Space Geodesy and Plate Motions

SETH STEIN

Department of Geological Sciences, Northwestern University, Evanston, IL 60208

In the past decade, space-based geodetic observations have become a key tool in plate tectonic studies. These data have demonstrated that plate motions on time scales of years are quite similar to those averaged over millions of years, and that many plate interiors are generally rigid. These results have considerable implications for global geodynamics and for regional tectonic studies including analysis of the earthquake cycle. Space geodesy is also capable of characterizing the variations in time and space of deformation within plate boundary zones, an application that will be of increasing significance in years to come.

INTRODUCTION

The kinematics of the lithosphere are the primary constraints on its dynamics, and on the kinematics and dynamics of the deeper solid earth. As a result, determination of plate motions has been a major research area since the formulation of plate tectonics. Initially, marine geophysics, paleomagnetism, seismology, and continental geology provided the primary observational data for identification of plate boundaries and assessment of the motion along them. In the past decade, space-based geodetic observations have acquired comparable significance in plate tectonic studies. The results of the Crustal Dynamics Project, reviewed in this volume, show the range of techniques that have been used and results that have been derived. This paper considers some of the ways in which the space geodetic results relate to previous conceptions about plate tectonics, and may shape them further in years to come.

Prior to the advent of space geodesy, estimates of the present rates and directions of plate motions could only be derived from relative plate motion models, which are developed using the data from plate boundaries. The plate motions predicted by these models provide basic constraints for a wide variety of tectonic studies, including regional processes [e.g. DeMets et al., 1990], plate driving forces [e.g. Forsyth and Uyeda, 1975; Wortel et al., 1991], and mantle flow [e.g. Hager and O'Connell, 1980]. These models have two potentially serious limitations. First, they reflect plate motions averaged over millions of years. Second, the data from different plate boundaries are combined by assuming that the plates are rigid, so their relative motion can be found from the deformation within the narrow boundary zones between them.

Space-based geodesy does not face either of these two limitations, because the approach is quite different. It is an extension of traditional geodesy, which finds the relative positions of points on the earth's surface and, via measurements at different times, the change in their relative positions. The space-based techniques provide sufficiently high accuracy over long baselines that plate motions can be detected in a few years. Moreover, measurements can in principle be made between any points on the earth's surface. As a result, the relative motion of sites within plate interiors can be measured, thus making it possible to test the rigidity of plates.

As the techniques of space geodesy were being developed, among the primary questions that it was hoped they could address were:

1) How do plate motions on time scales of years compare with those averaged over millions of years?

2) How does deformation vary in space and time in plate boundary zones?

3) How rigid are plate interiors?

As the results in this volume summarize, three space geodetic techniques, Very Long Baseline radio Interferometry (VLBI), Satellite Laser Ranging (SLR), and the Global Positioning System (GPS) are now yielding valuable results on each of these questions.

PLATE MOTIONS ON DIFFERENT TIME SCALES

Conventional relative plate motion models are derived by combining rates of plate motion, inferred from magnetic anomalies at midocean ridges, with directions of plate motion, inferred from the azimuths of transform faults and earthquake slip vectors at plate boundaries [Morgan, 1968; Le Pichon, 1968; Chase, 1972; Minster et al., 1974; Chase, 1978; Minster and Jordan, 1978; DeMets et al., 1990]. These data are systematically inverted to yield a global model of the geologically

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instantaneous (covering the past few million years) motion between plates (Figure 1). Such a model is described by a set of angular velocity vectors (Euler vectors) specifying the motion of each plate relative to one arbitrarily fixed plate. The angular velocity vector describing the motion between any pair of plates can then be determined by vector subtraction. Angular velocity vectors are specified in spherical coordinates by their rotation rate (magnitude) and Euler pole (latitude and longitude). The velocity of one plate relative to another at any point along their mutual boundary is the cross product of the appropriate angular velocity vector and the point position vector.

Two crucial assumptions are made in generating a relative motion model from the data. First, the plates are treated as rigid, so that results from different boundaries can be combined by vector addition. Under this rigid plate hypothesis, almost all of the relative motion between plates is assumed to occur in narrow zones at their boundaries, whereas the plate interiors deform at a much lower rate, and so can be treated as rigid. Second, the different data types, which represent plate motions averaged over different time periods, are combined. The spreading rates derived from magnetic anomalies represent plate motions averaged over millions of years. Transform fault orientations represent their morphology, and thus sample plate motions on different time scales depending on the features used. Earthquake slip vectors in fact record the motion only during an earthquake, which is assumed (with varying degrees of justification) to represent plate motions over years to hundreds of years, depending on the recurrence interval. The resulting combination, a mixture of estimates with different time scales, yields a smoothed representation of plate motions averaged over several million years.

The utility of a relative plate motion model depends on the

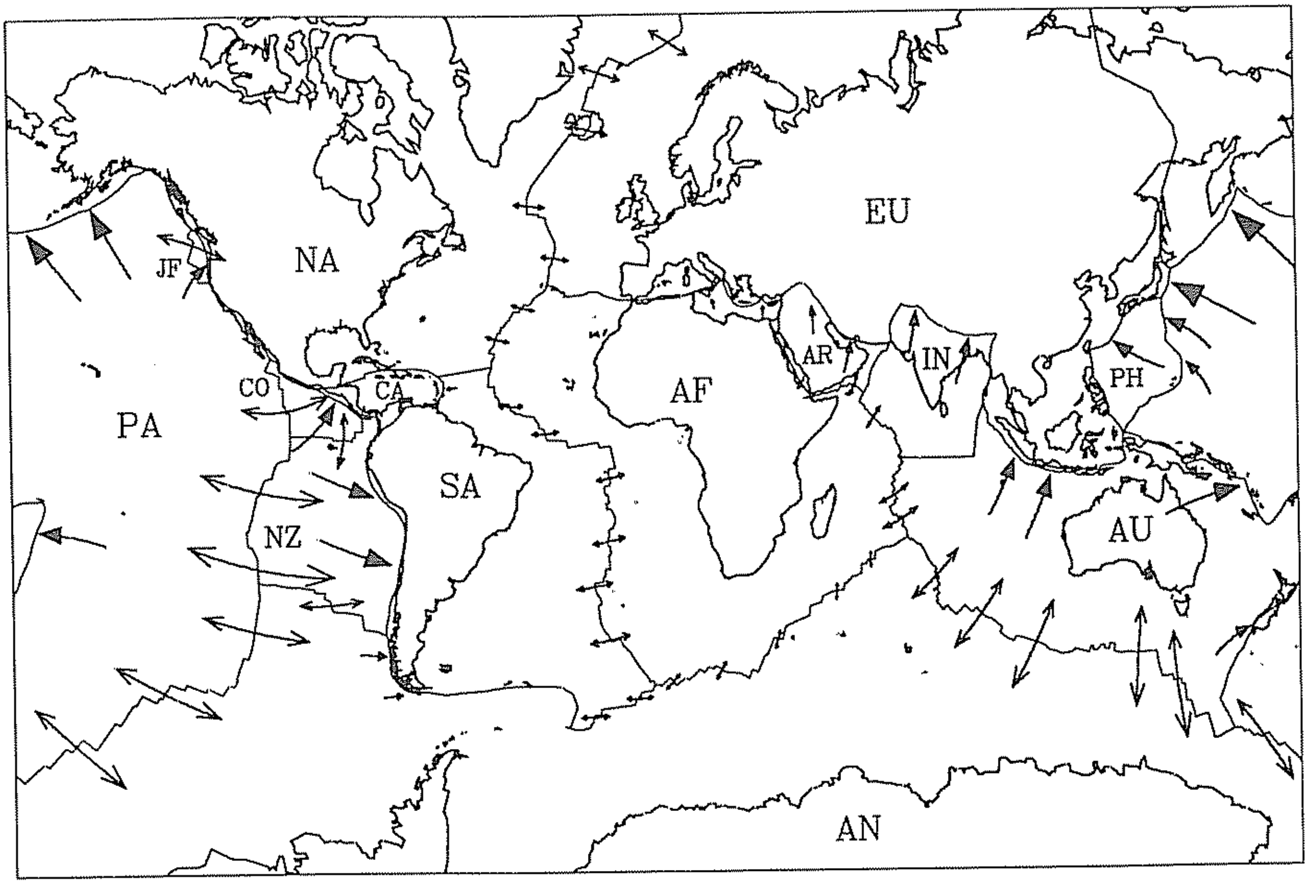

Fig. 1. Plate motions and assumed geometry for the NUVEL-1 global relative plate motion model. The plate boundaries are assumed to be ideal narrow boundaries, except for diffuse boundary zones between India and Australia and North and South America. Relative plate velocities are shown by arrows. The 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. 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 where convergence is asymmetric and the polarity is known. Each convergence arrow points toward the overthrust plate. Figure by Tom Shoberg. [Gordon and Stein, 1992].

