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LARGE SCALE DEFORMATION OF THE WESTERN U.S. CORDILLERA

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INTRODUCTION

Destructive earthquakes occur throughout the western U.S. Cordillera (WUSC), not just within the San Andreas fault zone. But because we do not understand the present-day large-scale deformations of the crust throughout the WUSC, our ability to assess the potential for seismic hazards in this region remains severely limited. To address this problem, we are using a large collection of Global Positioning System (GPS) networks which spans the WUSC to precisely quantify present-day large-scale crustal deformations in a single uniform reference frame. Our work can roughly be divided into an analysis of the GPS observations to infer the deformation field across and within the entire plate boundary zone and an investigation of the implications of this deformation field regarding plate boundary dynamics.

INVESTIGATIONS

We have used data from continuous and campaign GPS, very long baseline interferometry (VLBI), satellite laser ranging (SLR), and DORIS geodetic networks (see http://cfa-www.harvard.edu/space_geodesy/WUSC/) throughout the WUSC and the world. 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.

Estimation of a uniform set of station velocities from a vast amount of space geodetic data from different techniques requires methods for (1) reducing an enormous number of raw geodetic observations to geodetic parameter estimates such as site positions and velocities, Earth orientation parameters, satellite orbital parameters, and radio source locations, and (2) combining the results to form a self consistent set of site velocities in a uniform reference frame.

The basic approach that we take is to analyze the data in subnetworks, and then subsequently combine the subnetwork solutions using procedures analogous to sequential least squares. One of the main advantages of this "distributed processing" strategy is that it allows for subsets of stations to be analyzed in parallel. An important feature of the particular approach to distributed processing that we have adopted is that the reference frame is not defined until the very last step in the analyses. This is achieved by applying loose constraints when reducing the raw data such that reference frame indeterminacy is regularized, but without affecting the invariant properties of the parameter estimates [e.g., Herring et al., 1991; Heflin et al., 1992]. Hence, different analysts can share data products without having to worry about the particular values the other analysts have adopted to define their reference frames.

Our data analyses can be divided into five main steps (Figure 1). The first step, which involved reduction of the raw space geodetic data, was largely performed by others, including SOPAC, SCEC, and Goddard Space Flight Center, and LAREG. The raw GPS data, for example, were analyzed at Scripps Orbit and Permanent Array Center (SOPAC), the Southern California Earthquake Center(SCEC), and the Harvard-Smithsonian Center for Astrophysics. The basic products of this first step were nominally, for each network/subnetwork, sets of one-day site-position estimates, Earth orientation parameters, and associated error covariance matrices. These data products are stored in SINEX (Software INdependent EXchange) format [cf. ftp://igscb.jpl.nasa.gov/igscb/data/format/sinex.txt] or equivalent files.

The second step in our analyses applies only to the GPS data sets. Once the GPS parameter estimates were obtained from the raw data for the different subnetworks, they were combined using the GLOBK software [Herring, 1999] to form total network solutions. A more detailed description of the mathematics involved in data combination and specific implementation in the GLOBK software can be found in Dong et al. [1998] and Herring [1999].

In the third step, we used the GLOBK software to estimate GPS and VLBI site velocities from all available solution files. For GPS, we used the total network and campaign combinations obtained in step two. For VLBI, we used the SINEX files provided by Goddard Space Flight Center (GSFC). SINEX files for SLR and DORIS networks, available from Laboratoire de Recherche en Geodesie (LAREG) already contain site velocities, therefore we did not need to go back to the site position data for these networks. We estimated site velocities for the GPS and VLBI networks separately. 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.

In the fourth step, we combined the resulting velocity estimates derived from the different techniques to estimate a single set of site velocities for all stations in all networks. We used the GLOBK analysis software to determine these velocity estimates, accounting for the fact that the reference frames implicit to the velocity estimate sets used as input depend in a complicated way on numerous factors, including the locations of the particular stations in each set. This velocity combination is similar to that of the data combination described in step two above, except that in this step the velocities of the stations are being adjusted to form a uniform time dependent reference frame rather than a static reference frame for the positions of the stations at a single epoch. We made no attempt to constrain the relative positions of collocated or nearly collocated stations. Instead, the velocity estimates of stations located within 1km of one another were constrained to be equal, effectively tying the velocities of all antennas located at the same site. Consequently, after step four, some velocities reflect data from more than one station, possibly from more than one space geodetic technique.

