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THE PLATE TECTONIC APPROXIMATION: Plate Nonrigidity, Diffuse Plate Boundaries, and Global Plate Reconstructions

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ABSTRACT

The central assumption of plate tectonics, that plate interiors are rigid, remains a useful but uncertain approximation. Strain rates of stable plate interiors are bounded between 10^{-12}–10^{-11} year^{-1} and $\sim 4 \times 10^{-10}$ year^{-1}. The narrowness of all plate boundaries, the other main assumption of plate tectonics as originally conceived, is contradicted by many observations, both in the continents and in the oceans. Some diffuse plate boundaries in both continents and oceans exceed dimensions of 1000 km on a side. Diffuse plate boundaries cover ~15% of Earth's surface. The maximum speed of relative plate motion across any one diffuse plate boundary ranges from ~2 to ~15 mm/year, which is faster than some upper bounds on intraplate motion across stable plate interiors ($\leq$2 mm year^{-1}). Strain rates in diffuse plate boundaries can be as high as $\sim 10^{-8}$ year^{-1}, ~25 times higher than the upper bound on strain rates of stable plate interiors, but ~600 times lower than the lowest strain rates across typical narrow plate boundaries. The poles of rotation of the plates flanking a diffuse oceanic plate boundary tend to be located in the diffuse boundary, which is a consequence of the strong coupling across the boundary.

INTRODUCTION

In the three decades since the theory of plate tectonics was proposed (Wilson 1965, Morgan 1968, McKenzie & Parker 1967), there have been many

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opportunities to test its central assumptions and the predictions that result from them. Here I examine how well these assumptions have fared, examine where some have failed, and discuss how the plate tectonics model has consequently been revised. In this review, I assume that plate tectonics is a phenomenological approximation to the real behavior of Earth's near surface and that the main question of interest here is not whether plate tectonics is true, but how accurate an approximation it is.

Here the term plate tectonics is used in a narrow sense that distinguishes it from seafloor spreading, continental drift, global tectonics, and other terms related to mobilistic views of the solid Earth. The central assumption of plate tectonics is that the plates are rigid. In his original paper on plate tectonics, Wilson (1965) acknowledged his debt to the ideas of SW Carey but distinguished his proposals from those of Carey in "that the plates between deforming zones are not readily deformed except at their edges" (p. 344). In the introduction to the same paper, Wilson (1965) made it clear that he was proposing that the plates are rigid. Both McKenzie & Parker (1967) and Morgan (1968) emphasized the importance of the assumption of plate rigidity, the latter writing, "It is of interest to see how far this simplifying concept of rigidity can be applied..." (p. 1961). Morgan (1968) further noted that it is the assumption of rigidity that gives the theory mathematical rigor while making it clear that rigidity was a hypothesis and pointing to some regions where it clearly did not apply. In part of this review, I discuss lower bounds and upper bounds on the nonrigidity of stable plate interiors.

A second central assumption of plate tectonics, as originally conceived 30 years ago, is that plate boundaries are narrow. Wilson's (1965) plate boundaries, which he referred to as mobile belts, consist of transform faults, spreading ridges, and "mountains," broadly interpreted to include island arcs. McKenzie & Parker (1967) described plate boundaries in terms of lines, implying extreme narrowness. Morgan's (1968) map showing the world's plates indicates that the boundaries are all narrow (Figure 1). Although these pioneers did not believe it was strictly true, narrowness of plate boundaries was a central assumption of plate tectonics as originally conceived and as illustrated in almost every textbook in use today.

As is documented below and has been clear for some time, in many regions of the planet surface, both of these two central assumptions cannot be true—either (*a*) plates are nonrigid, with the distance between different points on the same plate changing with time at rates that are measurable, or (*b*) many boundaries between plates, including some in oceanic lithosphere, are very wide. Many workers have abandoned the second assumption and kept the first.

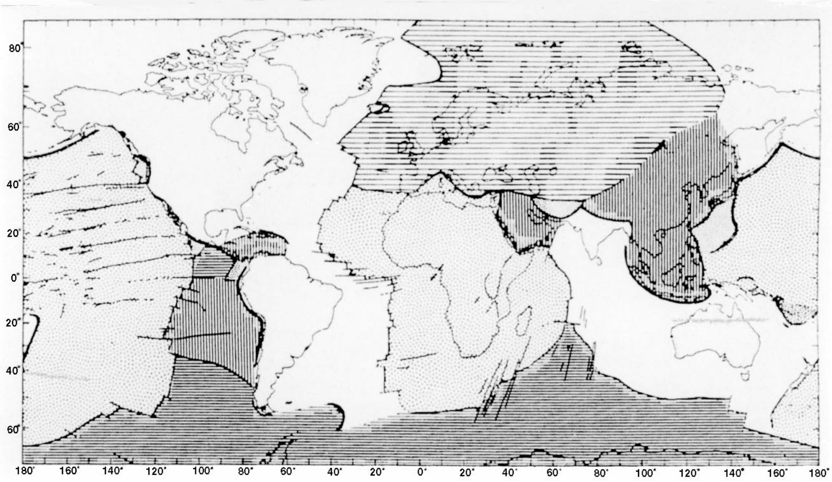

Figure 1 Representative map of the global mosaic of plates separated by narrow plate boundaries. From Morgan (1968).

Over the past three decades, the precision and accuracy of measurement of plate tectonic displacements and velocities has steadily improved. This is attributable in part to each of the following: the continually increasing coverage by marine geophysical surveys, especially marine magnetic and bathymetric surveys; dramatic improvements in the resolution of marine bathymetric surveys due to multibeam and side-scan sonar techniques; the advent of satellite altimetry, which provides maps of the marine gravity field in otherwise sparsely charted waters; improvements in the geomagnetic reversal time scale; the advent and development of space geodesy, which allows the position and velocity of many sites on land to be precisely estimated; and a greater understanding of and confidence in the available data.

Typical precisions and accuracies of plate tectonic rates discussed in the 1960s and 1970s were in centimeters per year. In contrast, the central problems at present and over much of the past decade concern processes occurring at rates typically below a centimeter per year and are expressed in millimeters per year. The rates relevant to understanding the nonrigidity of stable plate interiors may be less, perhaps much less, than a millimeter per year. Progressing from centimeters per year to millimeters per year, and eventually to even lower rates, increasingly tests the limits of the plate tectonic approximation. It thus seems appropriate to ask at what range of rates plate tectonics remains a useful approximation.

INTRAPLATE DEFORMATION VERSUS DIFFUSE PLATE BOUNDARIES

In deforming zones, such as the equatorial Indian Ocean, plate tectonics as it was originally conceived clearly fails. Thus, one of the two original central assumptions of plate tectonics, that the plates are rigid and that the boundaries are narrow, is false for the regions containing these deforming zones. Researchers have been divided as to how best to describe them. One interpretation is to consider such areas to be regions of intraplate deformation, implying that they lie within the interior of a plate that is deforming, which in effect abandons the assumption of plate rigidity while retaining the assumption of narrow boundaries between plates. A second interpretation is to consider these areas to be diffuse plate boundaries, which in effect continues to assume that plate interiors are rigid but relaxes the assumption that plate boundaries are narrow. I believe that both of these interpretations are in some sense true and that a sound case can be made for either one.

On the other hand, I disagree with the idea that these two interpretations represent distinct models that each make predictions that can be compared with observations. As far as I can tell, the assumption of intraplate deformation leads to no new predictions and is therefore not a hypothesis that can be falsified. It is a scientific dead end—no possible observation or experiment can prove that it is wrong.

In contrast, the diffuse plate boundary interpretation implies that a deforming zone is bounded by two (or more) rigid or nearly rigid plates in motion relative to each other. The key is to construct experiments that test the rigidity of the plates hypothesized to exist on either side of the zone of deformation. In many cases, including the equatorial Indian Ocean, plate reconstructions can make potentially falsifiable predictions of the relative motion across the deforming zone, which can be tested with independent data. Many predictions to date have been tested and found to be consistent with observations (see for example Gordon et al 1990, DeMets et al 1994b).