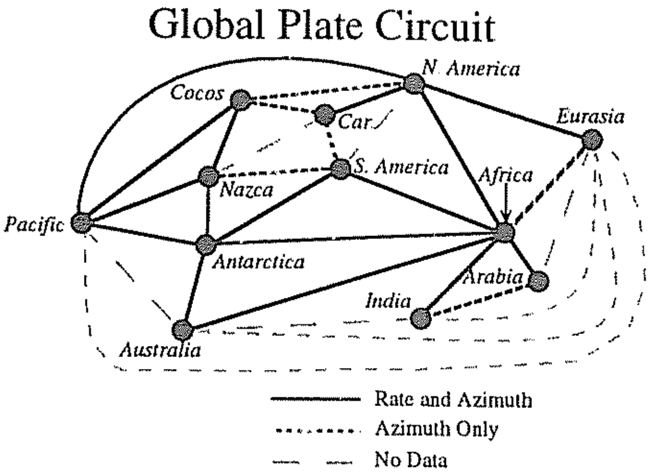

Fig. 2. Plate circuits used in global plate motion model NUVEL-1. Lines indicate boundaries and show whether rate and azimuthal data, azimuthal data alone, or none, are used. Rates are measured directly only at midocean ridges. Rates at subduction zones, where only azimuthal data are available, are inferred by closure. After DeMets et al. [1990].

validity of the two assumptions. For example, the rate of motion along subduction and continental transform boundaries is derived from the closure of global circuits (Figure 2). The closure process neglects intraplate deformation, including motion behind arcs. This approximation, together with the fact that the data used average over different time scales, made it natural to ask how useful the global relative motion models are for describing plate motions on time scales of thousands of years or less. Whether the long term and short term plate motions are comparable is important for a variety of questions. One of the most interesting applications is estimation of earthquake recurrence intervals, where the predicted relative motion on plate boundaries is compared to the inferred seismic slip in major earthquakes and the estimated interval between such earthquakes [e.g. Kanamori, 1977].

The Crustal Dynamics Project provided a natural framework to address this issue, by comparison of the plate motions shown by space geodesy, with a time scale of years, to those predicted by relative motion models. The utility of this comparison depends on the quality of both the space geodetic data and the conventional plate motion model [Gordon and Stein, 1992]. To facilitate the comparison, a new global relative plate motion model, NUVEL-1 (Table 1), was derived from conventional data (spreading rates, transform fault orientations, and earthquake slip vectors) [DeMets et al., 1990]. NUVEL-1 was derived using considerably more data than previous models, and yielded a significantly better fit to the data (Figure 3). The improved fit reflected a variety of factors including a better distribution of data along plate boundaries, determination of all spreading rates over a uniform 3 My interval, and adoption of a plate geometry in which India and Australia were treated as

TABLE 1: NUVEL-1 Euler Vectors (Pacific Plate Fixed)

Plate	Latitude °N	Longitude °E	ω (deg–m.y.$^{-1}$)
Africa	59.160	–73.174	0.9695
Antarctica	64.315	–83.984	0.9093
Arabia	59.658	–33.193	1.1616
Australia	60.080	1.742	1.1236
Caribbean	54.195	–80.802	0.8534
Cocos	36.823	–108.629	2.0890
Eurasia	61.066	–85.819	0.8985
India	60.494	–30.403	1.1539
Nazca	55.578	–90.096	1.4222
North America	48.709	–78.167	0.7829
South America	54.999	–85.752	0.6657

Additional Euler Vectors (Pacific Plate Fixed)

Juan de Fuca	35.0	26.0	0.53
Philippine	1.2	-45.8	1.0
Rivera	31.0	-102.4	2.26

Each named plate moves counterclockwise relative to the Pacific plate. NUVEL-1 Euler vectors are from DeMets et al. [1990]. The 3.0 Ma Juan de Fuca-Pacific Euler vector is from Wilson [1988], the Philippine-Pacific Euler vector is from Seno et al. [1993], and the 3.0 Ma Rivera-Pacific Euler vector is from DeMets and Stein [1990].

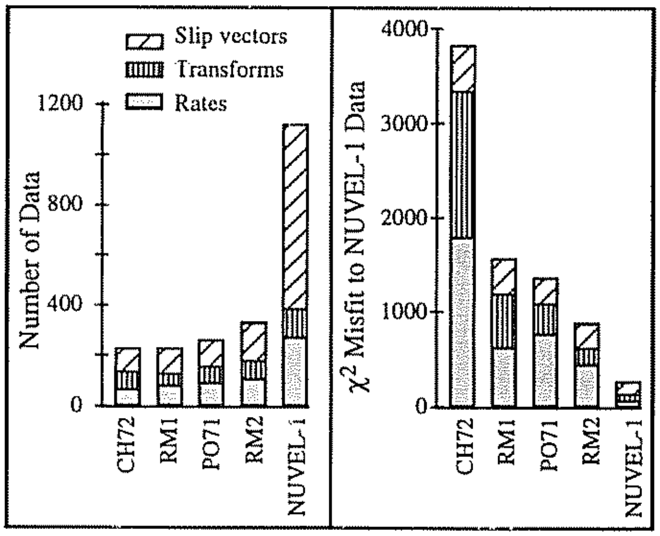

Fig. 3. Comparison of NUVEL-1 to various earlier global plate motion models [DeMets et al., 1990]. Left: Number of data used to derive the models: CH72 [Chase, 1972], RM1 [Minster et al., 1974], P071 [Chase, 1978], RM2 [Minster and Jordan, 1978], and NUVEL-1. Data are of 3 types: slip vector azimuths, transform fault azimuths, and spreading rates. Right: The misfit to NUVEL-1 data for the various models. Each vertical bar showing total misfit is separated into three segments giving the misfit to each type of plate motion data.

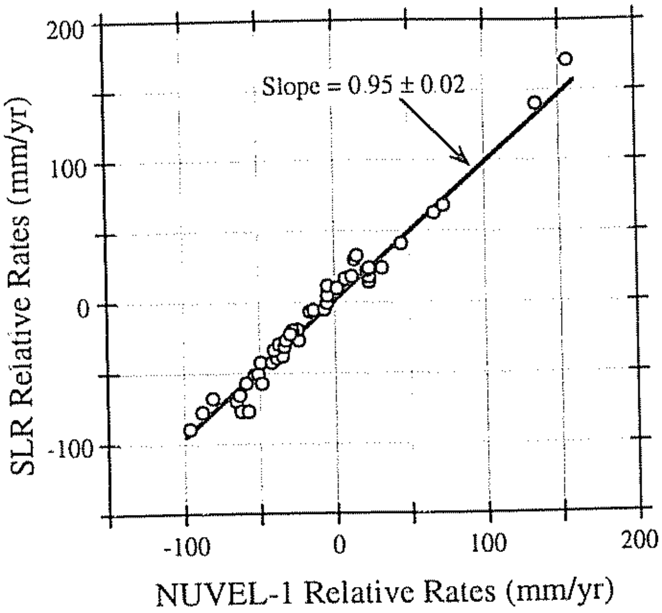

Fig. 4. Comparison of rates determined by satellite laser ranging with those predicted by the NUVEL-1 global plate motion model. The space geodetic rates are determined from SLR tracking sites on five major plates. The sites are located well away from plate boundaries to reduce the effects of deformation associated with such boundaries. The slope of the line is 0.95 ± 0.02, indicating that with some interesting exceptions, the space geodetic observations are in excellent agreement with the NUVEL-1 predictions. [Smith et al., 1990].

separate plates (Figure 1) [Wiens et al., 1985; Gordon et al., 1990].

NUVEL-1 has proved a useful standard against which global [Smith et al., 1990; Ma et al., 1992] and regional [Clark et al., 1987; Ward, 1988, 1990; Feigl et al., 1990; Ma et al., 1990; Caprette et al., 1990; Argus and Gordon, 1990, 1991; Dixon et al., 1991a] space geodetic data can be compared. To date, the agreement between NUVEL-1 and space geodetic data has been excellent, as illustrated by Figure 4.

This agreement is a striking and important result of the Crustal Dynamics Project. It is consistent with the prediction that episodic motion at plate boundaries, as reflected in the occasional large earthquakes, will give rise to steady motion in plate interiors due to damping by the underlying viscous asthenosphere [Elsasser, 1969]. Thus in a few short years, the issue has shifted from whether plate motions on the different time scales are comparable, to what causes the differences in the few cases where the difference is significant.

PLATE BOUNDARY ZONES

Despite the power of the rigid plate model, it has long been recognized that the boundaries between plates are often diffuse, rather than the idealized narrow boundaries assumed in the rigid plate model. The initial evidence for this notion comes from the distribution of seismicity (Figure 5) and the topography, which often imply a broad zone of deformation between the plate interiors. This effect is especially evident in continental interiors, such as the India-Eurasia collision zone in the Himalayas or the Pacific-North America boundary zone in the Western U.S., but can also sometimes be seen in oceanic lithosphere, as in the India-Australia boundary zone in the Central Indian Ocean. Figure 6 shows a comparison between the idealized plate boundaries used in NUVEL-1, and possible diffuse boundaries [Gordon and Stein, 1992]. These zones cover about 15% of Earth's surface.

Space geodesy is providing better characterization of the deformation in plate boundary zones as a function of time and space. The concept that motion is distributed predates plate tectonics, originating from the hypothesis that the 1906 San Francisco earthquake represented episodic slip on the San Andreas Fault due to steady far-field motion [Lawson, 1908]. With the development of plate tectonics, data from seismology, geology, and geodesy have led to the concept that the boundary zone between major plates is characterized by displacement that varies in time and space. How the displacement varies differs between boundary zones.