In the fifth step, we rotated the velocity field from the global geodetic reference frame implicit to the velocity estimates obtained in step four into a North America-fixed reference frame. We realized this reference frame by estimating via a weighted-least squares analysis that rigid rotation which minimized the velocities of 59 sites assumed to define a stable North America plate interior, including sites on the Colorado Plateau. We then subtracted the contribution of this rotation from the velocities of all of the stations in the network. The resulting horizontal components of the velocities in this reference frame for sites in the western United States are shown in Figure 2.

RESULTS

Following the determination of the first generation WUSC solution, we placed high priority on the dissemination of the velocity estimates. With in-kind support from the Smithsonian Astrophysical Observatory, we constructed a web-site which allows anyone to access the data, and to determine their own velocity reference frame [see http://cfa-www.harvard.edu/spacegeodesy/WUSC/]. This velocity field was used in several recent investigations of the southwestern U.S. [Bennett et al., 1999; Shen-Tu et al., 1999; Flesch et al., 2000; Kreemer et al., 2000; Wernicke et al., 2000; Bennett et al., 2001a; Bennett et al., 2001b; Bos et al., 2001; Friedrich et al., 2001; Niemi et al., 2001]. This solution was also used as the "proof of concept" for the viability of PBO [see Fig. 2 of Silver et al., 1998].

The Bennett et al. [1999] results confirmed a number of features previously observed through independent local and very sparse space geodetic studies, including a dominant pattern of right-lateral shear associated with the San Andreas fault, rates of the western-most sites of 46-48 mm/yr relative to a North America reference frame, and some 11-13 mm/yr of extension and shear east of the Sierra Nevada in the Basin and Range Province north of latitude 36N. To the south of 36N, the solution indicated that the southernmost San Andreas fault system accommodates effectively all interplate motion, and that the southern Basin and Range is not deforming significantly. At latitude 37N, the eastern California shear zone (ECSZ) exhibited simple shear oriented ~N40W relative to North America, with a fairly well defined transition zone from localized shear to diffuse spreading in the Basin and Range. Bennett et al. [1999] also reported that the ECSZ-Basin and Range transition region involved a significant component of contraction normal to the overall shear zone trend, with sites in the central Great Basin converging on the ECSZ at a few mm/yr. The orientation of the convergence is in reasonable accord with the Late Cenozoic geologic history of the Death Valley region, which contains numerous northwest-trending folds and other indicators of northeast contraction.

One of our major objectives was to compare estimates of crustal deformation obtained from geology, historical seismicity, and geodesy. These types of data are essential in developing realistic models of seismic hazard, and in linking short-time-scale observations with longer-term geologic processes. Earlier investigations [e.g., Bennett et al., 1998] had suggested, based on the accuracy of the velocity estimates at that time, that contemporary Basin and Range deformation is slow and broadly distributed, rather than being concentrated in the relatively narrow zones of historical earthquakes near the margins of the province. As the accuracy of our results improved, deviations from the average strain-rate model became significant. The largest of these, and the most difficult to explain, was a baseline in north-central Nevada indicating rapid, range-normal crustal shortening at a rate of 2-3 mm/yr in an area where the geology indicates range-normal crustal extension via late Holocene normal faulting [Wernicke et al., 2000]. The disagreement in sign of the geologic velocity field demonstrated that "non-Reidian" behavior may be widespread and detectable using continuous GPS. Wernicke et al. [2000] explored the implications of the conflicting geodetic and geologic data. We found that one possible explanation is that the region of shortening represents the contractile side of a slowly east-propagating deformation pulse generated by the 1915 Pleasant Valley and 1954 Dixie Valley and Fairview Peak earthquakes. Such pulses, which are transient effects not recorded by faulting, are predicted by a broad class of physical models.