ASSESSING THE PLATE TECTONIC APPROXIMATION

Central Role of Quantification, Error Propagation, and Statistics

Given that no real material is rigid, the central question of plate tectonics is not whether the plates are rigid, but how nonrigid they are. No qualitative analysis can answer this question. A quantitative approach is required. Before discussing specific results for diffuse plate boundaries and plate nonrigidity, I review the development of some of the quantitative tools required to assess plate nonrigidity, beginning with their use in global plate motion models.

Minster et al (1974) were the first to propagate the uncertainties from observations to the set of angular velocities describing the relative motions of the plates. They were thus the first to quantify the uncertainties in the global set of relative angular velocities. Among their specific discoveries using this quantitative approach was (*a*) the demonstration that earthquake slip vectors along the Aleutian trench were systematically and significantly misfit, relative to other data believed to record the motion between the Pacific and North American plates, and (*b*) the first demonstration of resolvable motion between the North American and South American plates.

Later work has been strongly influenced by the conservative approach of Minster et al (1974) in assigning an uncertainty to a plate motion datum. They first subjectively assign an uncertainty based mainly on the quality of a measurement. They next assign an uncertainty from the dispersion of the data when fit to a model. In every case, they retained the larger of the two estimates, which in most cases was the subjectively estimated uncertainty. Consequently, the dispersion of all the data in their global model is less than expected from their assigned uncertainties; the standard deviation of the data about the values predicted by the models was on average only 74% as large as the assigned uncertainties for rates and 83% as large as the assigned uncertainties for azimuths.

Minster & Jordan (1978) assigned uncertainties to all data subjectively and in deliberately conservative fashion. Consequently, the standard deviation of the data was on average only 60% as large as the assigned uncertainties, even less than in their prior study. DeMets et al (1990) also assigned uncertainties subjectively and aimed at making them consistent with those of Chase (1978) and Minster & Jordan (1978), resulting in conservatively assigned uncertainties. The standard deviation of their data was on average about half of the uncertainties assigned: only 43% of rate, 55% of transform fault azimuth, and 49% of earthquake slip vector assigned uncertainties.

Thus, over time, the dispersion of the data about the best-fitting model has decreased relative to the uncertainties assigned to the data. The decrease has come about in part because of an increase in the number of adjustable parameters, for example, with the splitting of the Indo-Australian plate into two or three plates. Whatever the cause of the decrease in relative dispersion, however, the decrease itself points to what is now a weakness of these data sets—the absence of objectively estimated uncertainties that are consistent with the dispersion of the data. The conservative bias of the assigned uncertainties may cause some false hypotheses to be accepted when the data should have been interpreted as indicating rejection. The conservative bias of the assigned uncertainties may be hindering progress in the rigorous testing of the rigid plate hypothesis. New methods are probably needed to estimate uncertainties objectively and realistically. I have previously discussed some approaches to estimating these uncertainties objectively (Gordon 1995). The simplest approach, probably too simple, is to multiply all assigned uncertainties by a uniform multiplicative constant so that the normalized standard deviation of the data is one, which is effectively accomplished by using an F-ratio test instead of a chi-square test for assessing closure of a plate motion circuit (Gordon et al 1987).

Efforts to quantify, to incorporate uncertainties, and to use appropriate statistics in the investigation of finite rotations of plates have long lagged behind those for instantaneous plate motion, which is described by angular velocities. In recent years, the quantification of finite rotations has not only caught up with but has surpassed that in instantaneous plate motions. The work of Stock & Molnar (1983) illustrated some important geometrical relationships between the location and distribution of crossings of magnetic anomalies and fracture zones for a given age flanking a midocean ridge and the uncertainty in the corresponding best-fitting rotation. A rigorous method for estimating uncertainties in crossings and propagating them to the uncertainty region in the rotation was presented by Chang (1988). Chang's approach is similar to that of Gordon et al (1987) in one respect: Both assumed that the relative size of subjectively estimated errors are correct and that realistic errors can be found by multiplying all assigned errors by a uniform multiplicative constant irrespective of data location and data type.

Some applications of tests for closure of plate motion circuits are discussed below in the section on rigidity of plate interiors.

Plate Boundary Zones as a Significant Fraction of Earth's Surface

Figure 1 shows the 15 assumed-rigid plates defined by Morgan (1968), in the first paper after Wilson (1965) to propose the extent and boundaries of the global mosaic of plates. The larger plates in the figure include a Pacific plate, an Antarctic plate, an American plate, an African plate, a Eurasian plate, an Indo-Australian plate, and a China plate [actually referred to as "blocks" by Morgan (1968)]. The figure also illustrates the assumption that boundaries between plates are narrow. In contrast, Figure 2 shows a more recent view of global plate boundaries, which emphasizes the fact that boundaries are in many places diffuse and wide and in some places very wide, not only in the continents but also in the oceans. Some notable specific differences between the original view (Figure 1) and the more recent one (Figure 2) is that the American plate

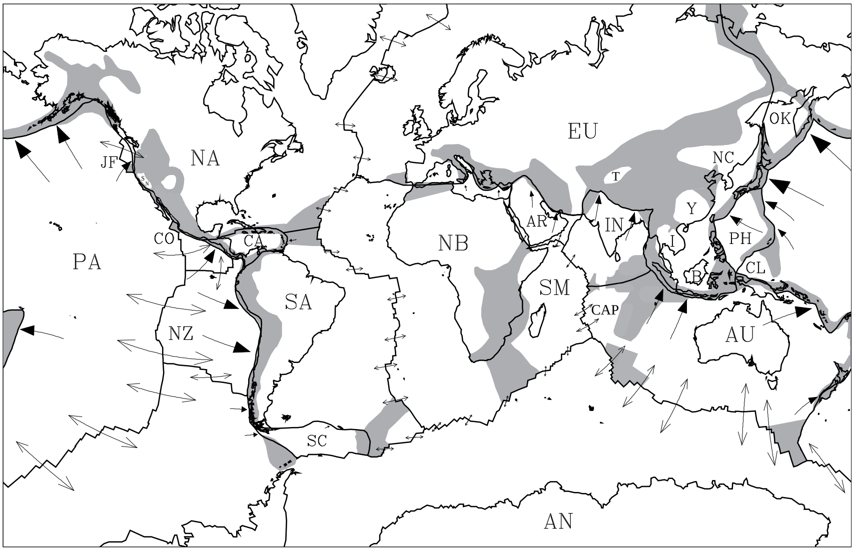

Figure 2 Map showing idealized narrow plate boundaries, velocities between plates, and regions of deforming lithosphere, which can be regarded as diffuse plate boundaries. Plate velocities are shown by *arrows*. The *length of the arrows* shows what the displacement would be if the plates were to maintain their present relative angular velocity for 25 million years (My). The plate separation rate across mid-ocean ridges is shown by *symmetrical diverging arrows with unclosed arrowheads at both ends*. The plate convergence rate is shown by *asymmetrical arrows with one solid arrowhead*, which are shown on the underthrust plate if convergence is asymmetric and the polarity is known. The outlines of deforming zones are approximate, and the existence of some deforming zones is speculative. Separate small plates or blocks are labeled in southeast Asia, but their uncertainly located and possibly nonexistent boundaries are not shown in their entirety. Deformation has been inferred from seismicity, topography, other evidence of faulting, and nonclosure of plate motion circuits. These deforming regions, which constitute diffuse plate boundaries, cover ~15% of Earth's surface. Future observations may demonstrate that deforming lithosphere covers an area larger or smaller than shown here. Idealized plate boundaries (*solid curves*) are after Argus & Gordon (1991a), with the addition of the Scotia plate and several other minor changes. Plate abbreviations: B, Borneo; AN, Antarctica; AR, Arabia; AU, Australia; CA, Caribbean; CAP, Capricorn; CL, Caroline; CO, Cocos; EU, Eurasia; I, Indo-China; IN, India; JF, Juan de Fuca; NA, North America; NB, Nubia; NC, North China; NZ, Nazca; OK, Okhotsk; PA, Pacific; SA, South America; SC, Scotia Sea; SM, Somalia; Y, Yangtze. [Modified with permission from Gordon & Stein (1992, p. 334) and Gordon (1995). Copyright 1992, American Association for the Advancement of Science (AAAS).]

of Morgan (1968) is now treated as two distinct North American and South American plates separated by a diffuse plate boundary (Ball & Harrison 1970, Minster et al 1974, Bergman 1986, Argus 1990, DeMets et al 1990, Müller & Smith 1993); the African plate is now treated as distinct Nubian and Somalian plates separated by a diffuse boundary (Chase 1978, Gordon & Stein 1992, Jestin et al 1994; D Chu & RG Gordon, manuscript in preparation); and the Indo-Australian plate is now treated as three distinct plates, India, Capricorn, and Australia, separated by two diffuse boundaries that meet in a triple junction (Wiens et al 1985, Gordon et al 1990, Royer & Chang 1991, Royer & Gordon 1997). The regions in Figure 2 shown as plate boundaries were defined mainly from the distribution of the locations of earthquakes with magnitudes $>\sim$5.5 and from topography, with additional information from other indicators of current deformation. There are many subjective elements in defining the edges of some of these regions and in deciding when significant earthquakes are considered intraplate rather than part of a plate boundary. Nevertheless, the conclusion is inescapable that the Earth's surface cannot be covered completely by a mosaic of nearly rigid plates and that $\sim$15% of Earth's surface is now covered by plate boundary zones in which the motion between or among the plates is accommodated.

