at present, advances in GPS receiver technology will allow denser and more continuous measurements. ☐

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Absolute far-field displacements from the 28 June 1992 Landers earthquake sequence

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ON 28 June 1992, the largest earthquake in California in 40 years (surface-wave magnitude $M_s = 7.5$) occurred near the small town of Landers, in southeastern California, and was followed three hours later by the nearby M_s 6.5 Big Bear earthquake[1]. Fortuitously, the Landers earthquake sequence coincided with the first week of the official three-month test period of the International Global Positioning System and Geodynamics Service[2] (IGS), giving us an unprecendented opportunity to detect absolute pre-, co- and post-seismic displacements at a distance of 50–200 km from the main rupture with millimetre-level precision. Mutual and independent confirmation of some of our geodetic results are demonstrated by Bock *et al.* in this issue[3]. For the Landers earthquake, the observed displacements indicate that the depth of the bottom of the rupture is shallower towards the northern end, displacements were dominantly symmetric, and the rupture extended further south on the Johnson Valley fault than has been mapped on the basis of surface ground offsets. The combined geodetic moment for the Landers and Big Bear earthquakes (1.1×10^{20} N m^{-1}) agrees well with teleseismic estimates.

The Landers and Big Bear earthquakes and their aftershocks occurred along faults that form a triangle bounded to the southwest by the San Andreas fault (Fig. 1). Extensive surface rupture resulting from these events has been reported along the Johnson Valley and Camp Rock/Emerson faults. Ground breakage occurs along a 70-km stretch of these faults, reaching a maximum surface offset of 6.7 m (ref. 1). The Landers earthquake occurred toward the southern end of the hypothesized 'Mojave shear zone', which trends N 35° W across the Mojave Desert, into Owens Valley and the northern Basin and Range province[4,5]. This zone reportedly carries 7–8 mm yr^{-1} of the relative motion between the Pacific and North American plates, and may be a manifestation of a subcrustal fault[4,5]. Aftershocks following the Landers earthquake line up along this apparent shear zone from as far south as the San Andreas fault, to further north than our station GOLD shown in Fig. 1. The pattern of aftershocks is sparse on the Camp Rock fault segment which underlies the northernmost 13 km of the visible surface rupture[6]. Using a new geodetic tool for earthquake studies, we have estimated permanent surface displacements in southern California due to the cumulative effect of events on 28 June, and show that geodetic methods provide valuable information on aspects of the rupture mechanism not available with other techniques. We also offer an explanation for the unexpected lack of aftershocks on the Camp Rock fault.

Since 21 June 1992, a worldwide network of stations has been routinely receiving precise microwave ranging data from the United States Department of Defence's 18-satellite Global Positioning System (GPS)[7], and transmitting the data to IGS data centres to be made available to analysis centres and geodynamics researchers. Regional GPS networks benefit from the precise orbit determination and reference frame stability supplied by an extensive tracking network[8-10]. A regional array of receivers operated jointly by the Jet Propulsion Laboratory (JPL) and Scripps Institution of Oceanography has been operational in southern California since 1990 (ref. 11). A simultaneous analysis of GPS data from the California array combined with the global network data has allowed us to estimate the absolute displacements, in the international terrestrial reference frame[12] (ITRF), of three stations located within 50–200 km from the Landers earthquake rupture, with 2-mm precision in the horizontal plane.

To reduce systematic errors that can be introduced by mixing different types of GPS receivers and antennas, we have analysed