These "rate debate" issues were further explored in the Wasatch region along the eastern margin of the Basin and Range. Here there are no sign differences between geologic and geodetic velocity fields, but both are now well enough determined to permit a meaningful quantitative comparison [Friedrich et al., 2001]. We compared present-day deformation rates obtained from space geodesy with geologic displacement rates over at least four temporal windows, ranging from the last millennium up to 10 Myr, for the Wasatch fault and adjacent fault zones. This strain rate across this region is 2-3 times higher than the average contemporary strain rate across the entire province, and coincides with the location of the Wasatch, Oquirrh, and Stansbury normal faults. The vertical component of the displacement rate on the Wasatch fault since 10 Ma were 1.0-1.4 mm/yr from 10 to 6 Ma, slowing to 0.2-0.3 mm/yr averaged over the past 6 Ma. Averaged over the Holocene the rate is 1.5-2.0 mm/yr, but < 0.6 mm/yr averaged over the late Pleistocene. The cumulative vertical displacement record across all three faults also shows time-variable strain release rates ranging from 2-4 mm/yr over the past 10 ka to < 1 mm/yr averaged over the past 130 ka. To be consistent with the apparent change from Pleistocene to Holocene time, conventional earthquake recurrence models would require an accordingly large variation in strain accumulation or loading rate on a 10 kyr time scale, for which there appears to be no obvious geophysical explanation. Rather, clustering on the 10 ka time scale would likely result from complexities in frictional failure laws with relatively constant loading, implying high Holocene strain release rates and comparatively low, uniform strain accumulation rates on the 100 ka time scale. If so, measurements of strain accumulation and strain release may be strongly time-scale dependent for any given fault system, and thus fault offset history and geodetic strain may in general not agree. In Niemi et al. [2001], we investigated whether the observed pattern of broadly distributed strain could, in fact, be due to localized deformation on a small number of faults, as had been suggested earlier by Thatcher et al. [1999] based on modeling of campaign-mode results across the Basin and Range. By compiling known late Quaternary slip rates on normal faults across the region, we found that both fault slip and loading may be relatively evenly distributed on faults throughout the northern Basin and Range.

In Bennett et al. [2001b], we estimated the relative motions of the Colorado Plateau (CP), Sierra Nevada-Great Valley (SNGV) microplate, and the central Great Basin (CGB) using GPS data. SNGV-CP motion is 11.4+- 0.3 mm/yr, N47W, whereas SNGV-North America (NA) motion is ~12.4 mm/yr, N47W, slower than previous geodetic estimates, and ~7 counterclockwise from Pacific (P)-NA motion. CGB-CP motion is 2.8+-0.2 mm/yr, N84+-5W, consistent with roughly east-west extension within the eastern Great Basin (EGB). Velocity estimates from the EGB reveal diffuse extension, with more rapid extension of 20+-1 nstr/yr concentrated in the eastern half which includes the Wasatch fault zone, as reported by Friedrich et al. [2001]. SNGV-CGB motion is 9.3+-0.2 mm/yr, N37+-2W, essentially parallel to P-NA motion. Our estimate is significantly slower than previous geodetic estimates for the western Great Basin (WGB), but generally consistent with paleoseismological inferences. The WGB region accommodates N37W directed right-lateral shear at rates of (1) 57+-9 nstr/yr across a zone of width ~125 km in the south (latitude ~36N), (2) 25+-5 nstr/yr in the central region (latitude ~38N), and (3) 36+-1 nstr/yr across a zone of width ~300 km in the north (latitude ~40N). We found that average extension in the direction of WGB shear is 8.6+-0.5 nstr/yr, comparable to average east-west extension of 10+-1 nstr/yr across the northern Basin and Range, but implying a different mechanism of extension. We also found that an alternative model for shear-parallel deformation, in which extension is accommodated across a narrow, more rapidly extending zone which coincides with the central Nevada seismic belt, fits the data slightly better.

There have been no reportable inventions or new technology under this grant.

NON-TECHNICAL SUMMARY

Destructive earthquakes occur throughout the WUSC, not just within the San Andreas fault zone. But because we do not understand the present-day large-scale deformations of the crust within this region (extending from the Pacific coast to the Wasatch Front), our ability to assess the potential for seismic hazards remains severely limited. GPS geodesy is the only practical method for determining detailed crustal deformation at this scale. GPS networks now cover many sub-regions within the WUSC. These networks do not, however, provide a single, coherent picture of the present-day crustal deformation field if treated independently; biases which inevitably affect each realization of the geodetic reference frame are significant relative to the expected low velocities. We are addressing this problem by combining geodetic data products derived independently from these small scale networks, which are already widely available, using a technique specifically designed to render these reference frame errors negligible. We are determining, for the first time, a coherent crustal velocity field for the entire WUSC. We are using the new velocity results to understand the kinematics of deformation and to determine parameters (e.g., fault slip rates, strain rates) for models appropriate to particular regimes of deformation within the WUSC that we have identified.