In my view, the recogtion that plate boundaries in many places are not narrow but wide is the most important way in which the original plate tectonic model must be modified. The central assumption of the rigidity of plate interiors, however, still seems a very useful approximation when applied to $\sim$85% of Earth's surface.

Comparison of Angular Speeds Accommodated Across Diffuse Plate Boundaries with Those Across Narrow Boundaries

A logical method for comparing rates of relative plate motion is to examine the angular speeds or rotation rates between neighboring plates (e.g. that between North America and South America) and to compare these with the angular speeds of relative rotation between pairs of plates sharing a narrow boundary. If a plate is large, then the angular speed is a useful and compact representation of the speed of a plate. Sites on a large plate will span much of the range of possible angular distances between the pole of rotation and 90° from the pole of rotation, where the maximum possible linear surface velocity occurs. The angular speed is important also when considering the possible effect of an unrecognized diffuse plate boundary on reconstructions through a circuit of plates, such as the Pacific-Antarctic-Africa-North America circuit used to estimate the relative positions and velocities of the Pacific and North American plates (e.g. Stock & Molnar 1988).

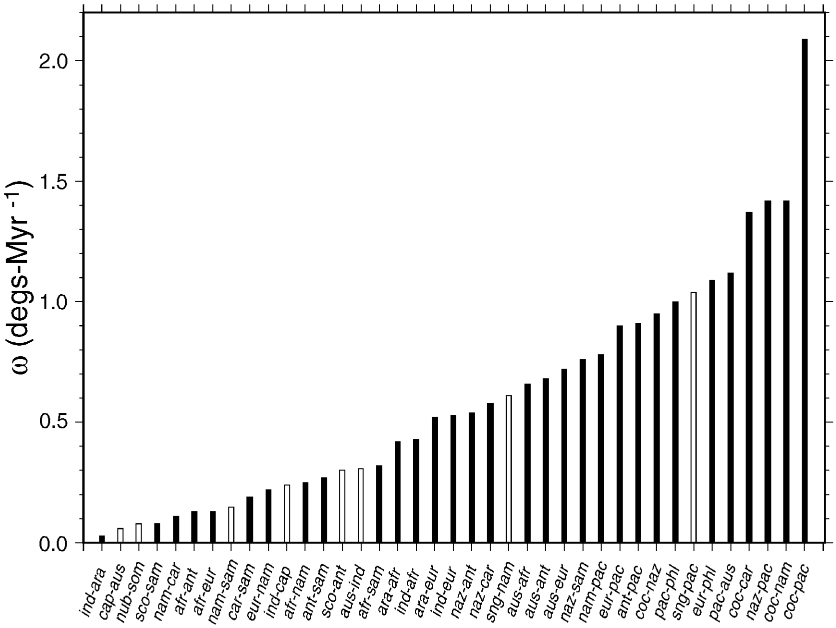

Figure 3 Angular speeds of plate pairs sharing a common boundary. *Solid bar*: angular speed accommodated across a narrow plate boundary; *open bar*: angular speed accommodated across a diffuse plate boundary. Plate abbreviations: afr, Africa; ant, Antarctica; ara, Arabia; aus, Australia; car, Caribbean; cap, Capricorn; coc, Cocos; eur, Eurasia; ind, India; JF, Juan de Fuca; nam, North America; nub, Nubia; naz, Nazca; pac, Pacific; phl, Philippine; sam, South America; sng, Sierra Valley–Great Valley; sco, Scotia Sea; som, Somalia. Note that the angular speeds of plate pairs separated by a diffuse plate boundary tend to fall in the range of the lower rates, but they are interleaved with them and do not form a distinctly slower group.

Angular speeds between all adjacent plates range from 0.03° to 2.09° per million years (My) (Figure 3). Except for the fastest angular speed, that of the Cocos relative to the Pacific plate, the angular speeds are nearly uniformly distributed between 0.03° and 1.42° My^{-1} with no obvious clustering of angular speeds about any one value. Five angular speeds in Figure 3 are for plate pairs separated by a diffuse boundary: Capricorn-Australia, Nubia-Somalia, North America-South America, India-Capricorn, and Australia-India. Four of these diffuse boundaries are purely oceanic, and the fifth (Nubia-Somalia) has a significant oceanic component (D Chu & RG Gordon, manuscript in preparation). The five angular speeds range from 0.06° to 0.31° My^{-1}, which places them among the slower angular speeds, as they are comparable to the angular velocities of the Caribbean plate or the African plate or the South American plate relative to many of their neighbors. Thus, rates of rotation of

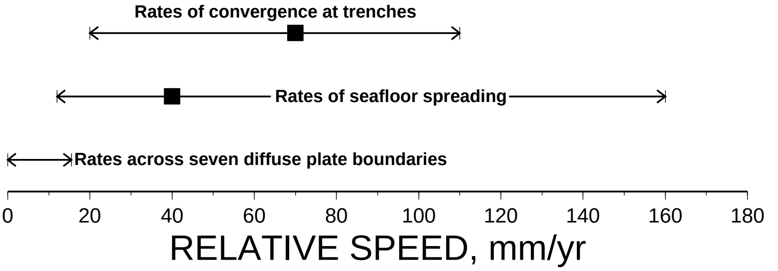

Figure 4 Comparison of the range of maximum speeds accommodated across seven diffuse plate boundaries (Capricorn-Australia, North America–South America, Nubia-Somalia, Nubia-Eurasia, India-Capricorn, Sierra Nevada–North America, and India-Australia), with the range of spreading rates and convergence rates across narrow plate boundaries.

plates across diffuse plate boundaries are comparable to the slower rates of rotation across narrow plate boundaries.

Argus & Gordon (1991b) assumed that the Sierra Nevada and Great Valley of California compose a single rigid or nearly rigid Sierra Nevadan microplate between the San Andreas fault system and the Great Basin. Few earthquakes and only minor faults occur therein except near the San Andreas fault system. Figure 4 also shows the rates of rotation of the Sierra Nevada microplate relative to the North American plate (0.61° My^{-1}) and relative to the Pacific plate (1.04° My^{-1}), which are both in the upper half of the range of angular speeds (Argus & Gordon 1991b; DF Argus & RG Gordon, manuscript in preparation). The Great Basin and possibly the Colorado Plateau and Rocky Mountains, which together separate the microplate from the North American plate, compose a diffuse plate boundary. The boundary between the microplate and the Pacific plate is about 100 km wide and is also arguably a diffuse plate boundary. Alternatively, the microplate can be regarded as one large element of a larger diffuse plate boundary, that between the Pacific and North American plates, in which case the rate of rotation is 0.75° My^{-1}.

The substantial overlap between rates of relative plate rotation across narrow and diffuse plate boundaries is consistent with the interpretation of the latter as plate boundaries.

Comparison of Surface Speeds Accommodated Across Diffuse Plate Boundaries with Those Across Narrow Boundaries

The tectonics and deformation across any small region between two plates is related more directly to the velocity of a surface point on one plate relative to the other than to the relative angular velocity between the two plates. Because the poles of rotation of plates separated by diffuse plate boundaries tend to lie within or near the diffuse boundary, a given angular speed tends to correspond to a lower surface speed than that of motions across narrow boundaries.