Figure 7 illustrates this issue schematically, for a strike-slip boundary zone between two major plates. A number of factors categorize the zone. The first is its width: oceanic boundary zones are generally narrow, whereas continental zones are generally wider. The second is how the motion is distributed in space. Possibilities include a single fault system taking up most of the motion [e.g. Thatcher, 1979; Prescott et al., 1981], a smooth distribution of motion [e.g. England and Jackson, 1989], or motion taken up by a few relatively large microplates or blocks [e.g. Beck, 1980; Engeln and Stein, 1984; Engeln et al., 1988; Acton et al., 1991]. Each of these possibilities appears to occur, sometimes within the same boundary zone. For example, in the broad deformation zone between the Pacific and North American plates [Hamilton and Myers, 1966; Atwater, 1970; Minster and Jordan, 1984, 1987; Weldon and Humphreys, 1986], the San Andreas Fault system takes up approximately 75% of the motion [DeMets et al., 1987], the Great Basin appears to be a region of diffuse deformation [Thompson and Burke, 1974], and the Sierra Nevada appears to rotate as a rigid block [Argus and Gordon, 1991].

The distribution of the motion in time is a related and also important issue. Motion on boundary segments such as subduction zone thrust faults or strike slip faults is thought to occur primarily in occasional large earthquakes [e.g. Kanamori, 1977; Sieh, 1981]. These earthquakes are the culmination of the seismic cycle, during most of which the fault is essentially locked and steady motion occurs only at a distance from it. There are also, however, boundaries on which little of the predicted plate motion has been observed in earthquakes, suggesting that either the motion is aseismic [Kanamori, 1977] or the recurrence time is very long. The spatial and temporal distribution of the motion are related, so it is desirable to characterize them jointly. For example, prior to the advent of space geodesy, the difference between the 32-36 mm/yr rate of motion on the San Andreas inferred for the past several thousands of years

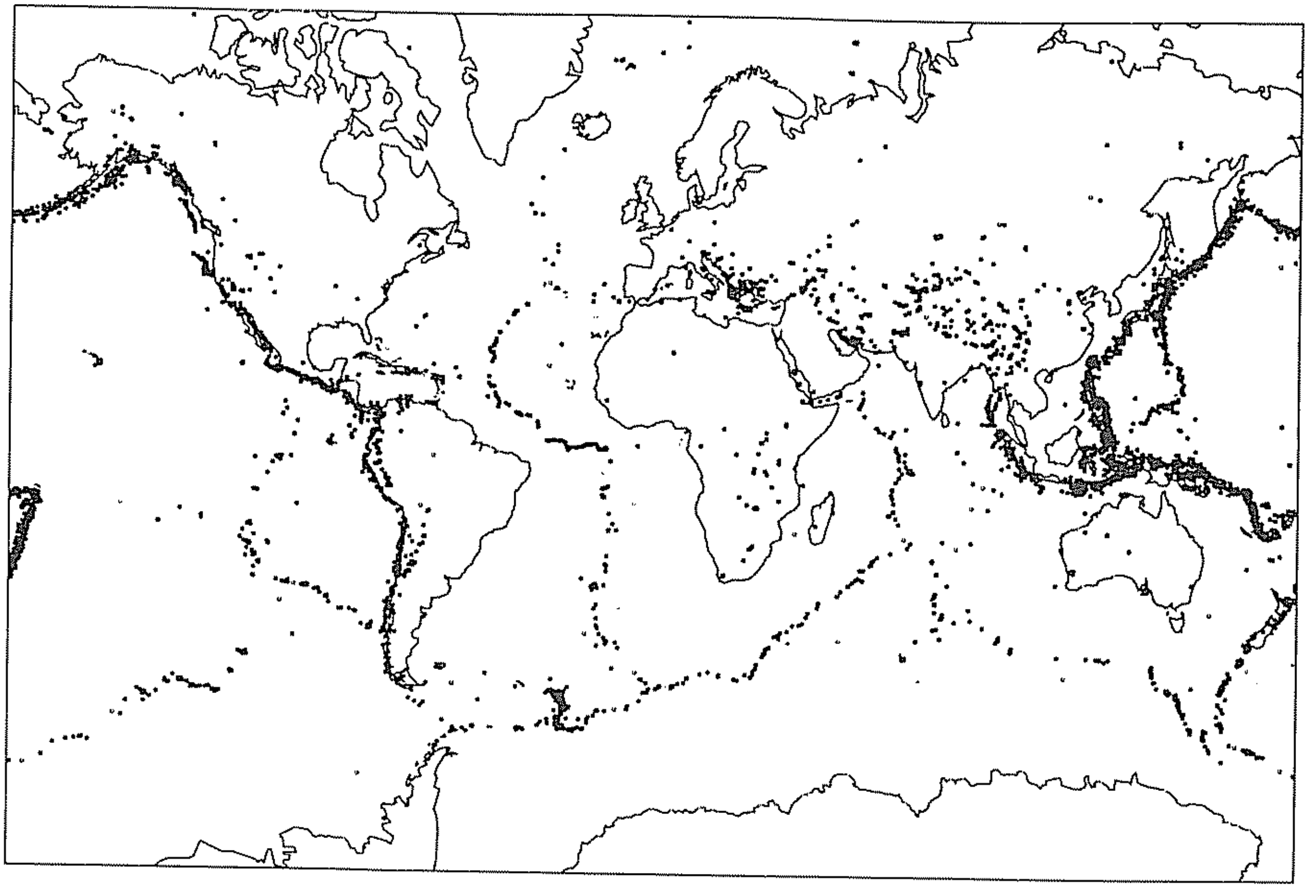

Fig. 5. Epicenter map of earthquakes shallower than 50 km and with magnitudes of at least 5.5 from 1963 to 1987 from the catalog of the National Earthquake Information Center. Bands of earthquakes are narrow along most oceanic plate boundaries and wide along most continental and some oceanic plate boundaries. Figure by Tom Shoberg. [Gordon and Stein, 1992].

[Prescott et al., 1981; Sieh & Jahns, 1984] and the 3-Ma average Pacific - North America plate motion of 48 mm/yr could be interpreted as reflecting either the difference between short and long term rates, or the remainder being accommodated elsewhere in the boundary zone.

Space geodesy greatly facilitates characterization of plate boundary zones. Although the distribution of seismicity and surface faulting illustrate the extent of plate boundary zone deformation, estimation of slip rates from these data is difficult. In contrast, space geodesy can give direct results throughout a boundary zone. The most striking results to date have come for the Pacific-North America boundary zone. A series of studies using VLBI data from the Western U.S. [Clark et al., 1987; Ward, 1988, 1990; Ma et al., 1990; Argus and Gordon, 1990, 1991] show the velocity relative to the stable interior of North America increasing across the boundary zone to the 48 mm/yr predicted by NUVEL-1 (Figure 8). The situation is different further south in the Gulf of California, where the boundary occurs in oceanic lithosphere and appears narrow, based on the distribution of seismicity and the bathymetry. GPS measurements across the presumed narrow boundary zone give opening rates consistent with NUVEL-1 (Figure 9). These observations, together with the observation that a Pacific-North America Euler vector from VLBI data is nearly identical to the Pacific-North America Euler vector of NUVEL-1 [Argus and Gordon, 1990], imply that the long term plate motion from NUVEL-1 adequately describes the net motion across the boundary zone on short time scales. An interesting feature of these studies is that the space geodetic data are inconsistent with the more rapid Pacific-North America relative motion predicted by relative motion models predating NUVEL-1, illustrating that appropriate global models are needed for comparison with space geodetic data.

The details of the deformation in plate boundary zones are thus a major subject of current research. In the western U.S., relatively large scale features can be studied with VLBI [Argus and Gordon, 1991], and smaller scale features are being studied with GPS [e.g. Feigl et al., 1990; Hager et al., 1991; Meertens and Smith, 1991; Hudnut et al., 1991]. The power of space geodesy for this application is demonstrated by the recent observa-

