Present-day pattern of Cordilleran deformation in the western United States

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ABSTRACT

We present the first detailed geodetic image of the entire western United States south of lat 42°N, merging both campaign and continuous Global Positioning System (GPS) and very long baseline interferometry (VLBI) data sets in a combined solution for station velocities having a single, uniform reference frame. The results are consistent with a number of features previously observed through local geodetic studies and very sparse space geodetic studies, including a dominant pattern of right-lateral shear associated with the San Andreas fault, rates of the westernmost sites (along the California coast) of 46–48 mm/yr relative to a North America reference frame, and some 11–13 mm/yr of deformation accommodated east of the Sierra Nevada in the Basin and Range province north of lat 36°N. South of 36°N, the solution also shows that the southernmost San Andreas fault system accommodates effectively all interplate motion and that the southern Basin and Range is not deforming significantly. At lat 37°N, the eastern California shear zone appears to exhibit simple shear oriented between ~N20°W and ~N40°W relative to North America, with a fairly well defined transition zone from localized shear to diffuse spreading in the Basin and Range. Enigmatically, this transition involves a significant component of contraction normal to the overall shear-zone trend; sites in the Great Basin move southwestward at up to ~5 mm/yr toward sites within the eastern California shear zone. To the north, in contrast, there appears to be a relatively smooth transition from east-west spreading within the eastern Great Basin to northwest-southeast shear across the westernmost Basin and Range.

INTRODUCTION

Practical limitations on the scope of geodetic networks have resulted in either densely sampled local studies, with no means to tie the detailed observations to other densely sampled areas, or very sparse networks with just a few stations covering very large areas. Conventional (i.e., ground-based) networks are limited to apertures of 50–100 km, with no possibility to create network solutions in a common reference frame at larger scale. Even in the case of dense Global Positioning System (GPS) sampling, it has not been feasible until quite recently to attempt merging disparate data sets, collected at different times in different areas, into a single large-scale solution.

This limitation has been a major obstacle in understanding active tectonic processes in diffusely deforming continental crust; such processes are of great scientific and societal interest. For example, in the western United States (Fig. 1), it has long been known that deformation of the northern Basin and Range province, as indicated by patterns of seismicity and Holocene faulting, amounts to ~20%–25% of the rate of relative motion between the Pacific and North America plates. Thus far, however, there have been only tantalizing glimpses of the large-scale pattern from very sparse, space-based networks (e.g., Dixon et al., 1995).

METHOD

We used data from the GPS and very long baseline interferometry (VLBI) geodetic networks listed in Table 1. We chose to work with these particular geodetic networks because (1) as space geodetic networks, they provide vector measurements with respect to an external reference frame, (2) data products necessary to estimate precise velocities for these networks were readily available, and (3) these networks provide fairly uniform coverage of the western United States. We did not include all of the sites from the particularly dense networks in southern California (e.g., Shen et al., 1997).

Our data analyses followed a three-step distributed processing procedure (e.g., Blewitt et al., 1993). The first step involved reduction of the raw GPS phase data and VLBI group delays and was largely performed by others (Table 1). The basic products of this first step are, for each network, sets of one-day site-position estimates, Earth orientation parameters, and error covariance matrices.

In the second step, we used these parameter estimate sets to estimate a single self-consistent set of site velocities. We used the GLOBK analysis software (Herring, 1998) to determine these velocity estimates, accounting for the fact that the reference frames implicit to the parameter estimate sets used as input depend in a complicated way on numerous factors, including the locations of the particular stations in each set. The product of this analysis was a set of velocity estimates for 423 globally distributed GPS and VLBI stations, including more than 150 stations in the western United States with uncertainties less than or equal to ~1 mm/yr (1 σ).

We excluded from our solution all site-position data whose evolution was obviously not well described by a constant velocity, except that we allowed for discrete offsets due to earthquakes, antenna changes, etc. We made no attempt to tie the positions of collocated stations. Instead, the velocity estimates of stations located within 1 km of one another were constrained to be equal, effectively tying the velocities of GPS and VLBI antennas located at the same site. Consequently, some velocities reflect data from more than one station, possibly from both VLBI and GPS. In what follows, we make no distinction between velocities derived from VLBI, GPS, or combined VLBI and GPS data.