Rates of seafloor spreading, which provide one set of references for what constitutes fast or slow motion, vary from a low of 12 mm/year across the Arctic Ridge to a high of 160 mm/year across the East Pacific Rise, between the Pacific and Nazca plates, with a median of about 40 mm/year (Figure 4). [Much slower localized divergence may be occurring in at least two regions, between Nubia and Eurasia across the Terceira rift in the Azores, where the divergence rate is only ∼4 mm/year (Argus et al 1989), and between the Indian and Arabian plates across the Dalrymple trough in the Arabian Sea, where the divergence rate is only ∼2 mm/year (Gordon & DeMets 1989). In neither region are there correlatable magnetic anomalies.]

Convergence rates between the stable interiors of plates meeting at deep sea trenches range from a low of ∼20 mm/year along the southern Chile trench, where the Antarctic plate underthrusts the South American plate, to ∼110 mm/year along the Australia-Pacific plate boundary, with a median rate of ∼70 mm/year (Figure 4). (In quoting these lower limits, I have omitted slowly converging plate boundaries, such as that between Nubia and Eurasia, for which the mutual boundary lacks a well-defined trench with an associated set of earthquakes with slip on a shallowly inclined plane. Back-arc spreading leads to faster convergence rates in some regions, but here I confine my discussion to the velocities between the major plates.)

Speeds across the diffuse plate boundaries are almost always less than these values (Figure 4). When the pole of rotation lies in the diffuse plate boundary, as is true for several such boundaries, the speed of one plate relative to another becomes vanishingly small near the pole of rotation. Of greater interest is the fastest speed along the edge of a plate adjacent to the diffuse plate boundary and relative to the other plate: 2–3 mm/year for the motion of the Capricorn relative to the Australian Plate (Royer & Gordon 1997), ∼4 mm/year for South America relative to North America (DF Argus & RG Gordon, unpublished manuscript), ∼6 mm/year for Nubia relative to Somalia (or vice versa) (D Chu & RG Gordon, manuscript in preparation), ∼7 mm/year for Nubia relative to Eurasia, ∼10 mm/year for the Indian plate relative to the Capricorn plate (DeMets et al 1994a, Royer et al 1997), ∼12 mm/year for the Sierra Nevada-Great Valley microplate relative to the North American plate (Argus & Gordon 1991b; DF Argus & RG Gordon, manuscript in preparation), and 15–16 mm/year India relative to Australia (Royer & Gordon 1997) (Figure 5). The continental diffuse plate boundary between Southeast Asia and the Eurasian plate indicates that

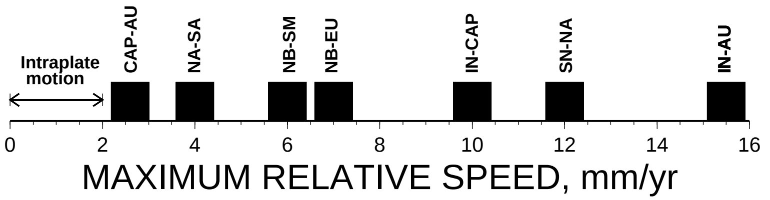

Figure 5 Comparison of the upper bounds on intraplate speed for the stable interiors of the North American and Eurasian plates ("intraplate motion") with the maximum speeds across seven diffuse, mainly oceanic, plate boundaries. Plate name abbreviations: AU, Australia; CAP, Capricorn; IN, India; NA, North America; NB, Nubia; SA, South America; SM, Somalia; and SN, Sierra Nevada-Great Valley. Note that the upper bound on intraplate motion is less than the fastest motion estimated across each of these diffuse plate boundaries.

their relative velocity is ~10 mm/year (England & Molnar 1997), comparable to those shown in Figure 5.

Thus, diffuse plate boundaries are known to accommodate maximum speeds between bounding plates from 2–3 mm/year to 15–16 mm/year, with smaller relative speeds near poles of rotation. The highest speed across a diffuse plate boundary is smaller than the rate of convergence at any subducting boundary and slightly faster than the slowest well-documented rates of seafloor spreading. This certainly suggests that the diffuse boundaries are diffuse in part because their rates are less than some critical value needed to establish either localized seafloor spreading or localized subduction.

Paleomagnetic Test of the Cenozoic Global Plate Motion Circuit

Paleomagnetic data provide a means for independently testing the consistency of plate reconstructions. Such tests are most useful when plate motion circuits lack enough redundancy to construct strong tests for internal consistency. Acton & Gordon (1994) used paleomagnetic poles to test the motions since ~70 Ma of the global plate motion circuit that relates the motion of the Pacific plate to the plates surrounding the Atlantic and Indian Oceans. They compiled a set of 24 mean poles averaged from all available high-quality paleomagnetic data, which come from 78 studies on the Eurasian, Greenland, North American, South American, African, Indian, Australian, Antarctic, and Pacific plates. The poles from the non-Pacific plates are reconstructed into a reference frame in which the Pacific plate is held fixed. The tests they present differ from prior tests not only in their incorporation of many new data but also by incorporation of error budgets for each paleomagnetic pole that include estimates of plate-reconstruction uncertainties, random paleomagnetic uncertainties, and systematic paleomagnetic uncertainties. Each of the 24 mean poles, which range in age from 20 to 73 Ma, is typically the average of several formation mean poles. There are 3 mean poles from Africa, 2 from Australia, 4 from Eurasia, 1 from India, 3 from North America, 2 from South America, and 4 from the Pacific plate. The basic data used to estimate the mean poles are from 14,100 fully oriented paleomagnetic samples; 1,600 paleomagnetic samples from azimuthally unoriented cores; seven seamount poles; two effective magnetization inclinations from submarine volcanic ridges; 11 identifications of equatorial sediment facies; and 182 estimates of the skewness and 2 estimates of the amplitudes of magnetic anomalies that record ancient seafloor spreading in the Pacific. The uncertainty in the position of a reconstructed paleomagnetic pole is a combination of the uncertainty in the paleomagnetic pole and the uncertainty that accumulates as the paleomagnetic pole is reconstructed through multiple links of the plate motion circuit (Acton & Gordon 1994).

Acton & Gordon (1994) found that the means of the non-Pacific poles reconstructed into the Pacific reference frame show a surprising pattern: The poles for 27, 46, and 56 Ma sit atop one another in a standstill, with the reconstructed mean pole for 66 Ma located $\sim 7^\circ$ away. The observed Pacific plate poles are offset from these but with a similar but less distinctive pattern: The poles for 26, 39, and 58 Ma lie near one another but are offset by $\sim 7^\circ$ from the pole for 65 Ma. Despite the large uncertainties of some poles, Pacific plate poles differ significantly from coeval reconstructed mean non-Pacific poles. The difference between each Pacific pole and the corresponding mean, coeval, reconstructed, non-Pacific pole is significant at the 95% confidence level. For normal-polarity results, the reconstructed non-Pacific poles tend to predict lower (that is, more negative) inclinations (corresponding to less northward motion of the Pacific plate) and more westerly declinations for Pacific plate sites than predicted by the Pacific poles (Figure 6).

The bias-corrected angular distance between each Pacific plate pole and the corresponding coeval mean reconstructed non-Pacific pole is $9.1^{\circ}{}^{+9.3^\circ}_{-9.1^\circ}$, $9.5^{\circ}{}^{+4.1^\circ}_{-4.2^\circ}$, $9.3^{\circ}{}^{+4.9^\circ}_{-5.5^\circ}$, and $9.6^{\circ}{}^{+3.5^\circ}_{-3.8^\circ}$, respectively, for the poles at 26, 39, 58, and 65 Ma.

Repeating the same tests as described above, but assuming a paleomagnetic field with a 5% geocentric axial quadrupole component of the same sign as the dipole component (that is, $g_2^0/g_1^0 = 0.05$), decreases the inconsistency but fails to eliminate it. The Pacific poles for 39, 58, and 65 Ma (but not the pole for 26 Ma) differ at the 95% confidence level from their mean coeval reconstructed counterparts (Acton & Gordon 1994).