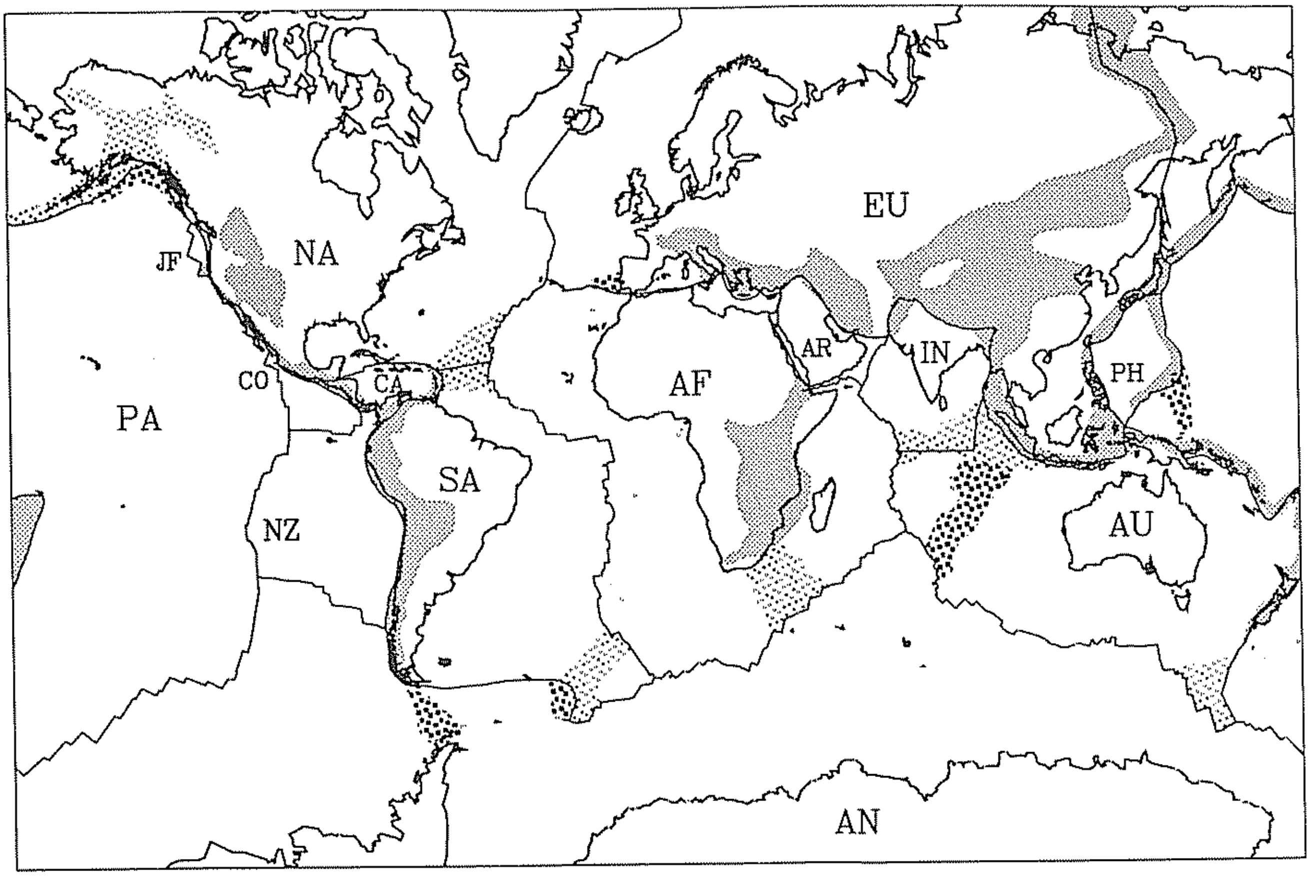

Fig. 6. Map showing idealized narrow plate boundaries and regions of deforming lithosphere. Velocities are shown in Fig. 1. The outlines of deforming regions are approximate and the existence of some deforming zones is speculative. Fine stipple shows mainly subaerial regions where the deformation has 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 mainly from the presence of earthquakes. (Compare with earthquake locations in Fig. 5.) These deforming regions form wide plate boundary zones, which cover about 15% of Earth's surface. Future observations may demonstrate that deforming lithosphere covers an area larger or smaller than shown here. Figure by Tom Shoberg. [Gordon and Stein, 1992].

tions of crustal deformation associated with the 1992 Landers, California, earthquake sequence [Blewitt et al., 1993; Bock et al., 1993].

GPS survey programs are also underway in other complex boundary zones including Caribbean-North America [Dixon et al., 1991b] and Caribbean-South America [Kellogg and Dixon, 1990; Freymueller and Kellogg, 1991]. Data from these surveys should, over the next decade, significantly improve our understanding of plate boundary zone processes. For example, a GPS program has begun in the Afar region at the Nubia-Somalia-Arabia triple junction [Ruegg et al., 1991a], where inland propagation of the Gulf of Aden spreading center has given rise to a deformation zone in which large rotations have been observed paleomagnetically [Courtillot et al., 1984]. The GPS data should show whether the complex tectonics of this area are more usefully modeled in terms of widespread "bookshelf" block faulting [Tapponnier et al., 1990] or the rotation of a few largely rigid blocks [Acton et al., 1991] (Figure 10). Part of this GPS program will also provide data on the opening of the East African rift, which is occurring sufficiently slowly to make its detection difficult with conventional plate motion data [DeMets et al., 1990].

PLATE RIGIDITY

Space geodesy has already demonstrated the validity of the rigid plate hypothesis. As discussed earlier, the excellent agreement between space geodetic results and global plate motion models indicates that global closure, and thus plate rigidity, is a

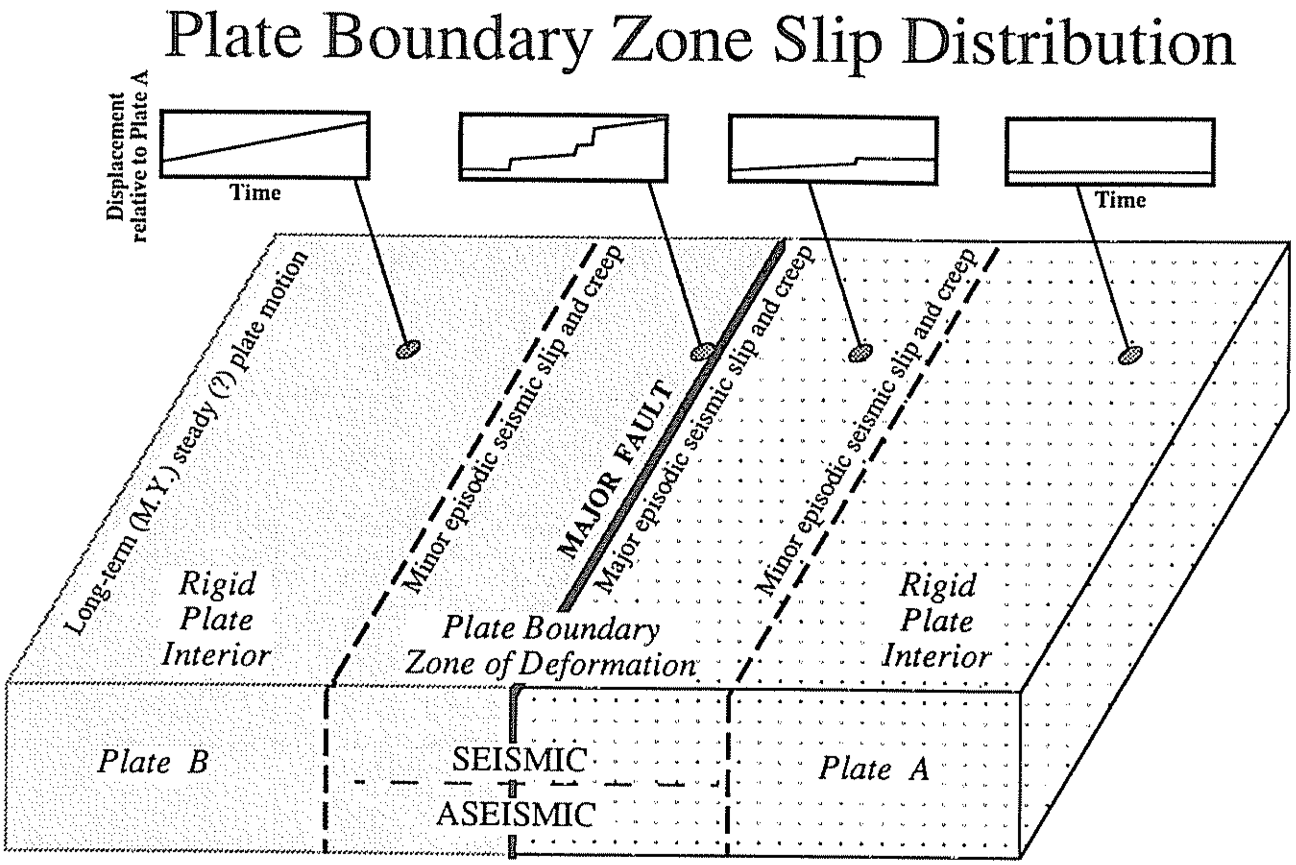

Fig. 7. Schematic illustration of the distribution of motion in space and time for a strike-slip boundary zone between two major plates.