In the third step, we rotated the velocity field from the global geodetic reference frame used for the data combination into a "North America–fixed" reference frame. As perfectly rigid materials are an idealization, so too is the concept of rigid plates as postulated in the theory of plate tec-

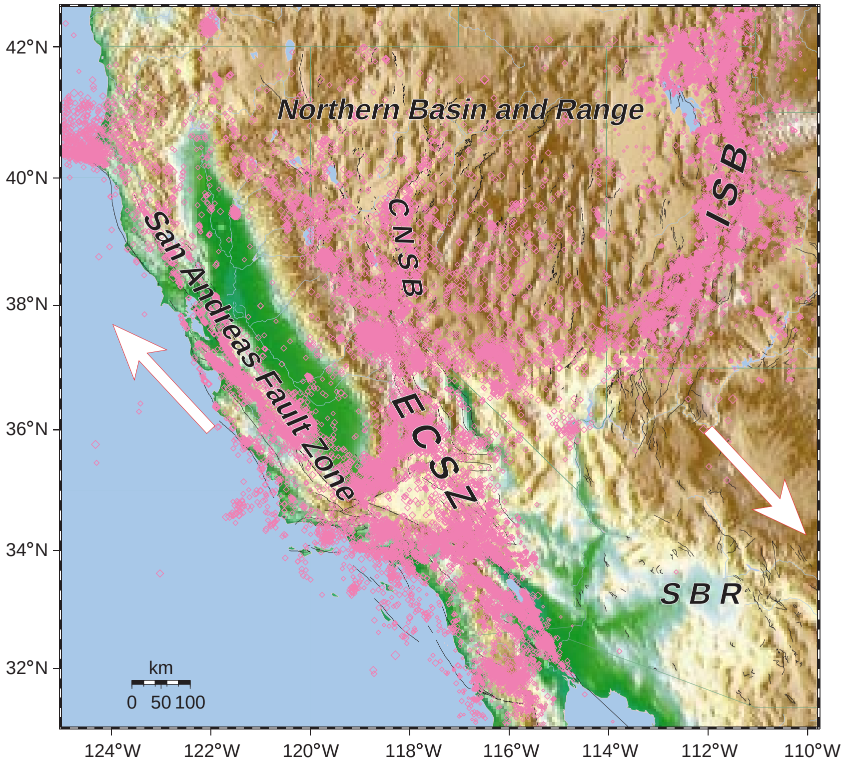

Figure 1. Pacific–North America plate boundary and major tectonic features of western United States. Magenta diamonds show seismicity from catalogues of California Institute of Technology, Centro de Investigación Científica y de Educación Superior de Ensenada (Mexico), University of Utah, and University of Nevada. ISB—Intermountain seismic belt, CNSB—central Nevada seismic belt, ECSZ—eastern California shear zone, SBR—southern Basin and Range. Northern Basin and Range province stands ~1 km above sea level (dark brown) in contrast to low-lying southern Basin and Range province (green and yellow).

tonics. Nonrigid behavior is particularly evident near the boundaries of continental plates, as in the western United States. However, a recent study of the rigid-plate hypothesis using data from the VLBI network (Argus and Gordon, 1996), found that, at a limit of about 2 mm/yr (95% confidence), the interiors of at least seven plates, including North America east of the Colorado Plateau, do appear stable. Of the three VLBI sites in North America within the Colorado Plateau, two have marginally significant motions with respect to this stable North America interior. An important question therefore remains as to whether a distinct boundary exists between the geophysically stable, undeforming part of North America and the area of deformation in the western United States, and, if so, where the boundary lies.

We realized a North America–fixed reference frame by estimating and subtracting from the velocity field that rigid rotation which minimized the velocities of 50 sites assumed to define a stable North America interior, including sites on the Colorado Plateau. The resulting horizontal components of the North America–fixed velocities for sites in the western United States are shown in Figure 2.

