"Intro. to Seismology". Stein + Wysession
Blackwell Publishing, 2003.

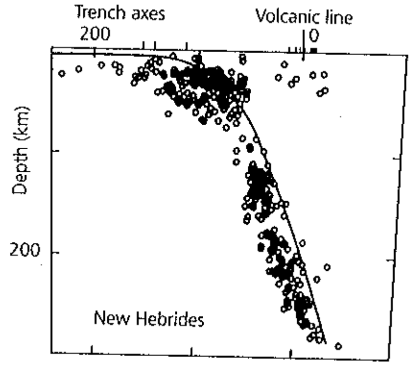

Fig. 5.1-5 Seismicity cross-section perpendicular to the New Hebrides trench showing the Wadati–Benioff zone. This dipping plane of earthquakes indicates the position of the subducting plate. (Isacks and Barazangi, 1977. *Island Arcs, Deep Sea Trenches and Back Arc Basins*, 99–114, copyright by the American Geophysical Union.)

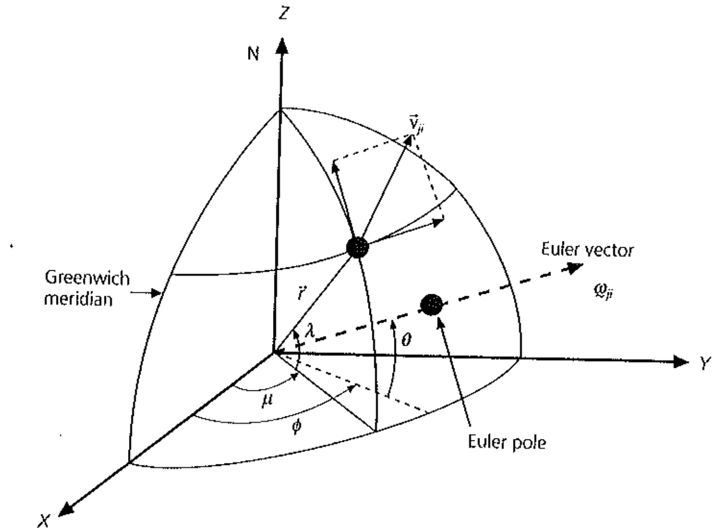

Fig. 5.2-1 Geometry of plate motions. Linear velocity at point r is given by $\mathbf{v}_{ji} = \boldsymbol{\omega}_{ji} \times \mathbf{r}$. The Euler pole is the intersection of the Euler vector with the earth's surface. Note that west longitudes and south latitudes are negative.

In summary, seismology provides crucial information about both *plate kinematics*, the directions and rates of plate motions, and *plate dynamics*, the forces causing plate motions. As we will see, seismicity is one of the major tools used to identify and delineate plate boundary zones, and earthquake mechanisms are among the primary data used to determine the motion within plate boundary zones. The mechanisms also provide information about the stresses acting at plate boundaries and within plates, which, together with earthquake depths and seismic velocity structure, are important in developing ideas about the forces involved and the physical processes by which rocks deform and cause earthquakes. Conversely, plate motion data are used to draw inferences about the locations and times of future earthquakes and their societal risks. Thus it is often hard, and sometimes pointless, to decide where seismology ends and plate tectonics begins, or vice versa.

5.2 Plate kinematics

Understanding the distribution and types of earthquakes requires an understanding of the geometry of plate motions, or plate kinematics. In this section we sketch some basic results, of which we assume most readers have some knowledge. As full exploration of this topic is beyond our scope, readers are encouraged to delve into the suggested literature.

5.2.1 *Relative plate motions*

A basic principle of plate tectonics is that the relative motion between any two plates can be described as a rotation about an *Euler pole*[1] (Fig. 5.2-1). This condition controls the types of boundaries and the focal mechanisms of earthquakes resulting from relative motions, as discussed later. Specifically, at any point r along the boundary between plate i and plate j, with latitude λ and longitude μ, the *linear velocity* of plate j with respect to plate i is

$$\mathbf{v}_{ji} = \boldsymbol{\omega}_{ji} \times \mathbf{r}. \tag{1}$$

This is the usual formulation for rigid body rotations in mechanics. $\mathbf{r}$ is the position vector to the point on the boundary, and $\boldsymbol{\omega}_{ji}$ is the angular velocity vector, or *Euler vector*. Both vectors are defined from an origin at the center of the earth.

The direction of relative motion at any point on the boundary is a small circle, a parallel of latitude *about the Euler pole* (not a geographic parallel about the North Pole!). For example, in Fig. 5.2-2 (*top*) the pole shown is for the motion of plate 2 with respect to plate 1. The convention used is that the first named plate ($j = 2$) moves counterclockwise (in a right-handed sense) about the pole with respect to the second named plate ($i = 1$). The segments of the boundary where relative motion is parallel to the boundary are transform faults. Thus transforms are small circles about the pole, and earthquakes occurring on them should have pure strike-slip mechanisms. Other segments have relative motion away from the boundary, and are thus spreading centers. Figure 5.2-2 (*bottom*) shows an alternative case. The pole here is for plate 1 ($j = 1$) with respect to plate 2 ($i = 2$), so plate 1 moves toward some segments of the boundary, which are subduction zones.