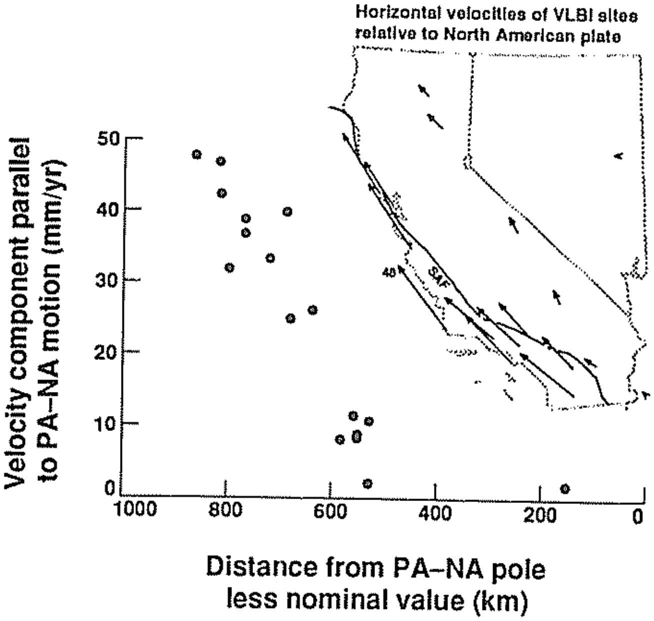

Fig. 8. Variation in motion across the Pacific-North America boundary zone from VLBI data from the Western U.S. Top: Horizontal vector velocities of VLBI sites in California, Nevada, and Arizona relative to stable North America. The velocity of the southwesternmost site nearly equals the predicted 48 mm/yr velocity of the Pacific plate relative to the North American plate. Bottom: Component of motion tangent to small circles centered on the NUVEL-1 Pacific-North America Euler pole (at 49°N, 78°W) versus angular distance from that pole. The velocity of western U.S. crustal blocks in most places increases monotonically with distance southwestward from the Euler pole. Although the figure suggests that the velocities increase smoothly with distance from the Euler pole, there is a large velocity discontinuity due to the approximately 35 mm/yr of time-averaged slip across the San Andreas fault in central California. Much of the remaining motion, approximately 13 mm/yr (the 48 mm/yr Pacific-North America velocity minus the 35 mm/yr San Andreas slip rate), is probably taken up in a shear zone a few tens of kilometers wide in the eastern Mojave desert and along the eastern edge of the southern Sierra Nevada. Figure by D. Argus. [Gordon and Stein, 1992]).

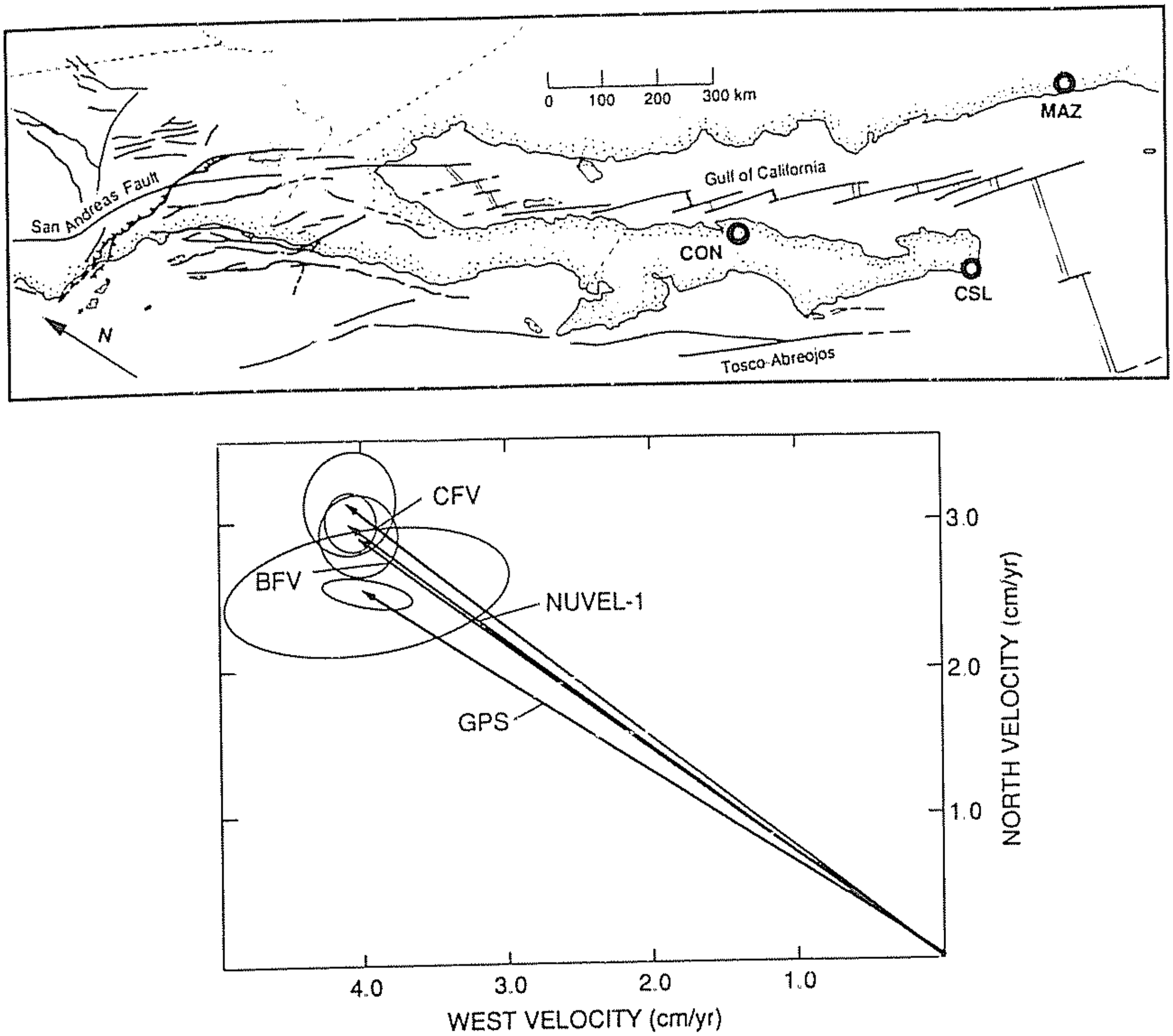

Fig. 9. Top: GPS survey geometry across the Pacific-North America boundary in the Gulf of California, showing sites at Cabo San Lucas (CSL), Mazatlan (MAZ), and Bahia de Conception (CON). Bottom: The motion of CSL with respect to MAZ shows the Gulf of California opening at a rate consistent with NUVEL-1. The NUVEL-1 predictions shown are for the vector derived from all the data (NUVEL-1), the best-fitting vector derived using data only from the Pacific-North America boundary (BFV), and the closure-fitting vector derived using the global data excluding that from the Pacific-North America boundary (CFV). [Dixon et al., 1991].

good assumption. In addition, direct space geodetic measurements within plate interiors show little motion.

Figure 11 illustrates this for VLBI baselines across the U.S. interior. The data show the baseline lengths changing by less than 3 mm/yr, corresponding to a net strain less than 10^{-9} yr^{-1} or 10^{-17} s^{-1}. Thus the plate is rigid to at least this level. These measurements are in reasonable accord with the average strain rate for the eastern U.S. of 10^{-11} yr^{-1} estimated from cumulative earthquake seismic moments (Figure 12) [Anderson, 1986], given that the seismicity presumably only samples a portion of the strain. Moreover, although the baseline length changes are formally significant, the data may not show any actual length change, given the uncertainties and error sources including possible local motion at Fort Davis (T. Herring and T. Clark, pers. com). Note that the Pietown baseline, which crosses the Rio Grande Rift, also shows little change. Other intracontinental baselines show even smaller changes.

An interesting feature of the observations shown is that the baselines cross the New Madrid seismic zone, the primary seismic zone within the essentially stable North American plate interior, where the great 1811-1812 earthquakes occurred [Nuttli, 1973]. Hence for the baselines shown, the strain rate inferred from seismicity should be highest in the New Madrid zone (Figure 12). For a strain rate of 2×10^{-8} yr^{-1}, a 100 km baseline would shorten at 2 mm/yr. Detection of such motion, though challenging, appears feasible. GPS measurements appear capable of measuring a 1000 km baseline to about 1-2 cm or better, as inferred from either comparisons with VLBI or measurement repeatability [Dixon, 1991]. Hence a program (Figure 13) of measurements with 1-2 cm uncertainty in each measurement should determine the rates to an uncertainty of about 2 mm/yr in 10 yr. If, as seems likely, the accuracy of individual measurements improves, the time period required will be reduced accordingly.

GPS measurements have been started in the New Madrid zone. One initial GPS survey has been combined with preexisting triangulation data to estimate shear strain rates. Although the shear strain in northern part of the seismic zone is not statistically different from zero [Snay et al., 1993], significantly higher rates have been identified in the southern portion of the zone [Liu et al., 1992]. Liu et al. [1992] note that these rates are too high to be sustainable over 10^5 - 10^6 My without producing fault offsets that are not observed, and suggest that the strain may be a transient feature. Successive GPS surveys should provide further insight into this intriguing issue, because the baseline changes give both normal and shear strain estimates. For example, the network shown in Figure 14 includes both the portion of the seismic zone in which the high shear strains are observed, and far-field sites that should provide estimates of the regional strain field.

FUTURE PROSPECTS

The success of space geodesy to date indicates that many important tectonic results will be forthcoming in the next decade. A wide variety of programs are either ongoing or planned, under both U.S. and foreign auspices. The results should provide valuable data on many tectonic questions.