The uncertainties presented in Figure 2 are based on the least-squares propagation of scaled observation errors and are intended to represent the statistical uncertainty due to errors in the space geodetic measurements. They do not reflect potential deficiencies in the constant-velocity model that we adopted to estimate site velocities. An important advantage of our method, as we demonstrate below, is that the overall pattern of crustal deformation is readily apparent despite the potential for such site-dependent biases (i.e., biases that are uncorrelated between sites). Statistical analysis of the postfit residual velocities for the horizontal components of the 50 sites used to determine the North America reference frame indicate that our velocity field is consistent with the notion of a stable North America plate at a level comparable to that found by Argus and Gordon (1996), i.e., about 2 mm/yr.

RESULTS AND DISCUSSION

Our aggregate velocity solution (Fig. 2) represents the first synthesis of independent geodetic networks throughout the entire Cordilleran deformation zone in the United States south of lat 42°N and, as such, provides the most coherent image of ongoing crustal deformation in this region to date. Consequently, our velocity field bears on a large number of tectonic problems over a variety of scales. We concentrate on only a few of the more general features in Figure 2. We anticipate that

TABLE 1. SPACE GEODETIC NETWORKS USED TO ESTIMATE VELOCITY FIELD

Network name*	General location	Data type†	Time span§	Analysis group#	Sample reference
BARD	Northern California	CGPS	1996.6–1998.3	SOPAC	King et al. (1995)
CORS	United States	CGPS	1996.6–1998.3	SOPAC	Strange (1994)
IGS	Global	CGPS	1996.6–1998.3	SOPAC	Beutler et al. (1994)
NBAR	Northern Basin & Range	CGPS	1996.6–1998.3	SAO	Bennett et al. (1998)
SCIGN	Southern California	CGPS	1996.6–1998.3	SOPAC	Bock et al. (1997)
STRC**	Southern California	FGPS	1988.1–1997.2	MIT	Bennett et al. (1996)
VLBI	Global	VLBI	1979.7–1998.4	GSFC	Ma and Ryan (1997)
YUCC	Eastern California shear zone	FGPS	1991.8–1997.9	SAO	Bennett et al. (1997)

*BARD—Bay Area Regional Deformation, CORS—NOAA's Continuously Operating References System, IGS—International GPS Service for Geodynamics, NBAR—Northern Basin and Range, SCIGN—Southern California Integrated GPS Network, STRC—Salton Trough–Riverside County, YUCC—Yucca Mountain–Death Valley.

†CGPS—Continuous GPS; FGPS—field (campaign) GPS.

§Of data that were included in our solution; does not necessarily reflect the total time span of data available.

#Organization that performed the first step of the analyses (see text). SOPAC—Scripps Orbit and Permanent Array Center, SAO—Smithsonian Astrophysical Observatory, MIT—Massachusetts Institute of Technology; GSFC—Goddard Space Flight Center. All GPS data were analyzed with GAMIT software (King and Bock, 1998). VLBI data were analyzed with CALC/SOLVE software (Ma and Ryan, 1997).