The magnitude, or rate, of relative motion increases with distance from the pole because

$$|\mathbf{v}_{ji}| = |\boldsymbol{\omega}_{ji}|\,|\mathbf{r}|\sin\gamma, \tag{2}$$

where γ is the angle between the Euler pole and the site (corresponding to a colatitude about the pole). All points on a plate

[1] This term comes from Euler's theorem, which states that the displacement of any rigid body (in this case, a plate) with one point (in this case, the center of the earth) fixed is a rotation about an axis.

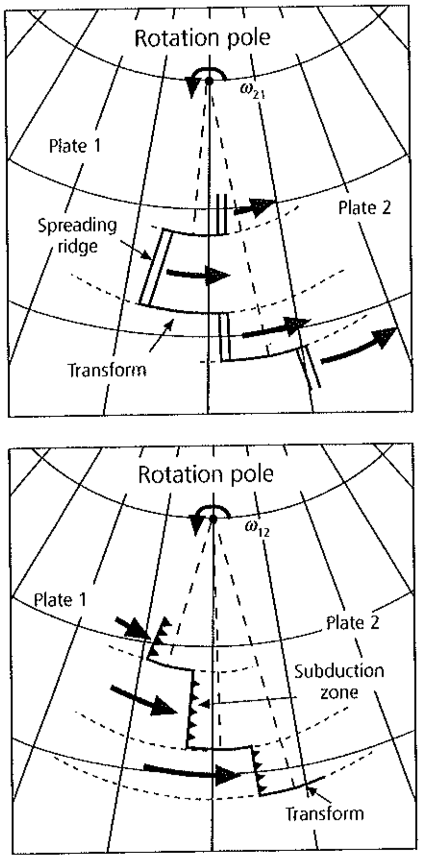

Fig. 5.2-2 Relationship of motions on plate boundaries to the Euler pole. Relative motions occur along small circles about the Euler pole (short dashed lines) at a rate that increases with distance from the pole. Note the difference the sense of rotation makes: ω_{ji} is the Euler vector corresponding to the rotation of plate j counterclockwise with respect to i.

boundary have the same angular velocity, but the magnitude of the linear velocity varies from zero at the pole to a maximum 90° away.

The components of the vectors can be written in Cartesian (x, y, z) coordinates (Fig. 5.2-1). The position vector is

$$\mathbf{r} = (a \cos\lambda \cos\mu, a\cos\lambda \sin\mu, a \sin\lambda), \tag{3}$$

where a is the earth's radius. Similarly, if the Euler pole is at latitude θ and longitude ϕ, the Euler vector is written (neglecting the ij subscripts for simplicity) as

$$\boldsymbol{\omega} = (|\boldsymbol{\omega}| \cos\theta \cos\phi, |\boldsymbol{\omega}| \cos\theta \sin\phi, |\boldsymbol{\omega}| \sin\theta), \tag{4}$$

where the magnitude, $|\boldsymbol{\omega}|$, is the scalar angular velocity or rotation rate. To find the Cartesian components of the linear velocity $\mathbf{v}$, we evaluate the cross product (Eqn 1) using its definition (Eqn A.3.28), and find

$$\mathbf{v} = (v_x, v_y, v_z),$$
$$v_x = a|\boldsymbol{\omega}|(\cos\theta \sin\phi \sin\lambda - \sin\theta \cos\lambda \sin\mu)$$
$$v_y = a|\boldsymbol{\omega}|(\sin\theta \cos\lambda \cos\mu - \cos\theta \cos\phi \sin\lambda)$$
$$v_z = a|\boldsymbol{\omega}| \cos\theta \cos\lambda \sin(\mu - \phi). \tag{5}$$

At the point $\mathbf{r}$, the north–south and east–west unit vectors can be written in terms of their Cartesian components using Eqn A.7.4,

$$\hat{e}^{NS} = (-\sin\lambda \cos\mu, -\sin\lambda \sin\mu, \quad \cos\lambda),$$
$$\hat{e}^{EW} = (-\sin\mu, \cos\mu, \quad 0), \tag{6}$$

so we find the north–south and east–west components of $\mathbf{v}$ by taking dot products of its Cartesian components (Eqns 5) with the unit vectors (Eqns 6), and obtain

$$v^{NS} = a|\boldsymbol{\omega}| \cos\theta \sin(\mu - \phi),$$
$$v^{EW} = a|\boldsymbol{\omega}|[\sin\theta \cos\lambda - \cos\theta \sin\lambda \cos(\mu - \phi)]. \tag{7}$$

We can then find the rate and direction of plate motion,

$$\text{rate} = |\mathbf{v}| = \sqrt{(v^{NS})^2 + (v^{EW})^2}$$
$$\text{azimuth} = 90° - \tan^{-1}[(v^{NS})/(v^{EW})], \tag{8}$$

such that azimuth is measured in the usual convention, degrees clockwise from North.