Among the many interesting results should be an improved insight into the nature of convergent boundary zones. The motion at these boundaries is less well known than at ridges and transforms, because the rate estimates from global plate motion models are derived from global closure. The intraplate deformation which the closure does not incorporate, in particular backarc extension and along-strike motion, appears to produce

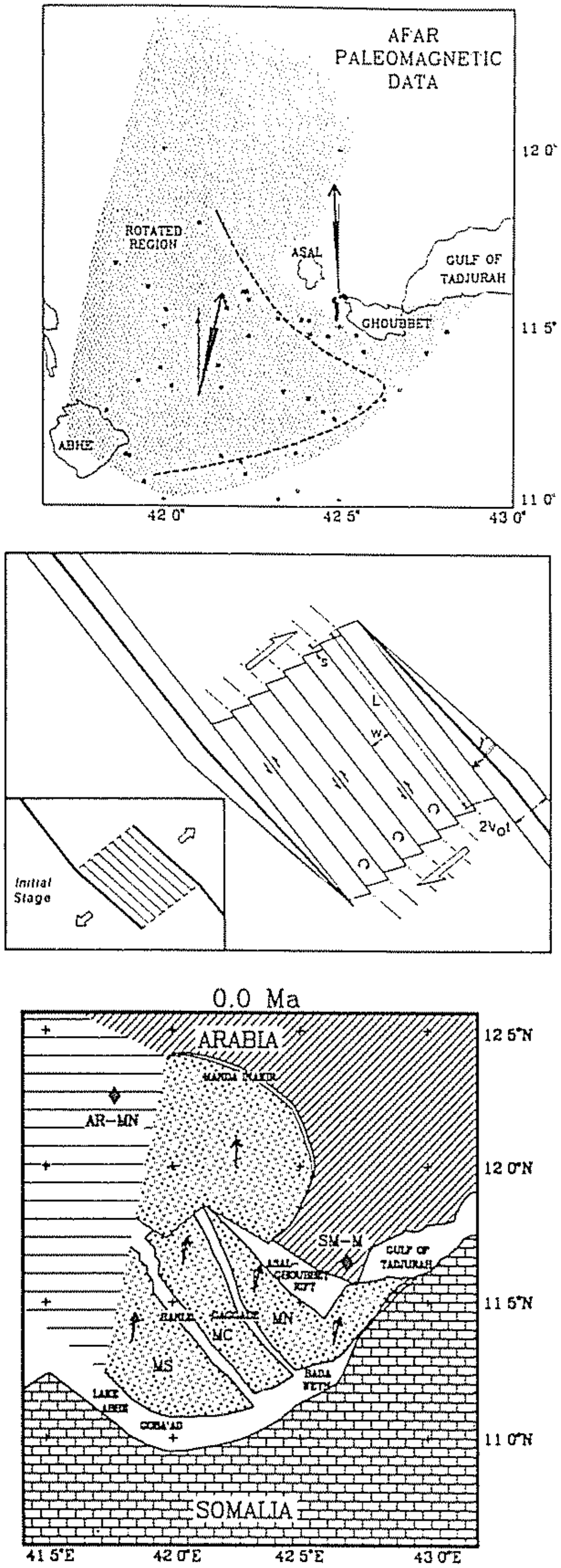

Fig. 10. Data and models for Afar, where inland propagation of the Gulf of Aden spreading center has given rise to a deformation zone. Top: Paleomagnetic data showing that sites within the shaded region have rotated with respect to sites outside it. Arrows denote mean paleomagnetic declinations for rotated and non-rotated areas. [Acton et al., 1991, after Courtillot et al., 1984]. Center: "Bookshelf" block faulting model for the tectonics, in which widespread faulting takes up the motion [Tapponnier et al., 1990]. Bottom: Microplate model for the tectonics of the area, in which motion occurs primarily via rotation of a few largely rigid blocks [Acton et al., 1991].

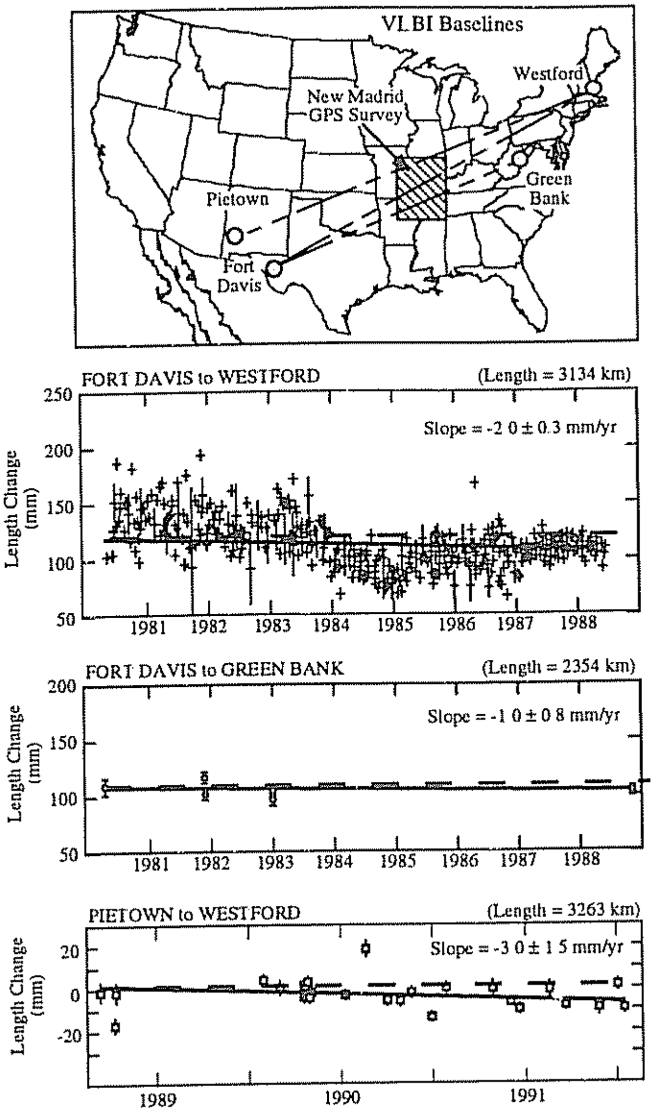

Fig. 11. Top: Selected VLBI baselines across the interior of the North American plate, that cross the New Madrid seismic zone area (box). Lower panels: Baselines from Fort Davis, Texas to Westford, Massachusetts, Fort Davis to Green Bank, West Virginia, and Pietown, New Mexico to Westford. Solid lines show best fit; dashed lines show the zero slope expected for no motion. VLBI data from Caprette et al. [1990] and Ma et al. [1992].

significant biases. Moreover, conventional geodesy, which yields valuable data at continental transform boundaries, is generally of limited use because many convergent boundaries are largely underwater, and those that are subaerial are particularly wide zones.

The possibility that the predictions of motion at subduction zones are biased is suggested by observations that the slip vectors of thrust faulting earthquakes at trenches often have a different trend from the plate motion [Jarrard, 1986; Ekstrom and Engdahl, 1989; DeMets et al., 1990; DeMets and Stein, 1990; McCaffrey, 1991]. Figure 15 illustrates this effect, via comparison of the best-fitting vector or pole derived for each plate boundary to the corresponding closure-fitting vector or pole predicted by data from the rest of the Earth. F-ratio tests for all 22 plate boundaries for which a best-fitting vector or pole could be determined show that the trench boundaries exhibit the most significant non-closures [Gordon et al., 1987]. All 4 best-fitting poles determined only from trench slip vectors (Caribbean-South America, Cocos-Caribbean, Cocos-North America, and Nazca-South America) systematically differ from their closure-fitting vectors. Thus trench slip vectors generally appear to be biased measures of plate motion, suggesting that the overriding plate is experiencing some non-rigid behavior.

The issue of these misfits is a long standing one, first noted for the Aleutian arc (Figure 16). Minster et al. [1974] postulated that a distinct Bering plate moved independently of the North American plate, and Engdahl et al. [1977] suggested that the focal mechanisms may be biased by seismic velocity heterogeneities due to the cold subducting slab. Subsequently, due to the availability of significantly larger focal mechanism data sets

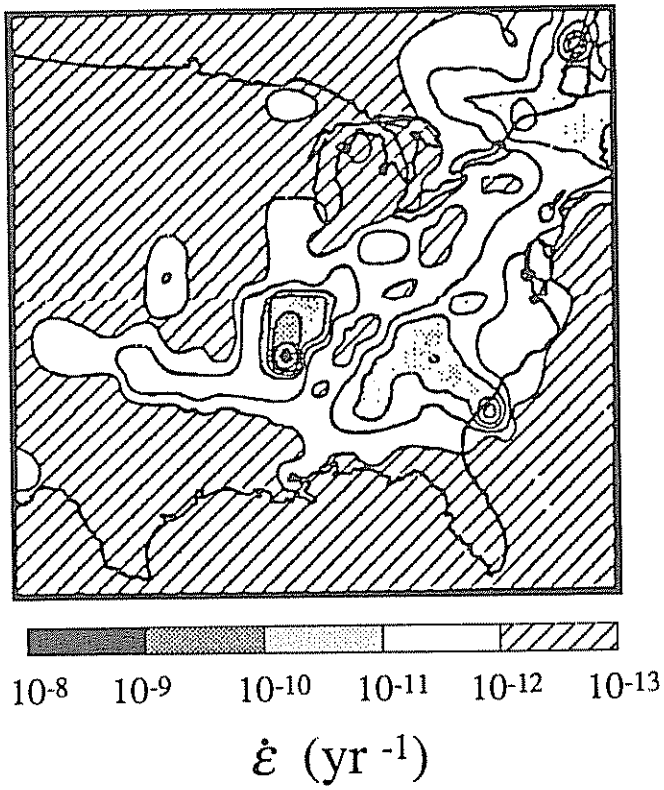

Fig. 12. Distribution of intraplate strain rates for the central U.S. inferred from cumulative earthquake seismic moment release [Anderson, 1986]. Note the relatively high (though low compared with plate boundaries) rates for the New Madrid zone.