**STRC data are also part of the SCEC data set (e.g., Shen et al., 1997).

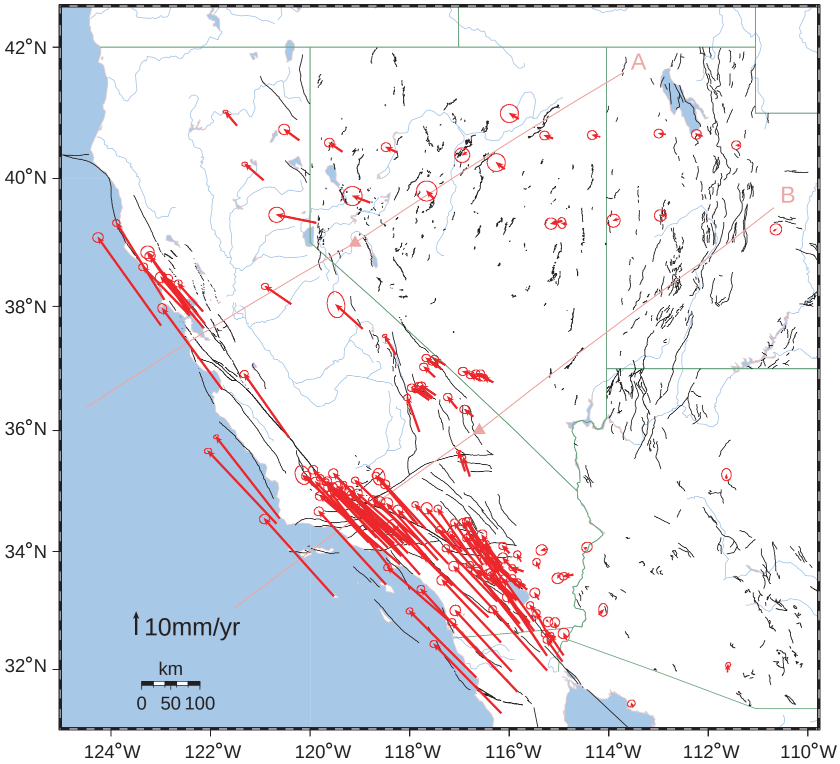

Figure 2. Estimates of horizontal velocities relative to stable North America for sites in western United States (arrows). Error ellipses represent 95% confidence level. Thin black lines represent mapped Quaternary faults. Pink lines show locations of profiles A and B in Figure 3 which are perpendicular to direction of NUVEL-1A Pacific–North America relative plate motion. Triangles show locations of points in profiles (zero) lying on common small circle to NUVEL-1A pole.

these velocities will be used in many, more detailed, future studies by ourselves and others.

Interpretation of geodetic velocity estimates in terms of geologic processes is complicated by the disparate time scales represented. Our GPS velocity estimates reflect the present-day pattern of deformation. It is difficult to assess the extent to which they represent the long-term average deformation. Our velocity estimates could be biased by postseismic deformation associated with large earthquakes, as is almost always the case in seismically active regions. Despite the potential for these temporal complexities, recent studies demonstrate a general consistency among the pattern of seismic strain release, the pattern of Quaternary faulting, and contemporary deformations estimated from geodetic observations (e.g., Shen-Tu et al., 1998; Ward, 1998).

From Figure 2, we see that there is little motion of the stations in southeastern California, Arizona, southern Nevada, and central Utah. These eastern sites typically have velocities of 1–2 mm/yr or less, and most are not significant at the 95% confidence level. At the level of resolution of our data (~2 mm/yr), therefore, this region appears to form part of stable North America. The largest rates relative to stable North America that we observe are 46–48 mm/yr, occurring, as expected, along the California coast. The steepest gradients in the velocity field are associated with the San Andreas fault system, which is clearly dominated by right-lateral shear. The orientations of most of the velocity estimates in California are ~N40°W, approximately parallel to the plate boundary in this area. Given the uncertainties in (1) the expected plate rates, based on modern geodetic studies (Larson et al., 1997), (2) plate-tectonic constraints from the past 3 m.y. (DeMets, 1995), and (3) the observed site motions, it appears that essentially all of the plate-boundary deformation south of lat 36°N is accommodated within about 100–200 km of the San Andreas fault.

To the north of lat 36°N, where the Intermountain seismic belt trends eastward and then northward away from the San Andreas fault zone and eastern California shear zone (Fig. 1), contemporary deformation extends as much as 1000 km east of the San Andreas (e.g., Dixon et al., 1995; Martinez et al., 1998). Extensional strain appears to accumulate fairly evenly across the northern Basin and Range province, in agreement with the pattern of Quaternary faulting, but in contrast to the strongly localized pattern of seismicity (Bennett et al., 1998) (Fig. 1). The transition from this extensional regime to the relatively undeforming eastern regime is at present not well resolved by our aggregate velocity field owing to uncertainties in rates in western Utah as compared with the velocity residuals within the North American plate. However, the first seven sites west of the Intermountain seismic belt consistently show westward motion either near or slightly greater than their 95 % confidence ellipses, supporting the hypothesis that the Intermountain seismic belt marks the western boundary of present-day stable North America. Our results are consistent with the rate estimate of Martinez et al. (1998) of 3 ± 1 mm/yr, east-west, across the Intermountain seismic belt. We further note that the velocity field across the northern Basin and Range contrasts sharply with what appears to be little or no deformation in the relatively low-lying southern Basin and Range, consistent with the hypothesis that significant buoyancy forces in the northern Basin and Range are largely responsible for the contrast (Jones et al., 1996).