In evaluating these expressions, it is important to be careful with dimensions. Although rotation rates are typically reported in degrees per million years, they should be converted to radians per year. The resulting linear velocity will have the same dimensions as Earth's radius. By serendipity, converting radius in km to mm and Myr to years cancel out, so only the degrees to radians ($\times \pi/180°$) conversion actually needs to be done to obtain a linear velocity in mm/yr. Plate motions are often quoted as mm/yr, because a year is a comfortable unit of time for humans and 1 mm/yr corresponds to 1 km/Myr, making it easy to visualize what seemingly slow plate motion accomplishes over geologic time.

To see how this works, consider Fig. 5.2-3, which shows the North America–Pacific boundary zone. The map is drawn in a projection about the Euler pole, so the expected relative motion is parallel to small circles like the one shown. By analogy to Fig. 5.2-2, this geometry predicts NW–SE-oriented spreading along ridge segments in the Gulf of California, which are rifting Baja California away from the rest of Mexico. Further north, the San Andreas fault system is essentially parallel to the relative motion, so is largely a transform fault. In Alaska, the eastern Aleutian arc is perpendicular to the plate motion, so the Pacific plate subducts beneath North America. Thus this plate boundary contains ridge, transform, and trench portions, depending on the geometry of the boundary.[2] In addition, the

[2] A good way to visualize the plate motion is to photocopy Fig. 5.2-3, cut along the boundary of the Pacific plate, and then photocopy the "Pacific" onto another piece of paper. Putting the "Pacific" beneath "North America" and rotating around a thumbtack through the pole shows the ridge, transform, and trench motions both forward and backward in time.