DISSEMINATION

With in-kind support from the Atherton Seidell Grant Program of the Smithsonian Institution, we have built a data dissemination system that allows users to manipulate and download our combined WUSC velocity solution using the World-Wide-Web. The URL for the web site is <http://cfa-www.harvard.edu/space_geodesy/WUSC/>.

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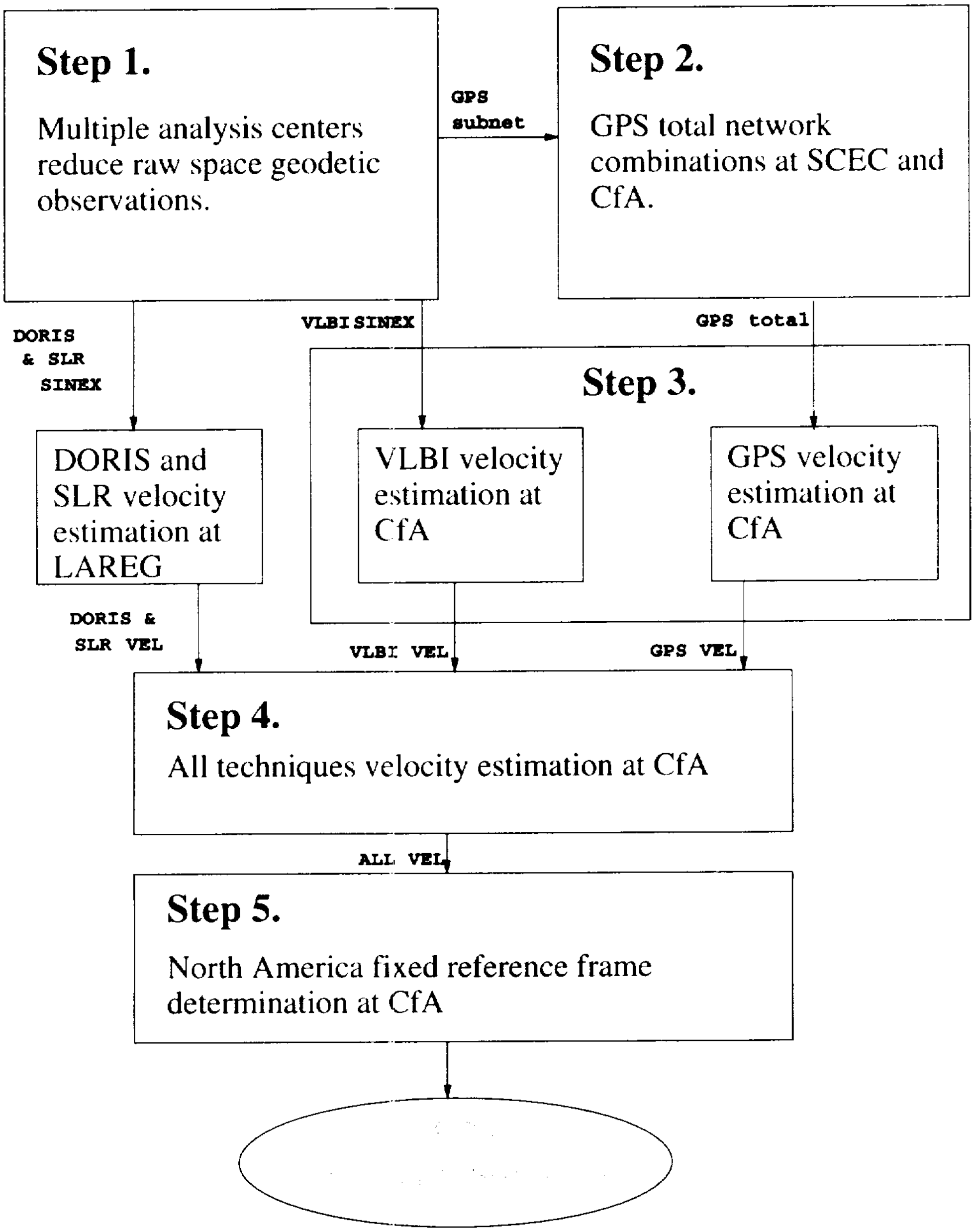

Figure 1 Five step distributed data analysis procedure. CfA = Harvard-Smithsonian Center for Astrophysics. SCEC = Southern California Earthquake Center. LAREG = Laboratoire de Recherche en Geodesie. WUSC = Western U.S. Cordillera.

