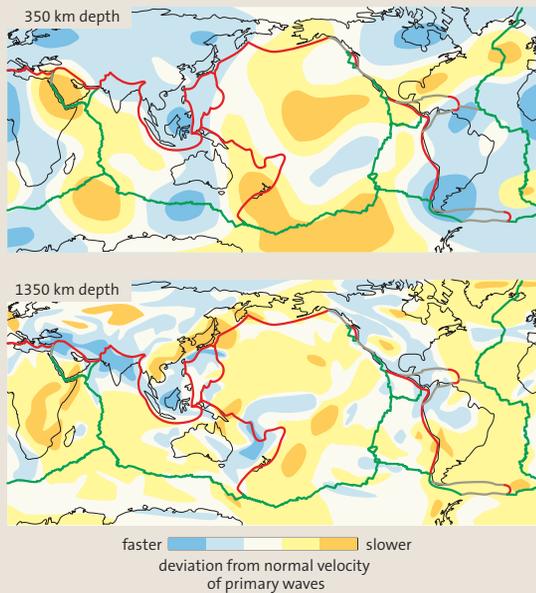


▲ Fig. 2.20 Three-dimensional illustration showing the results of seismic tomography in the Earth's mantle (Dziewonski, <http://www.seismology.harvard.edu/projects/3D/>).

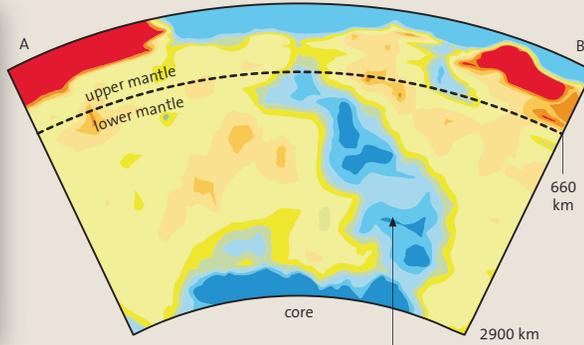
arrival time of earthquake waves: e = as expected; i = indifferent (partly decelerated, partly accelerated); - = decelerated; + = accelerated.



▲ Fig. 2.19 Principle of seismic tomography. Temperature anomalies in the Earth's mantle cause increasing and decreasing travel times of seismic waves. From a large number of travel time measurements, warm and cool bodies can be segregated.



◀ Fig. 2.21 Maps showing deviations of velocities of the seismic primary waves (P-waves) from a normal value in horizontal cuts through the upper mantle. Upper map shows patterns at a depth of ca. 350 km (Anderson and Dziewonski, 1984); lower map shows the pattern in the lower mantle at a depth of ca. 1350 km (Grand et al., 1997). Orange areas indicate hotter, rising zones, blue areas cooler descending ones. Plate boundaries are shown for reference.



faster slower
deviation from normal velocity
of primary waves

◀ Fig. 2.22 Cross-section through the Earth's mantle beneath North America showing results from seismic tomography (Grand et al., 1997). The cool area (blue) obliquely plunging towards the east is interpreted as the remains of oceanic lithosphere of the Farallon Plate that was subducted beneath the North American Plate over a period of about 100 million years.

equatorial Mid-Atlantic Ridge and the eastern Indian Ridge temperatures are unexpectedly low. Individual hot spots are difficult to detect

with seismic tomography because the relatively thin, finger-shaped protuberances are difficult to record with this method.