The plate motion circuit through the South Pacific and Antarctica was thus shown to fail paleomagnetic tests of consistency. These failures indicate that

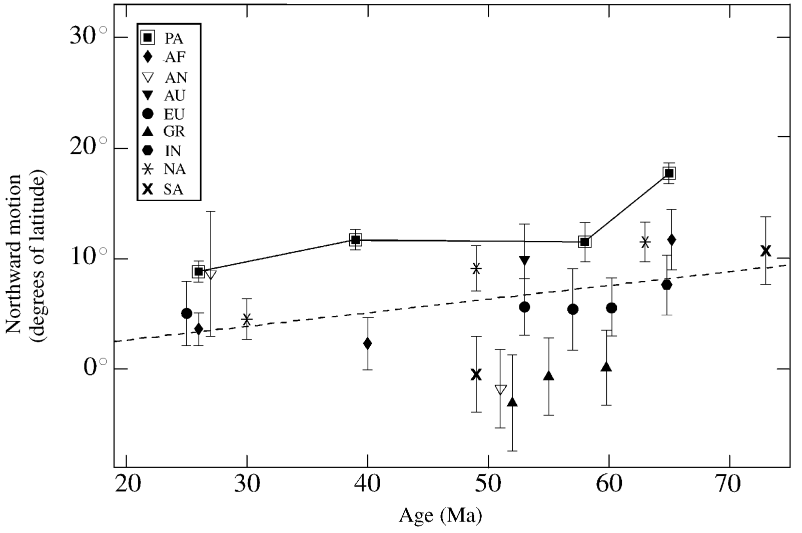

Figure 6 Observed and predicted northward motion of the Pacific plate relative to the paleomagnetic or spin axis, assuming a dipolar paleomagnetic field. The *solid squares* show the observed northward motion of the Pacific plate relative to the paleomagnetic axis, whereas the other symbols show that predicted from individual reconstructed non-Pacific paleomagnetic poles. The *solid line* connects the four observed estimates of northward motion, whereas the *dashed line* is a least-squares best-fitting straight line to the 20 predictions of northward motion. *Error bars* are $\pm 1\sigma$, and they include both paleomagnetic and—in the case of reconstructed poles—plate reconstruction uncertainties. Plate abbreviations: PA, Pacific; AF, African; AN, Antarctic; AU, Australian; EU, Eurasian; GR, Greenland; IN, Indian; NA, North American; and SA, South American. [Published with permission from Acton & Gordon (1994). Copyright 1994, AAAS.]

reconstructions of Pacific basin plates relative to surrounding plates inferred from this circuit are systematically in error. The cause of this discrepancy is unclear. Possibilities include an unrecognized plate boundary in the circuit, unmodeled systematic errors in paleomagnetic data, and plate nonrigidity, none of which are mutually exclusive.

How Rigid Are Stable Plate Interiors?

The background occurrence of small earthquakes in stable plate interiors, not to mention the occasional great earthquake, such as those that occurred in the New Madrid region of the United States in the nineteenth century (Johnston & Schweig 1996), shows that plate interiors are deforming. The observed subsidence of multiple kilometers in midcontinent basins over geologic time, which presumably include horizontal as well as vertical displacements, is further evidence for nonrigidity. Uplift of the Earth's surface over hotspot swells, such as that beneath and flanking the Hawaiian islands, also demonstrates some nonrigidity of plate interiors. In this section, I summarize and update a more extensive review of plate rigidity (Gordon 1995).

How much, when, and where does the lithosphere deform within true plate interiors, i.e. outside both narrow and diffuse plate boundaries? There may be no sharp contrast but rather a gradation in behavior between intraplate deformation and diffuse plate boundaries. These concepts may still be useful end members for discussion, however. Currently, it seems useful to distinguish between these two end members as follows: Deformation of stable plate interiors is smaller than the threshold of detection of space geodetic and conventional plate motion data (i.e. displacements or rates inferred from marine magnetic anomalies and displacements or orientations inferred from fracture zone and transform fault traces), whereas diffuse plate boundaries accommodate motion that is measurable (Wiens et al 1985, Argus 1990, DeMets et al 1990, 1994a,b, Gordon et al 1990, Argus & Gordon 1991b, Royer & Chang 1991, Freymueller et al 1996, Royer & Gordon 1997, Royer et al 1997). This apparent distinction may, however, be an artifact of the accuracy of currently available observations.

Little is known about actual rates of deformation of plate interiors. A lower bound on deformation rates can be obtained from the summation of seismic moments of earthquakes in stable plate interiors. For example, the average strain rate for the central and eastern United States estimated by this method is about 10^{-12}–10^{-11} year^{-1} (equivalent to 3×10^{-20} s^{-1} to 3×10^{-19} s^{-1}) (Anderson 1986). Integrated across a large plate 10,000 km across, this would correspond to 0.01–0.10 mm/year. Across the United States east of the Rocky Mountains, this integrates to only 0.003–0.03 mm/year.

Aside from summation of seismic moments, there have been three main sources of quantitative estimates of the nonrigidity of plate interiors: (*a*) tests for closure of plate motion circuits using geologically instantaneous plate velocity data (Gordon et al 1987), (*b*) tests for closure of plate motion circuits using plate reconstruction data (i.e. for motion requiring a description in terms of finite rotations) (Royer & Chang 1991), and (*c*) direct tests for plate rigidity using space geodetic data. Here I focus on the results from space geodetic data and from the motion since 3 Ma through the Pacific–Antarctic–Nubia–North America plate motion circuit.

Space geodesy is a term applied to several techniques for making precise position measurements between sites on Earth's surface that may be separated by as much as ~12,000 km. The three main techniques, very long baseline interferometry (VLBI), satellite laser ranging (SLR), and the Global Positioning System (GPS), are based on technologies developed for space-related research: radio astronomy for VLBI and satellite tracking for SLR and GPS.

How fast does one site on a stable plate interior move relative to another on the same plate interior? Let us assume that the outline of the stable plate interior has been carefully drawn to exclude deforming regions near boundaries with other plates. For the US portion of North America, for example, a conservative interpretation would exclude from the stable plate interior everything west of the plains, not only the Basin and Range and parts farther west, but also the Colorado Plateau, Rio Grande Rift, and the Rocky Mountains (Figure 7*a*).

Argus & Gordon (1996) found that geodetic data from VLBI can be used to place a useful upper bound on the speed of sites in the stable interior of North America (Figure 7*a*) and on a smaller network of sites in the stable interior of Europe (Figure 7*b*). They presented evidence that the error budgets usually used in analysis of VLBI are unrealistically small because the errors are propagated by assuming that errors between different observing sessions are uncorrelated, when they are in fact correlated. Using a conservative error budget, which they argue is realistic, they find that an upper bound of ∼2 mm/year can be placed on the speed of seven of the sites relative to stable North America and on two of the sites relative to stable Europe (Figure 8). Five of the North American sites are from the eastern United States and one from southeastern Ontario (Figure 7*a*); thus they span only a limited part of the North American interior. In their analysis, the speed of the site in Platteville (Colorado), which lies about 3000 km west of the other interior sites, has an upper bound of ∼3 mm/year relative to other sites in the stable interior of North America. The site in Fairbanks (Alaska) was not assumed to lie in the stable interior of North America; the upper bound on its velocity relative to stable North America was found also to be 3 mm/year. The upper bounds on intraplate nonrigidity, which may greatly exceed the actual value of intraplate nonrigidity, only slightly overlap the range of maximum rates across diffuse plate boundaries. The smallness of this overlap suggests that the space geodetic measurements are on the verge of placing upper bounds on plate nonrigidity that are smaller than the velocities across clearly deforming diffuse plate boundaries (Figure 5).