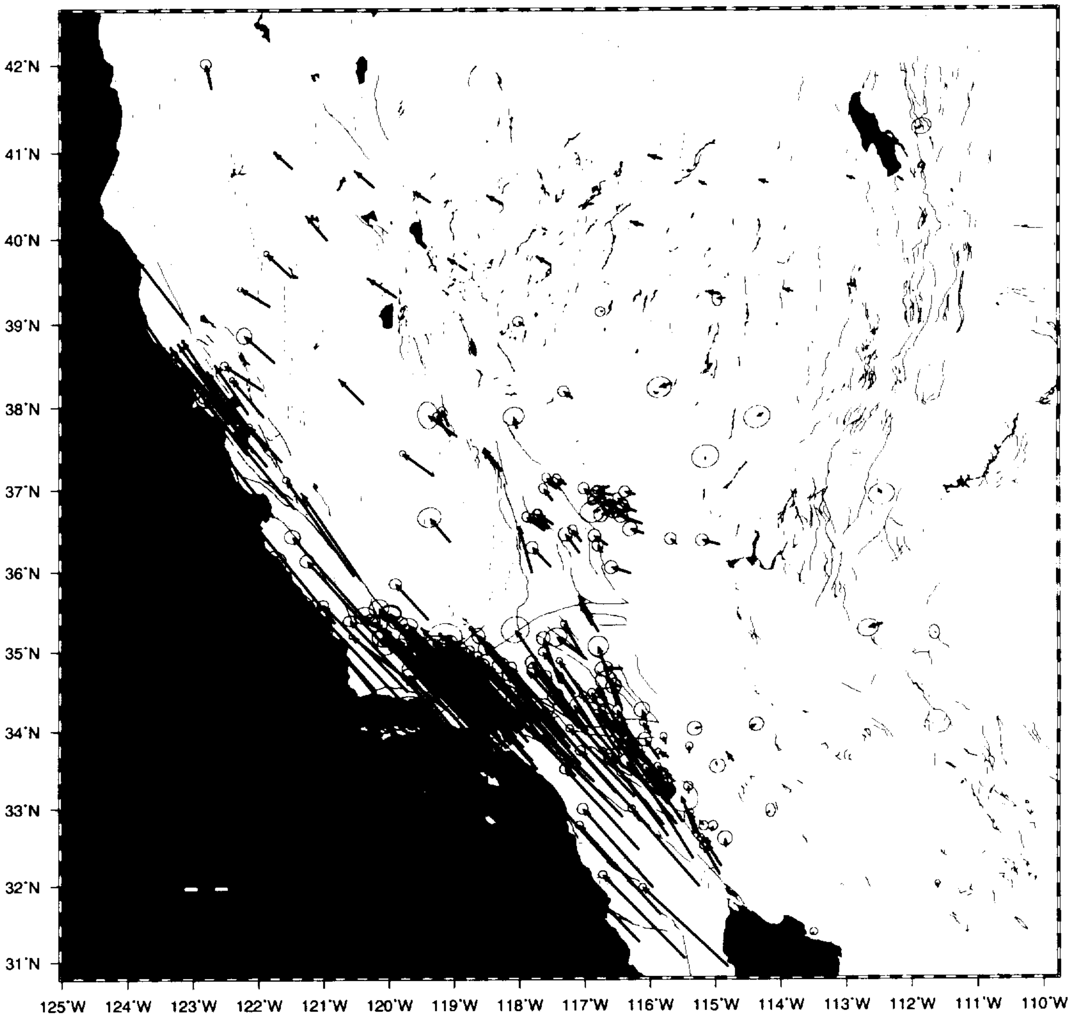

Figure 2 Estimates of horizontal velocities relative to stable North America for sites in western United States (arrows). Error ellipses represent 95‰ confidence level. Thin black lines represent mapped Quaternary faults. Also shown for reference is the NUVEL-1A estimate for Pacific-North America relative motion.