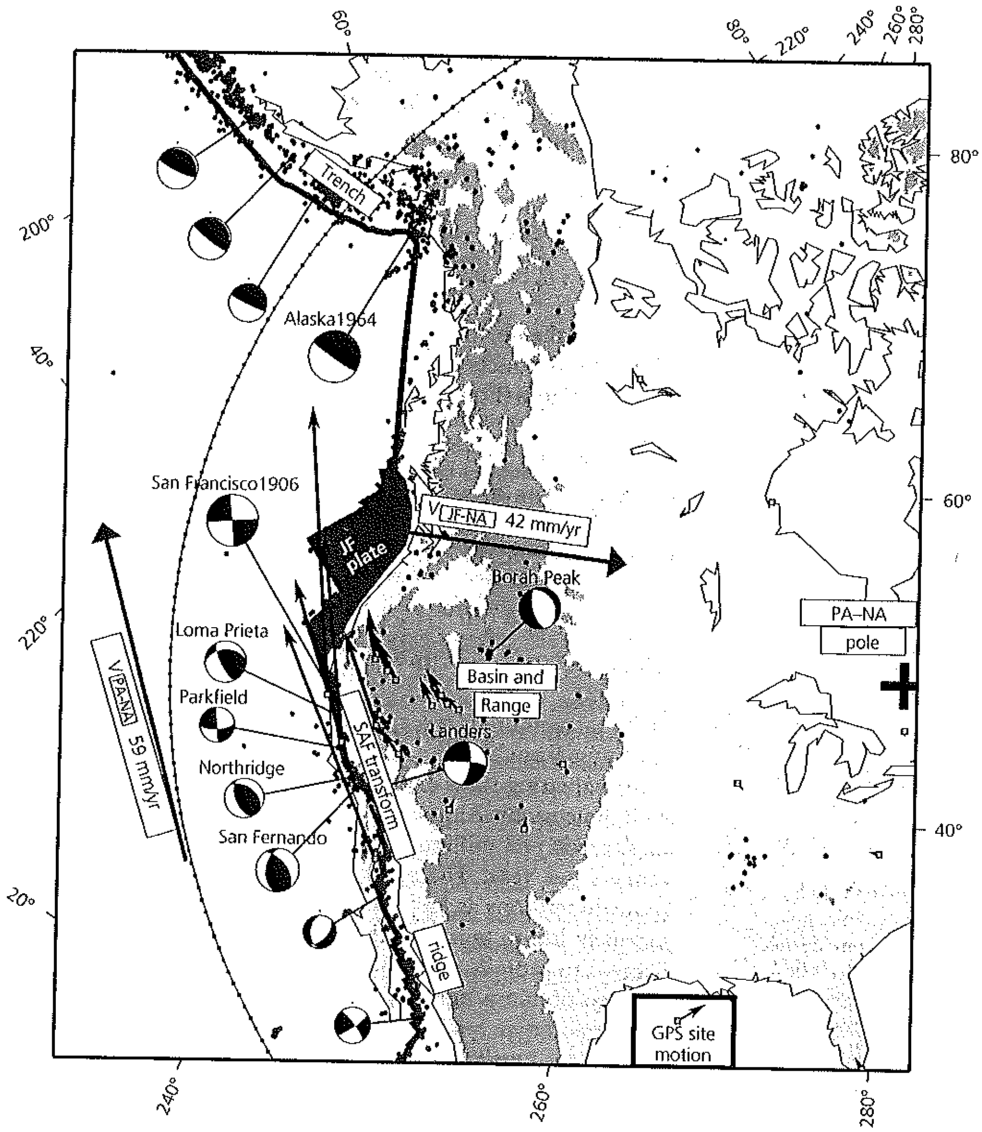

Fig. 5.2-3 Geometry and focal mechanisms for a portion of the North America–Pacific boundary zone that also includes the small Juan de Fuca (JF) plate. The map projection is about the Pacific–North America Euler pole, so the line with dots shows a small circle and thus the direction of plate motion. This small circle is further from the pole than the San Andreas fault, so the rate of motion on it is larger. The variation in the boundary type along its length from extension, to transform, to convergence, is shown by the focal mechanisms. The diffuse nature of the boundary zone is shown by seismicity (small dots), focal mechanisms, topography (elevation above 1000 m is shaded), and vectors showing the motion of GPS and VLBI sites (squares) (Bennett *et al.*, 1999) with respect to the stable interior of North America. The velocity scale is shown by the plate motion arrows; some site motion vectors are too small to be seen. (Stein and Klosko, 2002. From *The Encyclopedia of Physical Science and Technology*, ed. R. A. Meyers, copyright 2002 by Academic Press, reproduced by permission of the publisher.)

boundary zone contains the small Juan de Fuca plate, which subducts beneath the Pacific Northwest at the Cascadia subduction zone.

Equation 8 lets us find how the motion varies. The predicted motion of the Pacific plate with respect to the North American plate at a point on the San Andreas fault (36°N, 239°E) has a rate of 46 mm/yr at an azimuth of N36°W. The predicted direction agrees reasonably well with the average trend of the San Andreas fault, N41°W. Thus, to first order, the San Andreas is a Pacific–North America transform plate boundary with right-lateral motion. However, there are some deviations from pure transform behavior. As we will see, the rate on the San Andreas fault is less than the total plate motion because some of the motion occurs elsewhere within the broad plate boundary zone. In addition, in some places the San Andreas trend differs enough from the plate motion direction that dip-slip faulting occurs. Hence we think of the San Andreas as the primary feature of the essentially strike-slip portion of the plate boundary zone.

Similarly, at a point on the Aleutian trench near the site of the great 1964 Alaska earthquake (Fig. 4.3-15) (62°N, 212°E), we predict Pacific motion of 53 mm/yr at N14°W with respect to North America. This motion is into the trench, which is a Pacific–North America subduction zone. It is worth noting that for a given convergent relative motion either plate can be subducting. However, the relative direction is important, so the plates cannot be interchanged: if N14°W were the direction of motion of North America with respect to the Pacific, the motion would be away from the boundary, which would then be a spreading center with the same rate. As for the San Andreas, the actual boundary zone shown by earthquakes and other deformation is wider and more complicated than the ideal.

Earthquake focal mechanisms within the boundary zone are consistent with the overall plate motions and illustrate some of their complexities. In the Gulf of California we see both strike-slip faulting along oceanic transforms and normal faulting on ridge segments. The San Andreas fault system, composed of the main fault and some others, has both pure strike-slip earthquakes (Parkfield) and earthquakes with some dip-slip motion (Northridge (Section 4.5.3), San Fernando, and Loma Prieta) when it deviates from pure transform behavior. The seismicity also shows that the plate boundary zone is quite broad. Although the San Andreas fault system is the locus of most of the plate motion (Fig. 4.5-13) and hence large earthquakes, seismicity extends as far eastward as the Rocky Mountains. For example, the Landers earthquake shows strike-slip motion east of the San Andreas, and the Borah Peak earthquake illustrates the extensional faulting that occurs in the Basin and Range. These focal mechanisms are consistent with the motions shown by space-based geodetic measurements, discussed shortly, and with geologic studies.

5.2.2 *Global plate motions*

The relative plate motions show how the plate boundary geometry is evolving and has evolved. The Juan de Fuca plate is subducting under North America faster than new lithosphere is being added to it by sea floor spreading at its boundary with the Pacific plate, so this plate was larger in the past and is shrinking. Rotating the Pacific plate backwards with respect to North America shows that 10 million years ago the Gulf of California had not yet begun to open by sea floor spreading. These changes are part of the evolution of the plate boundary in western North America, in which the large oceanic Farallon plate that used to be between the Pacific and North American plates began subducting under North America at about 40 Ma,[3] leaving the Juan de Fuca plate as a remnant and forming the San Andreas fault.