Because the Fairbanks site is so far from the sites that are undoubtedly on the stable interior of the North American plate, it provides the lowest available upper bound on the average strain rate across a plate interior. Its upper bound speed of 3 mm/year, combined with its 5000 km distance from the cluster of sites in the eastern United States, gives an upper bound on strain rate of $\sim 6 \times 10^{-10}$ year^{-1} (2×10^{-17} s^{-1}), which is 60–600 times as large as the lower bound on strain rate of 10^{-12}–10^{-11} year^{-1} found from seismic moments. RG Gordon, D Chu, and DF Argus (manuscript in preparation) combine a 3-My plate motion circuit with space geodetic data to place an upper bound

(a)

(b)

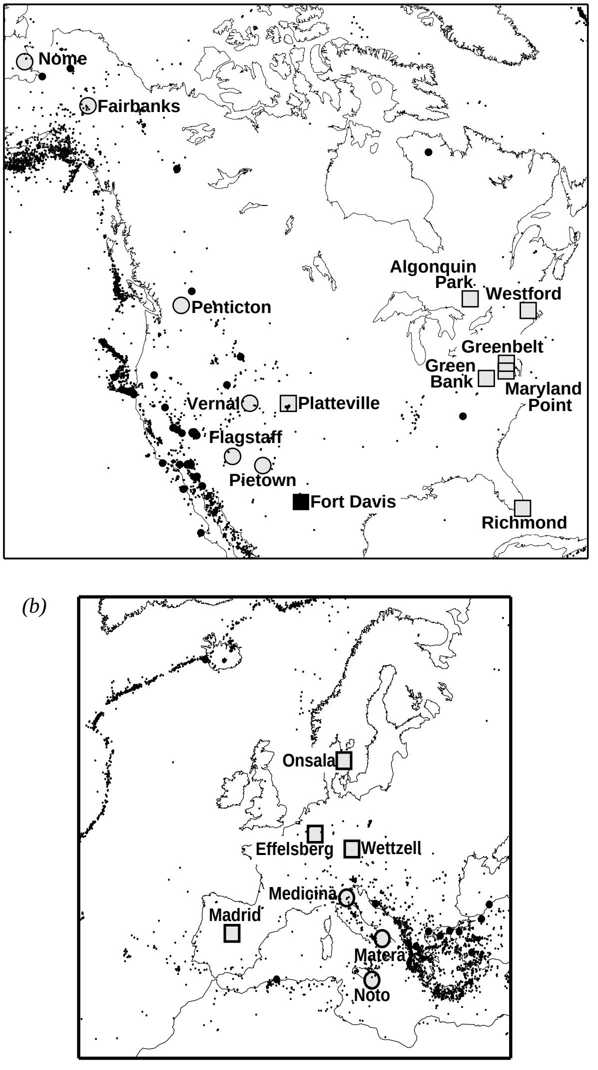

Figure 7 Location map for selected radio telescope sites on (*a*) North America and (*b*) Europe. *Shaded squares* are the sites that are assumed to be on the stable interiors of the North American and European plates. *Shaded circles* are sites that are either certain or suspected of being in the diffuse plate boundary between the North American and Pacific plates and between the European and African plates. The velocity of the site at Fort Davis (*black square* in *a*) was not estimated. Epicenters of earthquakes occurring between 1964 and 1993 are shown by *solid black circles*; the *smaller circles* show earthquakes with magnitudes between 4.5 and 5.5 and the *larger circles* show earthquakes with magnitudes exceeding 5.5. There are two sites at each of Green Bank and Westford. After Argus & Gordon (1996).

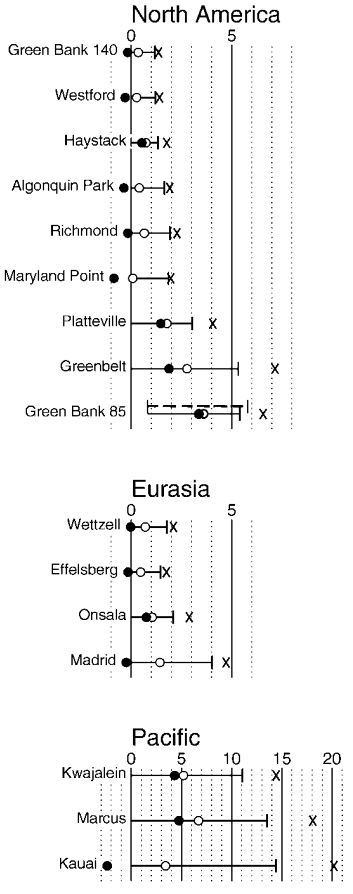

Figure 8 Speeds and confidence limits between sites and their home plates. Apparent observed speeds (*open circles*), unbiased speeds (*solid circles*), farthest points (*cross*) on the 95% confidence ellipses of the apparent observed speeds, and unbiased upper 95% confidence limits (*short vertical lines at the right-hand end of solid error bars*) are shown. For the present review, the unbiased upper 95% confidence limit is the important quantity—it gives the upper bound on the speed of the site relative to the rest of the plate, as permitted by the data. The underlying set of site velocities has been adjusted for predicted postglacial rebound. Locations of sites in North America and Europe are shown in Figure 7*a* and *b*. From Argus & Gordon (1996).

on plate nonrigidity. They estimate the motion between the Pacific and North American plates in three ways: (*a*) from the Pacific–Antarctic–Nubia–North America plate motion circuit for the past 3 My, (*b*) from seafloor spreading in the Gulf of California over the past 780,000 years (DeMets 1995), and (*c*) from space geodetic data (including VLBI, SLR, and GPS data). None of these three estimates differ significantly from one another. The difference between the result from the plate motion circuit and either of the other two estimates gives an angular velocity of nonclosure (Gordon 1995). The upper bound on this angular velocity of nonclosure is 0.15°/My, which corresponds to an upper bound on surface nonclosure of ~15 mm/year. Given that the global plate motion circuit encloses a great circle ~40,000 km long, the implied upper bound on average deformation rate is $\sim 4 \times 10^{-10}$ year^{-1} (1×10^{-17} s^{-1}), which is near that found for North America from the VLBI data. It follows that observations leave the nonrigidity of the plates uncertain within a factor of about 40–400.

Evidently, we are still very ignorant of the true degree of plate nonrigidity. To illustrate this, consider the effect of the two end member limits if extrapolated over Cenozoic time to global plate reconstructions. On a great circle, which has a circumference of 4×10^4 km, the minimum deformation rate of 10^{-12}–10^{-11} year^{-1} integrates to a velocity of 0.04–0.4 km/My, which gives a displacement over Cenozoic time (that is, the past 65 My) of 3–30 km, which is probably negligible compared with uncertainties in global plate reconstructions (Stock & Molnar 1988). On the other hand the upper bound on plate nonrigidity gives a rate of ~15 km/My for a displacement over Cenozoic time of ~1000 km, which is much larger than the uncertainties in global plate reconstructions and about the same size as the discrepancy, discussed above, between Pacific plate paleomagnetic poles and non-Pacific paleomagnetic poles reconstructed into the Pacific plate frame of reference (Acton & Gordon 1994).

Also comparable to this upper limit are the estimated displacements of Pacific hotspots relative to Atlantic hotspots over Cenozoic time (Molnar & Stock 1987). Acton & Gordon (1994) speculated that the paleomagnetic misfit and the hotspot misfit have the same explanation—an unmodeled error in the global plate motion circuit. They expressed skepticism that the misfits could be explained by widespread low levels of nonrigidity of the plates. The present analysis, however, suggests that we cannot confidently exclude this possibility. This by no means demonstrates that plate nonrigidity causes the misfits, especially because many of the paleomagnetic poles are reconstructed from a distance much less than a full Earth circumference, but it serves to underscore our ignorance of the actual deformation rate of stable plate interiors and of the importance of placing more stringent bounds on them.

Plate Boundary Strain Rates

The strain rates inferred across stable plate interiors can be compared with strain rates across plate boundaries. The type of narrow plate boundary for which it is easiest to quantify the strain rate is transform faults. Velocities across transform faults mainly range from 12 to 160 mm/year, and widths of well-imaged submarine transform faults range from ~500 m to ~2 km. The combination of these parameters gives strain rates from 6×10^{-6} to 3×10^{-4} year^{-1}, about 10^5 times higher than the upper bound on strain rates of stable plate interiors.