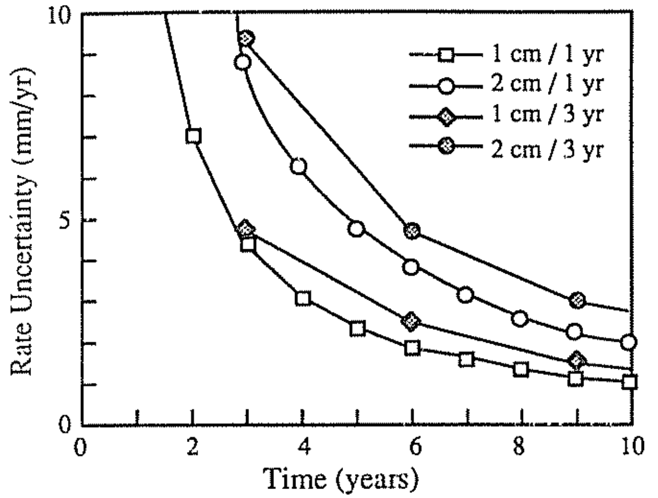

Fig. 13. Expected uncertainty (one standard deviation) in the estimate of the rate of motion between sites as a function of the total time span of observations and the accuracy of the site positions. The curves shown are for measurement uncertainties of 1 and 2 cm and observation intervals of 1 and 3 yrs. 3 mm/yr uncertainty is achievable for all cases after 10 years. (Figure by T. H. Dixon)

[Ekstrom and Engdahl, 1989] and marine geophysical data [Geist et al., 1988] for the Aleutians, and the recognition that such misfits are common at arcs, it is now thought that this discrepancy indicates deformation behind the arc. Support for this view is provided by the fact that a Pacific-North America Euler vector derived from VLBI data alone is essentially the same as that for NUVEL-1, and hence predicts quite similar motion at the Aleutian arc (Figure 16, bottom) [Argus and Gordon, 1990]. This similarity, especially when combined with the Gulf of California GPS survey results (Figure 9) suggests that NUVEL-1 correctly describes the motion between the interior of the Pacific and North American plates, whereas the slip vectors reflect motion of blocks within the arc relative to the Pacific. Deformation within overriding plates is also indicated by the focal mechanisms of intraplate earthquakes within and behind arcs [e.g. Stein et al., 1982; Ekstrom and Engdahl, 1989].

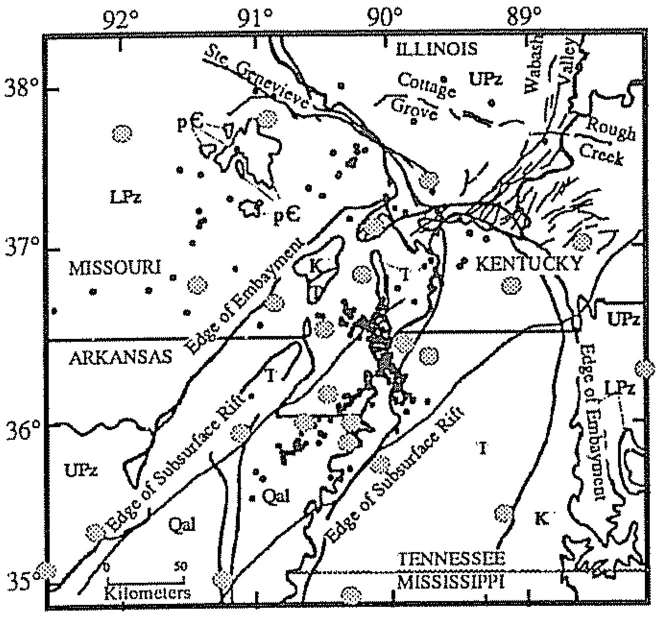

Fig. 14. Geometry of a GPS network (large dots) being used to study the New Madrid seismic zone. Also shown are inferred faults, earthquake epicenters (small dots) and major structural boundaries. Figure by John Weber, geology after McKeown and Pakiser [1982].

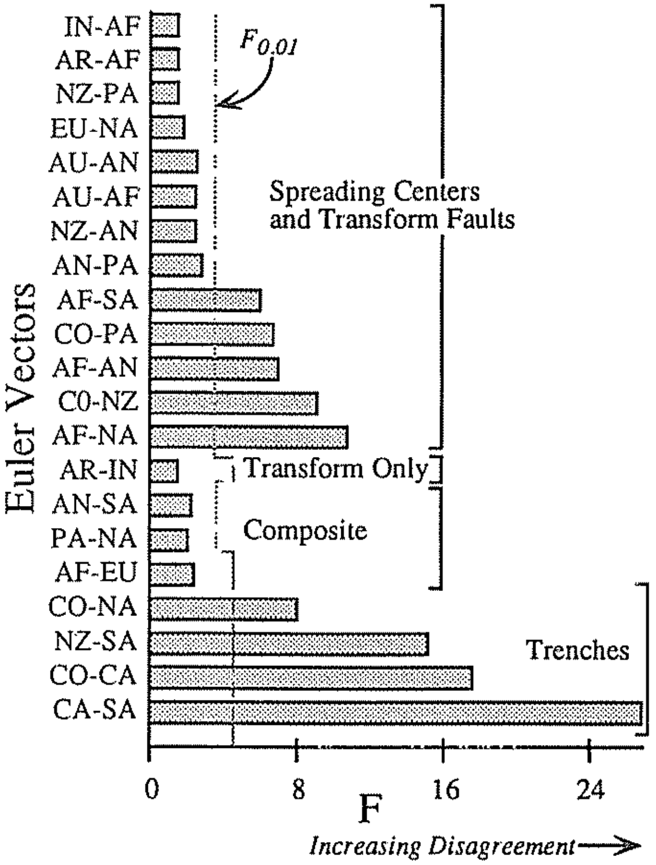

Fig. 15. Test for global plate circuit closure for pairs of best- and closure-fitting vectors determined for each plate pair for which both can be determined. Horizontal bars extending to the right of the curve labeled $F_{.01}$ indicate non-closure significant at the 1% risk (99% confidence) level for the F-ratio test, and hence significant differences between the best- and closure-fitting vectors. All 4 best-fitting poles determined only from trench slip vectors systematically differ from their closure-fitting vectors, suggesting that not all of the motion occurs at the trench plate boundary [DeMets et al., 1990].

Space geodetic data is becoming available to address these issues. Three sets of GPS observations have been completed across the Tonga Trench and the results show a convergence