At this point you may be wondering how Euler poles are found. Until recently, this was done by combining three different types of data from different boundaries. The rates of spreading are found from sea floor magnetic anomalies, which form as the hot rock at ridges cools and acquires magnetization parallel to the earth's magnetic field. Because the history of reversals of the earth's magnetic field is known, the anomalies can be dated, so their distance from the ridge where they formed shows how fast the sea floor moved away from the ridge. The directions of motion are found from the orientations of transform faults and the slip vectors of earthquakes on transforms and at subduction zones. Euler vectors are found from the relative motion data, using geometrical conditions we have discussed. The process is easy to visualize. Because slip vectors and transform faults lie on small circles about the pole, the pole must lie on a great circle at right angles to them (Fig. 5.2-2). Similarly, the rate of plate motion increases with the sine of the distance from the pole (Eqn 2). These constraints make it possible to locate the poles. Determination of Euler vectors for all the plates can thus be treated as an overdetermined least squares problem whose solution (Section 7.5) gives a *global relative plate motion model*. Because these models use spreading rates determined from magnetic anomaly data that span several million years, they describe plate motions averaged over the past few million years.[4]

Table 5.2-1 gives such a model, known as NUVEL-1A,[5] which specifies the motions of plates (Fig. 5.2-4) with respect to North America. The vectors follow the convention that each named plate moves counterclockwise relative to North America. Although the table lists only Euler vectors with respect to North America, the motion of plates with respect to other plates is easily found using vector arithmetic. For example,

$$\omega_{ij} = -\omega_{ji}, \quad (9)$$

so we reverse the plate pair using the negative of the Euler vector. The pole for the new plate pair is the antipole, with latitude of opposite sign and longitude increased by 180°. The magnitude (rotation rate) stays the same. We can also reverse the plate pair by keeping the same pole and making the rotation rate negative (clockwise rather than counterclockwise). Although we usually use positive rotation rates, negative ones sometimes help us visualize the motion. For example, the table shows the Pacific–North America pole at about −49°N, 102°E, so the North America–Pacific pole is at about 49°N, (102 + 180 = 282)°E, which is in southeastern Canada. Thus, about this pole, North America rotates counterclockwise with respect to the Pacific, or the Pacific rotates clockwise with respect to North America, as shown in Fig. 5.2-3.

For other plate pairs we assume that the plates are rigid, so all motion occurs at their boundaries. We can then add Euler vectors,

$$\omega_{jk} = \omega_{ji} + \omega_{ik} \quad (10)$$

because the motion of plate j with respect to plate k equals the sum of the motion of plate j with respect to plate i and the motion of plate i with respect to plate k. Thus if we start with a set of vectors all with respect to one plate, e.g., i, we use

$$\omega_{jk} = \omega_{ji} - \omega_{ki} \quad (11)$$

to form any Euler vector needed. These operations are easily done using the Cartesian components (Eqn 4), as shown in this chapter's problems. We can also perform the analogous operations on linear velocity vectors at a specific site.

[3] "Ma" is often used to denote millions of years before the present.

[4] The most recent magnetic reversal occurred about 780,000 years ago, so any plate model based on paleomagnetic data must average at least over that interval.

[5] NUVEL-1 (Northwestern University VELocity) was developed as a new ("nouvelle") model (DeMets *et al.*, 1990). The multiyear development prompted the suggestion that "OLDVEL" might be a better name. Due to changes in the paleomagnetic time scale the model was revised to NUVEL-1A (DeMets *et al.*, 1994). This change caused a slight difference in the rates of relative motion, but not in the poles and hence directions of relative motion.

Table 5.2-1 Euler vectors with respect to North America (NA).

Plate	Pole latitude (°N)	Longitude (°E)	$\|\omega\|$ (°/Myr)
Pacific (PA)	−48.709	101.833	0.7486
Africa (AF)	78.807	38.279	0.2380
Antarctica (AN)	60.511	119.619	0.2540
Arabia (AR)	44.132	25.586	0.5688
Australia (AU)	29.112	49.006	0.7579
Caribbean (CA)	74.346	153.892	0.1031
Cocos (CO)	27.883	−120.679	1.3572
Eurasia (EU)	62.408	135.831	0.2137
India (IN)	43.281	29.570	0.5803
Nazca (NZ)	61.544	−109.781	0.6362
South America (SA)	−16.290	121.876	0.1465
Juan de Fuca (JF)	−22.417	67.203	0.8297
Philippine (PH)	−43.986	−19.814	0.8389
Rivera (RI)	22.821	−109.407	1.8032
Scotia (SC)	−43.459	123.120	0.0925
NNR*	2.429	93.965	0.2064

Source: After DeMets *et al.* 1994.
*No net rotation, defined in Section 5.2.4.