Strain rates across diffuse oceanic plate boundaries are probably fastest where higher velocities are accommodated across them. For example, across the eastern part of the boundary between the Indian and Capricorn plates, a velocity of ~10 mm/year is accommodated across a zone about 1000 km wide, which indicates an average strain rate in this region of $\sim 10^{-8}$ year^{-1}. Calculations across other diffuse plate boundaries in regions far from the relevant pole of rotation indicate strain rates of 10^{-9}–10^{-8} year^{-1}. Thus the fastest strain rates across diffuse oceanic plate boundaries are only about 25 times faster than the upper bound on strain rates of stable plate interiors and about 600 times slower than the slowest strain rates across narrow plate boundaries.

Thus the fastest strain rates across diffuse plate boundaries appear to fit neatly between those for stable plate interiors and those for narrow plate boundaries. Given that strain rates across diffuse oceanic plate boundaries are vanishingly small near the poles of rotation, however, an overlap of ranges of strain rates is likely between those for stable plate interiors and those for diffuse plate boundaries.

DIFFUSE OCEANIC PLATE BOUNDARIES

Dimensions of Diffuse Oceanic Plate Boundaries

A precise estimate of the dimensions of most oceanic diffuse plate boundaries cannot be given, and the sizes of the boundaries are estimated mainly from the area over which earthquakes with magnitudes exceeding 5.5 or 6 occur but also from other evidence of deformation, including lineated gravity anomalies (McAdoo & Sandwell 1985), where available. More precise estimates can be obtained for a few regions. Along the Central Indian Ridge, Royer et al (1997) were able to use crossings of marine magnetic anomaly 5 and of associated fracture zone segments to identify a set of crossings that can be fit neither as part of the rigid Indian plate nor as part of the rigid Capricorn plate. These unfittable crossings begin just north of the unnamed fracture zone that is the first fracture zone south of the Vema fracture zone. They continue northward to just north of the unnamed fracture zone that is the first fracture zone south of the Vityaz fracture zone. These limiting fracture zones intersect the Central Indian Ridge near 10°S and near 6°S, respectively, showing that the extensional portion of the diffuse plate boundary is at least several hundred kilometers wide along the Central Indian Ridge. From a long north-south seismic profile along 81.5°E that crosses the entire contractional deformation zone, Chamot-Rooke et al (1993) estimated that the zone of significant deformation ranged from 8°S to just north of the equator, ~800 km. Similarly, Van Orman et al (1995) used a long north-south seismic profile along 78.8°E to estimate that the zone of significant deformation was 823 km in north-south extent. The zone of active deformation appears to broaden farther east but cannot be estimated as precisely. For the equatorial Indian ocean, the along-strike dimension of the zone of deformation is thousands of kilometers (Figure 9).

Plate motion data place much less certain limits on the present north-south extent of the diffuse boundary between the North American and South American plates. DF Argus & RG Gordon (unpublished manuscript) analyzed data that recorded plate motion along the Mid-Atlantic Ridge for the past 3 My, in order to estimate the present location of the North America–South America–Nubia triple junction. If the boundary is assumed to be narrow, it must lie between the Fifteen-Twenty transform fault (~15°N) and the Kane transform fault (~24°N). However, neither the azimuth of the Fifteen-Twenty nor that of the Kane transform fault is well fit by the best-fitting plate motion model. The azimuths of both, but especially that of the Kane, lie between the direction expected if they record North America-Nubia motion and that expected if they record South America-Nubia motion. Thus, DF Argus & RG Gordon (unpublished manuscript) speculated that the deformation is distributed beyond the corridor bounded by these two fracture zones and, therefore, is distributed across a north-south distance of 1000 km or more.

Nascent Plate Boundaries?

Diffuse plate boundaries, especially the convergent portions of the set of boundaries separating the Indian plate from the Capricorn and Australian plates, are often said to be nascent plate boundaries, that is, in the initial stages of formation of narrow plate boundaries. Although this may be true, there is no direct evidence that narrow plate boundaries form this way. Perhaps more important are the following observations about diffuse oceanic plate boundaries: 1. They cover a large fraction of Earth's ocean floor. 2. They are not ephemeral; for example, the boundary between the Indian and Capricorn plates has persisted

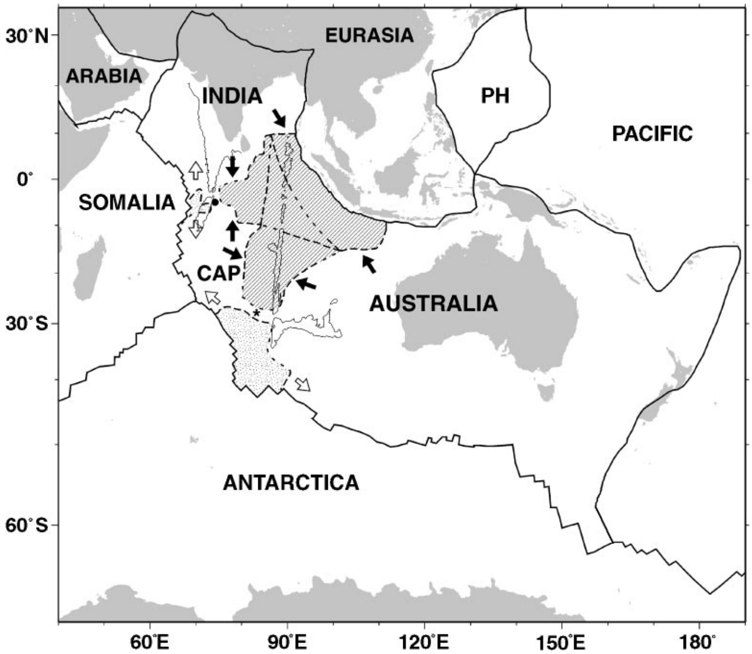

Figure 9 Plate geometry for the Indo-Australian "plate" proposed by Royer & Gordon (1997). Plate Abbreviations: CAP, newly recognized Capricorn plate; PH, Philippine Sea plate. *Stippled areas* denote diffuse boundaries accommodating horizontal divergence, whereas *hachures* denote diffuse boundaries accommodating horizontal convergence. *Small solid circle* shows the pole of rotation between the Indian and Capricorn plate, and the *star* shows that for the Capricorn and Australian plates. [Modified with permission from Royer & Gordon (1997). Copyright 1997, AAAS.]

for at least 18 My and perhaps much longer (Gordon et al 1997). 3. Possibly they can persist as long as the relative plate velocities are low.

Analogies to Deforming Zones on the Continents

The diffuse deformation characteristic of continental plate boundaries is often contrasted with the typical narrow plate boundaries of the oceans. The diffuse oceanic plate boundaries, however, exhibit behavior that resembles that of the continents in many ways. Deformation is distributed over horizontal distances that far exceed the plate thickness. Deformation within the wide bands of seismicity is incompletely specified by the relative motion of the rigid plates on either side. In zones of diffuse convergence, thickening can be widely distributed by thrust faulting. The lithosphere may fail by folding, presumably as part and parcel of the faulting process (Martinod & Davy 1992, Molnar et al 1993, Zuber & Parmentier 1996). As in mountains on continents, work is done against buoyancy forces in oceanic regions with folded or pervasively shortened lithosphere; therefore, these deformed oceanic regions can store potential energy. Thus, in spite of obvious differences in vertically integrated strength, strength profiles, and buoyancy profiles, regions of distributed oceanic deformation probably have more in common with continental deformation zones than with narrow oceanic plate boundaries.

Ridge-Mountain Transforms in Oceanic Lithosphere

In the classic paper in which he recognized transform faults and proposed the elements of plate tectonics, Wilson (1965) discussed a type of transform whereby a mountain is transformed into a mid-ocean ridge. He credits Carey (1955) with first recognizing such a transform when he proposed that the Pyrenees Mountains were shortened while rifting opened the Bay of Biscay. Wilson (1965) applied the terms mountain and mountain system broadly and included island arcs as mountains. Here, for the purposes of using the term ridge-mountain transforms, mountains include any zone across which convergence is accommodated, and ridges include any zone across which divergence is accommodated. Defined thus, ridge-mountain transforms have a literally pivotal role in diffuse plate boundaries in oceanic lithosphere and apparently occur in the boundaries separating (*a*) the Indian and Capricorn plates (Gordon et al 1990) (Figure 9), (*b*) the Capricorn and Australian plates (Royer & Gordon 1997) (Figure 9), (*c*) the Nubian and Somalian plates (D Chu & RG Gordon, manuscript in preparation) (Figure 10), and (*d*) the North American and South American plates (Argus 1990) (Figure 11).