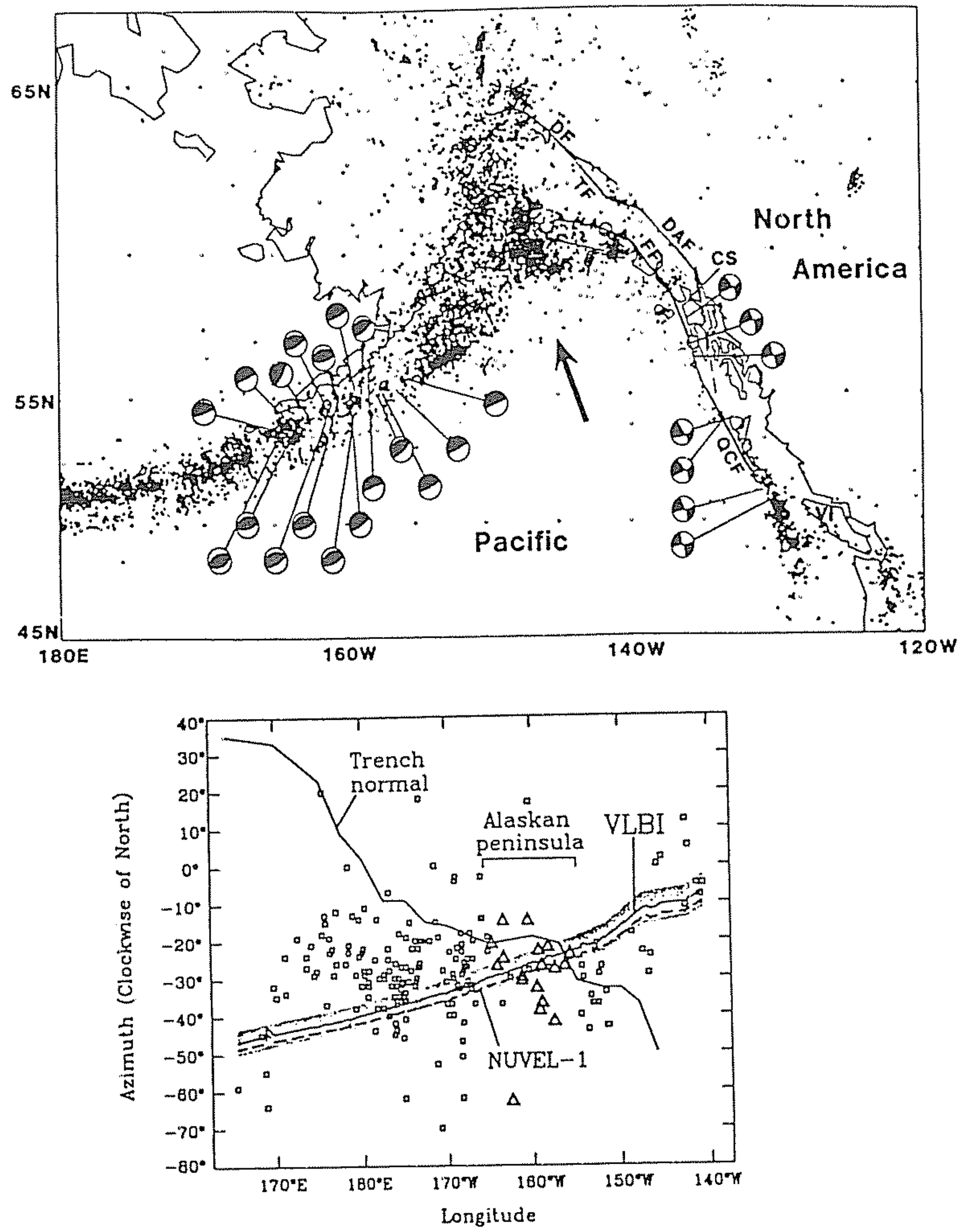

Fig. 16. Top: Focal mechanisms of shallow earthquakes along the Aleutian-Alaska portion of the Pacific-North America plate boundary. Black dots show epicenters of earthquakes from 1963 to 1985 with depths shallower than 50 km. The convergence direction predicted by NUVEL-1 is shown by the arrow. [DeMets et al., 1990]. Bottom: In the Aleutians (west of 160°W) the slip vectors trend counterclockwise from the Pacific-North America motion predicted by NUVEL-1 or VLBI. They are rotated toward the trench-normal, suggesting motion behind the trench. [Argus and Gordon, 1990].

rate in excess of the predicted Pacific-Australia motion, yielding an estimate of the backarc opening across the Lau Basin [Bevis et al., 1991]. Studies have also begun across continental convergent zones including the Himalayas [Jackson et al., 1991], the Caucasus [Reilinger et al., 1991] and the Andes [Ruegg et al., 1991b].

Each of these zones has a variety of tectonic features of special interest. For example, the Nazca-South America boundary illustrates a basic process in continental evolution, convergence between an oceanic plate and a continental plate, giving rise to a continental arc. Present estimates of the convergence rate are discordant [Stein et al., 1986]. NUVEL-1 predicts 82-84 ± 2 mm/yr, whereas the seismic slip history from large earthquakes [Plafker, 1972; Kelleher, 1972; Kanamori and Cipar, 1974; Cifuentes, 1989] has been interpreted as yielding a higher 187 ± 71 mm/yr convergence rate [Kanamori, 1977]. On the other hand, satellite laser ranging measurements [Smith et al., 1989; 1990] show the geodesic (great circle arc along the earth's surface) between Easter Island on the Nazca plate and Arequipa (Peru) shortening at 65 ± 3 mm/yr (Figure 17, top), significantly less than the 76 ± 2 mm/yr shortening predicted by NUVEL-1. If all the shortening occurred at the trench, the SLR results would imply convergence at about 70 mm/yr, a rate only 85% that predicted by NUVEL-1. As in other cases, the discrepancy may represent the differences between long and short term plate motion, local site effects, or intraplate deformation. The first seems least likely, given the size of the discrepancy compared to the typical good fit of NUVEL-1 to space geodetic data (Figure 4). The most interesting possibility is that the discrepancy reflects convergence across the Andes, at a rate in approximate accord with previous geological estimates [Jordan et al., 1983; Isacks, 1988]. In this interpretation, Arequipa, which lies in the western Andes, is moving at 13 mm/yr toward N76°E relative to the stable interior of South America [Gordon and Stein, 1992]. A few years of GPS data should adequately test this idea and yield good estimates of the shortening rate. An equally interesting parameter would be the uplift rate: fission track dating from Bolivia indicates that the uplift rate of the Andes increased significantly 10-15 Ma, may have been as high as 0.7 mm/yr by 3 Ma, and may be even higher at present (Figure 17, bottom) [Crough, 1983; Benjamin et al., 1987]. Detection of the uplift rate will require a much longer period of measurements than for the shortening, given the smaller signal and the lower accuracy of vertical measurements relative to horizontal ones [Dixon, 1991].

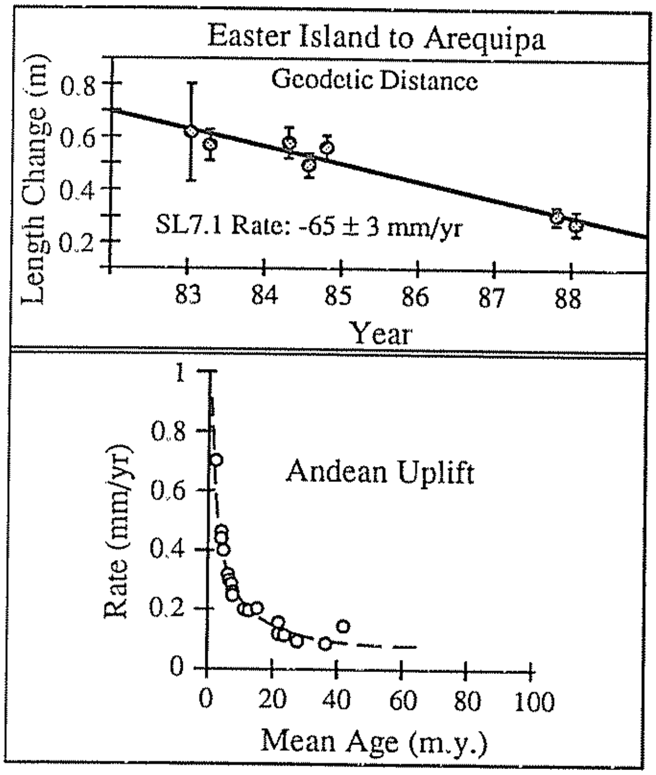

Fig. 17. Top: Geodesic length between Easter Island and Arequipa, Peru as a function of time, measured by satellite laser ranging [Smith et al., 1989]. The observed shortening is 85% of that predicted by NUVEL-1, possibly indicating that the remaining motion is taken up inland of Arequipa by Andean shortening. Bottom: Andean uplift rates as a function of time derived from fission-track dating, showing increase in uplift rates in past 40 Ma [Benjamin et al., 1987].

Space geodesy should thus provide valuable information on the continental convergence process, which is not obtainable by other techniques. For example, the Nazca-South America data should show whether the dramatic variations in the subduction geometry, which correlate with variations in the tectonics of the Andes [e.g. Sacks, 1977; Hasegawa and Sacks, 1981; Henry and Pollack, 1988], are reflected in the shortening and uplift rates. These data, and those from the other continental convergence zones, will be useful for testing and refining models of continental deformation [e.g. England and McKenzie, 1982; Molnar, 1988; Bird, 1989; England and Jackson, 1989; Wdowinski et al., 1989].

Another important application of space geodesy should be in characterizing diffuse boundary zones in the oceanic lithosphere. Although sea floor positioning equipment which makes use of GPS is under development [Young et al., 1990], it will be some time before routine measurements are made in remote areas. It thus seems likely that the first space geodetic results for oceanic boundary zones will come from observations of baselines between continents. Even such large scale data, however, has the prospects of constraining present day motion across boundary zones such as between India and Australia and North and South America (Figure 6).

DISCUSSION

The examples discussed here give a flavor for how space geodetic data are improving, and will continue to improve, knowledge of the kinematics of the lithosphere. In turn, these results will extend our understanding of the dynamics of the lithosphere. This use of kinematics to investigate the dynamics will be an extension of what has been done to date. To date, global plate motion models have made several key contributions. They support the rigid plate hypothesis and constrain its limits of applicability, permit analysis of net boundary zone motion, including rates at those which cannot be derived directly (e.g. subduction and continental transform), and hence constrain models of the boundary zone dynamics. Moreover, the inferred relative motions allow absolute motion determination, and hence constrain hot spot, driving force, and mantle flow models.

In years to come, space geodetic data will extend these applications in several ways. They will provide descriptions of plate boundary zone deformation, ideally including vertical motion, sufficiently detailed to constrain their thermal and mechanical structure (including mantle viscosity) and dynamics. They will shed light on boundary evolution via detailed results for boundaries in various evolutionary stages, such as the Gulf of California-Baja-Imperial Valley and East African Rift-Afar-Red Sea systems. They will improve understanding on time and space-dependent processes in boundary zones, such as spreading pulses and the seismic cycle. We can also expect improved understanding of how intraplate deformation is localized, and hence of strains and rheology within and below plate interiors. In summary, it appears that the next decade will be a fruitful and busy one both for those making measurements with space geodesy, and those using the results in combination with other data to investigate tectonic processes.

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S. Stein, Department of Geological Sciences, Northwestern University, Evanston, IL 60208.