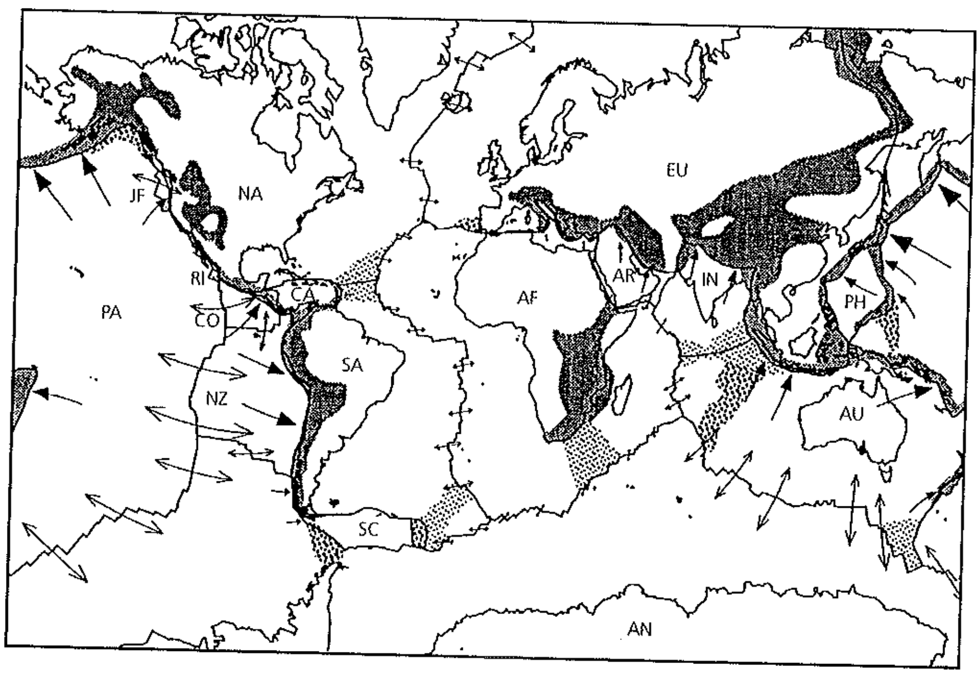

Fig. 5.2-4 Relative plate motions for the NUVEL-1 global plate motion model. Arrow lengths are proportional to the displacement if plates maintain their present relative velocity for 25 Myr. Divergence across mid-ocean ridges is shown by diverging arrows. Convergence is shown by single arrows on the underthrust plate. Plate boundaries are shown as diffuse zones implied by seismicity, topography, or other evidence of faulting. Fine stipple shows mainly subaerial regions where the deformation has been inferred from seismicity, topography, other evidence of faulting, or some combination of these. Medium stipple shows mainly submarine regions where the nonclosure of plate circuits indicates measurable deformation; in most cases these zones are also marked by earthquakes. Coarse stipple shows mainly submarine regions where the deformation is inferred mostly from the presence of earthquakes. The geometry of these zones, and in some cases their existence, is under investigation. (Gordon and Stein, 1992. *Science*, *256*, 333–42, copyright 1992 American Association for the Advancement of Science.)

Such vector addition is important because we only have certain types of data for individual boundaries (Fig. 5.2-5). Although spreading centers provide rates from the magnetic anomalies and azimuths from both transform faults and slip vectors, only the direction of motion is directly known at subduction zones. As a result, convergence rates at subduction zones are estimated by global closure, combining data from all plate boundaries (Section 7.5). Thus the predicted rate at which

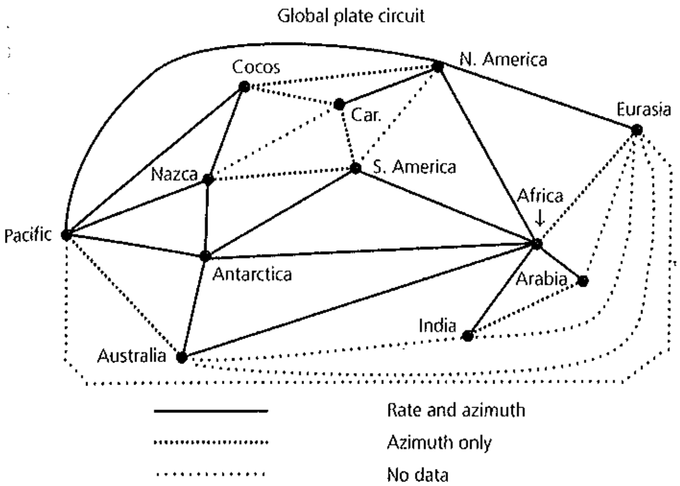

Fig. 5.2-5 Global plate circuit geometry for the NUVEL-1 plate motion model. Relative motion data are used on the boundaries indicated. (De Mets *et al.*, 1990. *Geophys. J. Int.*, *101*, 425–78.)

the Cocos plate subducts beneath North America, causing large earthquakes in Mexico, depends on the measured rates of Cocos–Pacific spreading on the East Pacific rise and Pacific–North America spreading in the Gulf of California. In some cases, such as relative motion between North and South America, no direct data were used because the boundary location and geometry are unclear, so the relative motion is inferred entirely from closure. Not surprisingly, the motions of plate pairs based on both rate and azimuth data appear to be better known.