Another way of expressing the same concept is that the pole of rotation between the bounding plates lies in the middle of the diffuse plate boundary that separates them. The pole of rotation of plates separated by a narrow boundary typically lies far from the plate boundary. It follows that plates must be coupled much more tightly across diffuse plate boundaries than across narrow boundaries.

Composite and Component Plates

That plates are evidently more tightly coupled across diffuse plate boundaries, especially oceanic diffuse plate boundaries, suggests that there is an important sense in which narrow plate boundaries define a "plate," such as the Indo-Australian plate, even if that plate contains two or more nearly rigid portions in relative motion and separated by diffuse plate boundaries. Royer & Gordon (1997) thus proposed the use of the terms "component" and "composite" plates to express these different concepts. In their terminology, the Indian, Capricorn,

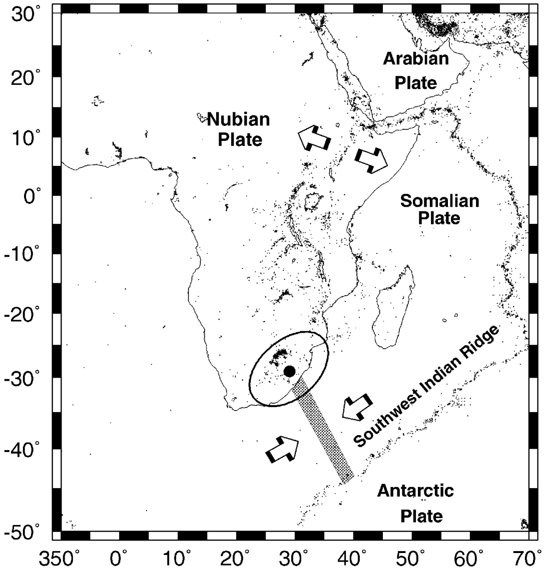

Figure 10 The pole of rotation (*solid circle*) for 0–3 Ma between the Nubian and Somalian plates lies a little south of the southern end of the East African Rift; the location of the pole indicates that convergence is accommodated in the portion of the boundary between the pole of rotation and the Southwest Indian Ridge. The *ellipse* surrounding the pole delimits the 95% confidence region. *Stippled region* intersects the Southwest Indian Ridge at a hypothetical triple junction location, for which the data are best fit if the boundary between Nubia and Somalia is localized and narrow where it intersects the Southwest Indian Ridge. It is more likely that the boundary is diffuse and wide. (From D Chu & RG Gordon, manuscript in preparation.)

and Australian plates are component plates, whereas the Indo-Australian plate is a composite plate comprising these three component plates, the diffuse plate boundaries that separate the components, and a hypothesized diffuse plate boundary between the Australian and Pacific plates west of the Macquarie Ridge (DeMets et al 1988). Composite plates are delimited by traditional narrow plate boundaries; component plates are at least partly delimited by the edge of a diffuse plate boundary but may also be delimited by narrow boundaries. Under this scheme of classification, other composite plates include the American plate, with North American and South American component plates, and an African plate, with Nubian and Somalian component plates.

Although component plates are in relative motion, their motion is strongly influenced by stresses transmitted from an adjacent component plate across their mutual diffuse plate boundary. Moreover, as is true in continental deformation zones (England & Jackson 1989), the relative motion of the bounding plates does

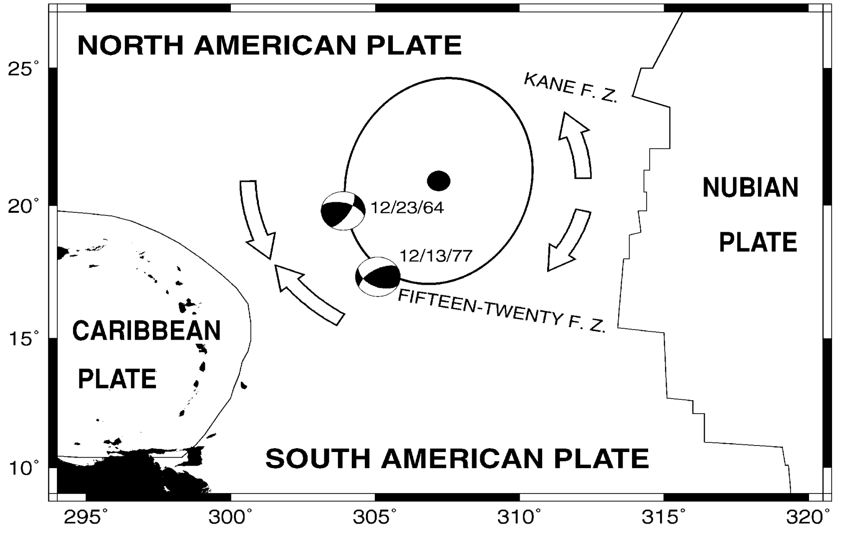

Figure 11 The optimal 0- to 3-Ma pole of rotation between the North American and South American plates lies between the Mid-Atlantic Ridge and the Lesser Antilles trench (Argus 1990; DF Argus & RG Gordon, unpublished manuscript). Northwest-southeast convergence must be accommodated between the pole of rotation and the trench, whereas north-south divergence is accommodated between the pole of rotation and the Mid-Atlantic Ridge. The locations of two earthquakes, which have composite thrust-strike slip mechanisms (Bergman 1986), indicate the approximate location of part of the convergent portion of the diffuse boundary, which presumably lies between the trench and the pole of rotation. The divergent portion of the boundary mainly lies between the pole of rotation and the Mid-Atlantic Ridge between the Fifteen-Twenty and Kane fracture zones, although it may continue outside of these bounds, especially north of the Kane fracture zone (Argus 1990; DF Argus & RG Gordon, unpublished manuscript).

not specify the motions within a diffuse oceanic plate boundary. These motions can only be understood by considering the dynamics of the deformation.

CONCLUSIONS

The central assumption of plate tectonics is the rigidity of plate interiors. The narrowness of plate boundaries, which was the other main assumption of plate tectonics as originally conceived, is contradicted by many observations, both in the continents and in the oceans. Deforming zones that can be interpreted reasonably as diffuse plate boundary zones cover ~15% of the Earth's surface. The lower bound on the nonrigidity of the stable plate interiors is 10^{-12}–10^{-11} year^{-1}, and the upper bound is $\sim 4 \times 10^{-10}$ year^{-1}. Plate nonrigidity is therefore uncertain by a factor of 40–400. When integrated along a great-circle path through a global plate motion circuit over Cenozoic time (i.e. the past 65 My), the lower bound gives a displacement of 3–30 km and the upper bound a displacement of ∼1000 km. Whether plate nonrigidity contributes significantly to misfits of global plate reconstructions to Cenozoic paleomagnetic data and hotspot tracks is unclear. Angular speeds across diffuse plate boundaries are mainly similar to the lower half of rates of rotation across narrow boundaries. The maximum speed of relative plate motion across each diffuse plate boundary is ∼2–∼15 mm/year, which is faster, albeit in some cases only slightly faster, than the upper bounds on intraplate motion across stable plate interiors (≤2 mm/year). Diffuse plate boundaries in oceanic lithosphere are not ephemeral, and some have clearly persisted for tens of millions of years. In the Indian Ocean, some of the diffuse boundaries have been demonstrated to be many hundreds of kilometers wide, and some of the same boundaries are thousands of kilometers long. The poles of rotation of the plates flanking a diffuse oceanic plate boundary tend to be located in the diffuse boundary; in each case, the pole lies between the part of the diffuse plate boundary accomodating convergence and the part accomodating divergence. The tendency for the poles to lie in the boundary is a consequence of the strong coupling across a diffuse oceanic plate boundary between the two plates flanking the boundary. It may be useful to define a two-tier nomenclature for some plates with an upper tier of composite plates and a lower tier of component plates. A component plate, such as the Indian, Capricorn, or Australian plate, is rigid or nearly rigid and delimited on at least one side by a diffuse plate boundary. A composite plate, such as the traditionally defined Indo-Australian plate, consists of two or more component plates and multiple diffuse plate boundaries.

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