East of the central Nevada seismic belt, the deformation field appears to be predominantly east-west extension, and west of the belt, there is a significant component of right-lateral shear (Bennett et al., 1998). A similar transition in the

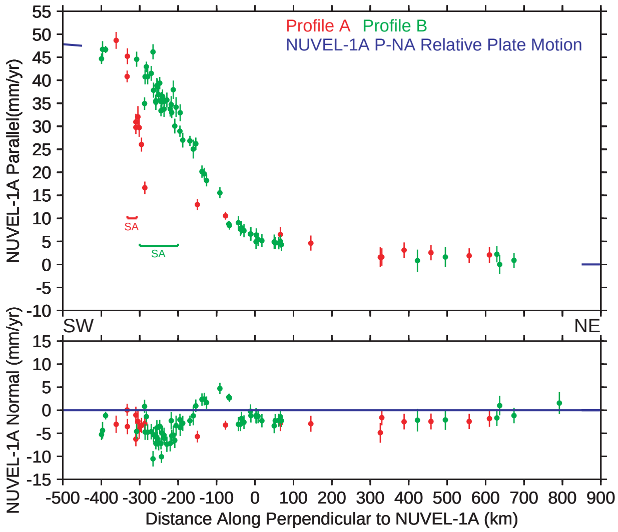

Figure 3. Velocities of sites within 200 km of profiles shown in Figure 2 projected onto directions parallel and perpendicular to direction of NUVEL-1A Pacific–North America relative plate motion. Blue lines show NUVEL-1A estimates of Pacific–North America rates. SA indicate locations of San Andreas fault zone within each profile.

style of deformation appears to occur to the south near the junction of the Intermountain seismic belt and the eastern California shear zone, where north-northwest–trending right-lateral shear in the Death Valley region gives way eastward to west-northwest extension in southern Nevada (Bennett et al., 1997; Wernicke et al., 1998). On the basis of these previous studies and Figure 2, we hypothesize a regional transition from extension in the east, through a combined, northward-widening zone of extension and right-lateral shear, to predominantly right-lateral shear in the west. Such a transition is consistent with regional patterns in the state of stress, which indicate east-west extension across the Intermountain seismic belt and with combined west-northwest–east-southeast extension and north-northwest–south-southeast shear across the western Basin and Range (Zoback, 1989).

Although few stations constrain the motion of the Sierra Nevada block, our velocity field appears to support the notion of significant counterclockwise rotation of the Sierra Nevada block with implications for compression to the west in California (e.g., Argus and Gordon, 1991). Kinematic modeling of active faults in the southwestern Great Basin, however, suggests that large counterclockwise rotation of the Sierra Nevada is at odds with the large geologically determined left-lateral slip-rate estimates of 4–7 mm/yr for the Garlock fault (Hearn and Humphreys, 1998). Further study will be necessary to resolve these issues.

We observe a significant component (5 mm/yr) of convergence between sites in the central Great Basin and the eastern California shear zone (Fig. 3), consistent with, though slightly larger than, those inferred in the kinematic modeling study of Hearn and Humphreys (1998). This convergence implies significant net crustal shortening between the central Great Basin and the eastern California shear zone, oriented at a high angle to the plate boundary. The orientation of this shortening is in reasonable accord with the late Cenozoic history of the Death Valley region, which contains numerous northwest-trending folds and other indicators of northeast-southwest contraction (e.g., Wernicke et al., 1988; Mancktelow and Pavlis, 1994). This apparent shortening may be indicative of “competition” between northwest-southeast plate-boundary shear and eastward buoyancy-driven collapse in the vicinity of lat 37°N, but further study is necessary to address the tectonic implications.

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