Figure 5.2-4 shows the predicted relative motions at plate boundaries around the world. As shown for the Pacific–North America boundary in Fig. 5.2-3 and discussed in general terms in later sections, the predicted motions correspond to the earthquake mechanisms. Moreover, we can use the plate motions to make inferences about future earthquakes. For example, even though we do not have seismological observations of large earthquakes along the boundary between the Juan de Fuca and North American plates, the plate motions predict that such earthquakes could result from the subduction of the Juan de Fuca plate beneath North America. Evidence for this subduction is given by the presence of the Cascade volcanoes (such as Mount Saint Helens and Mount Rainer) and paleoseismic records (Section 1.2.5) that are interpreted as evidence of large past earthquakes.

Figure 5.2-4 also illustrates that boundaries between plates are often diffuse. Seismicity, active faulting, and elevated topography often indicate a broad zone of deformation between plate interiors. This effect is evident in continental lithosphere, such as the India–Eurasia collision zone in Asia or the Pacific–North America boundary zone in the western USA, but can also sometimes be seen in oceanic lithosphere, as in the Central Indian Ocean. Plate boundary zones cover about 15% of the earth's surface, and about 40% of the earth's population lives within them.

Earthquakes are among the best tools for investigating plate boundary zones and other deviations from plate rigidity. They provide one of the best indicators of the location of boundary zones, so new earthquakes often change our views. We also use plate motion data, many of which are earthquake slip vectors. For example, Fig. 5.2-4 shows zones of seismicity in the Central Indian Ocean (Section 5.5.2) as boundaries between distinct Indian and Australian plates, rather than as within a single Indo-Australian plate, because spreading rates along the Central Indian Ocean ridge are better fit by a two-plate model. A similar argument justifies the assumption of a small Rivera plate distinct from the Cocos plate. Another approach is to use the global plate circuit closures (Fig. 5.2-5). Recall that forming a Euler vector from two others (Eqn 10) assumes that all three plates are rigid. Hence this assumption can be used to test for deviations from rigidity. To do this, we form a *best-fitting vector* for a plate pair, using only data from that pair of plates' boundary, and a *closure fitting vector* from data elsewhere in the world. If the plates were rigid, the two vectors would be the same. However, a significant difference between the two indicates a deviation from rigidity, or another problem with the plate motion model. For example, such analysis shows systematic deviations along some subduction zones, suggesting that the slip vectors of the trench earthquakes do not exactly reflect plate motions because a sliver of forearc material in the overriding plate moves separately from the remainder of the overriding plate (Section 5.4.3).

A variant of this approach is to examine the Euler vectors for three plates that meet at a *triple junction*, compute best-fitting Euler vectors for each of the three plate pairs, and sum them. For rigid plates, Eqn 10 shows that the sum should be zero. However, when this was done for the junction in the Central Indian Ocean, assuming that it was where the African, Indo-Australian, and Antarctic plates met, the Euler vector sum differed significantly from zero, indicating deviations from plate rigidity. As plate motion data improve, it seems that what was treated as a three-plate system may include as many as six resolvable plates (Antarctica, distinct Nubia (West Africa) and Somalia (East Africa), India, Australia, and Capricorn (between India and Arabia)). Hence models of plate boundaries and motions improve with time (Fig. 1.1-9). For example, although the model in Fig. 5.2-4 has a single African plate, recent models seek to resolve the motion between Nubia and Somalia (Fig. 5.6-2).

5.2.3 *Space-based geodesy*

New plate motion data have become available in recent years due to the rapidly evolving techniques of space-based geodesy. Using space-based measurements to determine plate motions was suggested by Alfred Wegener when he proposed the theory of continental drift in 1915. Wegener realized that proving continents moved apart was a formidable challenge. Although geodesy — the science of measuring the shape of, and distances on, the earth — was well established, standard surveying

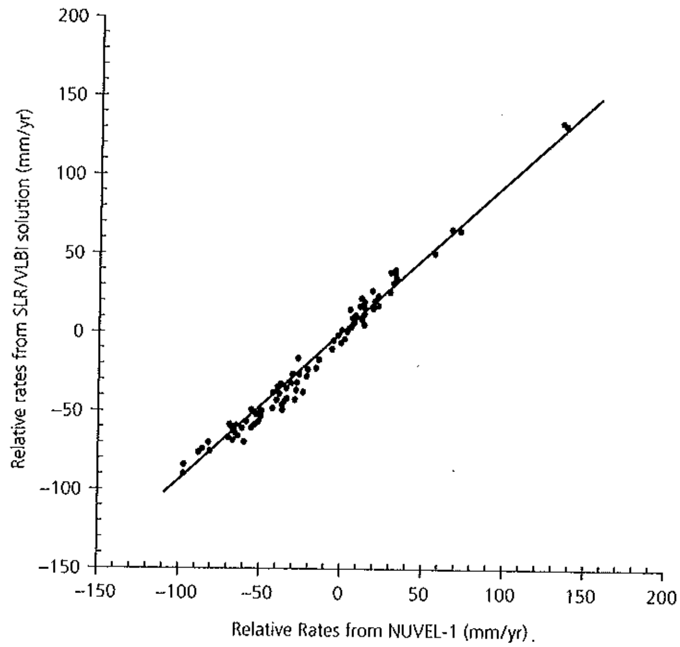

Fig. 5.2-6 Comparison of rates determined by space geodesy with those predicted by the NUVEL-1 global plate motion model. The space geodetic rates are determined from sites located away from plate boundaries to reduce the effects of deformation near the boundaries. The slope of the line is 0.94, indicating that plate motions over a decade are very similar to those predicted by a model averaging over 3 million years. (Robbins *et al.*, 1993, *Contributions of Space Geodesy to Geodynamics*, 21–36, copyright by the American Geophysical Union.)

methods offered no hope of measuring slow motions between continents far apart. Wegener thus decided to measure the distance between continents using astronomical observations.[6] However, because measuring continental drift called for measurement accuracies far greater than ever before to show small changes in positions over a few years, Wegener's attempts failed, and the idea of continental drift was largely rejected.

By the 1970s the story was very different. Geologists accepted continental drift, in large part because paleomagnetic measurements showed that continents had in fact moved over millions of years. It thus seemed natural to see if modern space-based technology could accomplish Wegener's dream of measuring continental motions over a few years. Three basic approaches were attempted. Each faced formidable technical challenges — and all succeeded. Hence, using the techniques discussed in Section 4.5.1, plate motions can now measured to a precision of a few mm/yr or better, using a few years of data from systems including Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and the Global Positioning System (GPS).

Space geodesy measures both the rate and the azimuth of the motions between sites, and can thus be used to compute relative plate motions. One of the most important results of space geodesy for seismology is that plate motions have remained generally steady over the past few million years. This is shown by the striking agreement between motions measured over a few years by space geodesy and the predictions of global plate motion models that average over the past three million years (Fig. 5.2-6). The general agreement is consistent with the idea that although motion at plate boundaries can be episodic, as in large earthquakes, the viscous asthenosphere damps out the transient motions (much like the damping element in a seismometer, Section 6.6) and causes steady motion between plate interiors. This steadiness implies that plate motion models can be used for comparison with earthquake data.

Space geodesy surmounts a major difficulty faced by models like NUVEL-1A: namely, that the data used (spreading rates, transform azimuths, and slip vectors) are at plate boundaries, so the model provides only the net motion across a boundary. By contrast, space geodesy can also measure the motion of sites within plate boundary zones. For example, Fig. 5.2-3 shows the motions of GPS and VLBI sites within the North America–Pacific boundary zone. Sites in eastern North America move so slowly — less than 2 mm/yr — with respect to each other that their motion vectors cannot be seen on this scale. These sites thus define a rigid reference frame for the stable interior of the North American plate. Sites west of the San Andreas fault move at essentially the rate and direction predicted for the Pacific plate by the global plate motion model. The site vectors show that most of the plate motion occurs along the San Andreas fault system, but significant motions occur for some distance eastward. The geodetic motions are consistent with the focal mechanisms and geological data. Thus, as discussed further in Section 5.6, the different data types are used together to study how the seismic and aseismic portions of the deformation vary in space and time in the diffuse deformation zones that characterize many plate boundaries. This is done both on large scales, as shown here, and for studies of smaller areas and individual earthquakes (Section 4.5).

Space geodesy is also used to study the relatively rare, but sometimes large, earthquakes within plates. Global plate motion models give no idea where or how often intraplate earthquakes should occur, beyond the trivial prediction that they should not occur because there is no deformation within ideal rigid plates. Space geodesy is being combined with earthquake locations, focal mechanisms, and other geological and geophysical data to investigate the motions and stresses within plates and how they give rise to intraplate earthquakes (Section 5.6.3).

5.2.4 *Absolute plate motions*

So far, we have discussed the relative motions between plates, which have traditionally been of greatest interest to seismologists because most earthquakes reflect these motions. However, in some applications it is important to consider *absolute* plate motions, those with respect to the deep mantle.

In general, both plates and plate boundaries move with respect to the deep mantle. To see this, assume that the African

[6] Using an extraterrestrial reference has a long history; in about 230 BC Eratosthenes found the Earth's size from observations of the sun's position at different sites, and navigators have found their positions by observing the sun and stars.