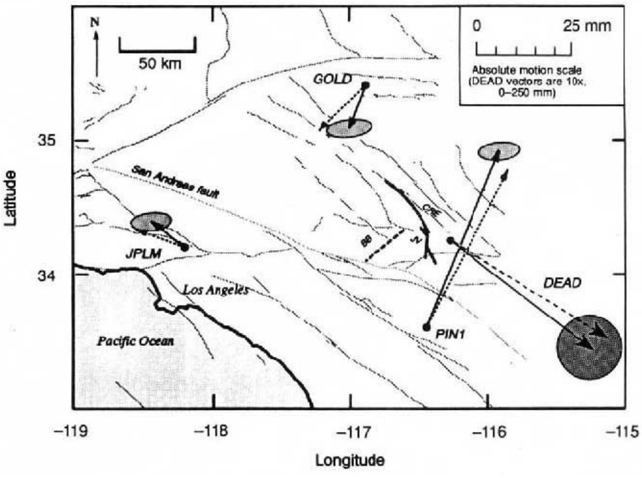

FIG. 1 Map showing absolute motions of Goldstone (GOLD), Pasadena (JPLM), Pinyon Flat (PIN1) and Deadman (DEAD). Solid arrows are the observed displacements with 95% confidence regions. The vectors and confidence region for DEAD is shown at 0.1 times the scale of the other stations. The model displacements, assuming an elastic half-space, are shown as dashed arrows. The surface trace of the model of the Lânders earthquake is shown by the solid heavy line. Dashed heavy line (BB) is the trace of the fault used to model the Big Bear earthquake. Shaded solid and dashed lines are active faults in the region: JV is the Johnson Valley fault; CRE is the Camp Rock/Emerson fault.

data from the 28-station homogeneous subset of the global network that uses 'Rogue' receivers (only three of which were operating in California at the time of the earthquake). Since early May 1992, we have been routinely producing high-precision estimates of GPS satellite orbits, station coordinates[13] and the Earth's pole of rotation[14].

Provided that the wobble of the Earth's pole is monitored and that we model the known tidal deformations of the solid Earth, the receiver coordinates of the global network can be defined such that distances between all stations and distances between each station and the Earth's centre of mass are consistent with the GPS observations. 'Absolute displacements' are defined here as the permanent change in these station coordinates due to the combined effect of the Landers and Big Bear earthquakes. This concept is emphasized because previous geodetic techniques have only been sensitive to relative motion between stations (which is inherently ambiguous). This ability to measure 'absolute displacements' allows us to investigate symmetric versus asymmetric displacements. In most models of earthquake ruptures so far (including our own) each side of the fault is assumed to move half the total slip distance. Asymmetric displacements could have profound implications for the evaluation of seismic hazard of areas affected by the fault[15].

The analysis presented here is based on data retrieved from 1 June to 26 July 1992 (that is, ±4 weeks from 28 June). A subset of the global stations were held fixed to their ITRF coordinates[10], which have been shown to be consistent with GPS observations[13]. The orientation of the Earth's pole of rotation was estimated every 24 hour interval. Two types of solution are used here. (1) To indicate the precision of our solutions, and to test for pre- and post-seismic motion, station coordinates were estimated independently every day. Relative positions are shown in Fig. 2. We include in these examples the estimates of JPLM with respect to DRAO at Penticton, British Columbia, Canada, which is the closest station (at 1,700 km) safely outside the zone of deformation. The several-millimetre northern displacement of JPLM relative to DRAO is evident. We conclude from this figure that we did not detect significant pre-or post-seismic motion of the three permanent stations at the few millimeter level. (2) To estimate rigorously co-seismic displacement, we reduced the data in a single solution, for which we assumed that all stations outside of California were stationary during this 8-week period, and the positions of the California stations were modelled as a step-function centred on 28 June. For simplicity, data from 28 June were not used. Unmodelled tectonic plate motion over this period would result in insignificant systematic errors in the step-function estimates at the 1 mm level. The formal standard deviations of the estimates were scaled by a factor of 2 to make them more consistent with the observed r.m.s. scatter of daily solutions, which was typically 3 mm for the north components, 5 mm for the east components, and 10–15 mm for the vertical components. Table 1 contains estimates of the absolute displacements for the three continuously operating California sites analysed.

In addition to the displacements at the three permanently operating receivers, displacements were estimated for Deadman Lake, a very-long-baseline interferometer (VLBI) station, which we occupied using GPS within hours of the main shock. These displacements are based on the difference between GPS-estimated coordinates and the VLBI coordinates for this station (both sets of coordinates being consistently expressed in the ITRF). Figure 1 indicates the estimated horizontal displacements for the 4 California stations. To within their 95% confidence ellipses, the displacement estimates for JPLM, PIN1 and GOLD have been mutually and independently confirmed by Bock *et al.*[3].

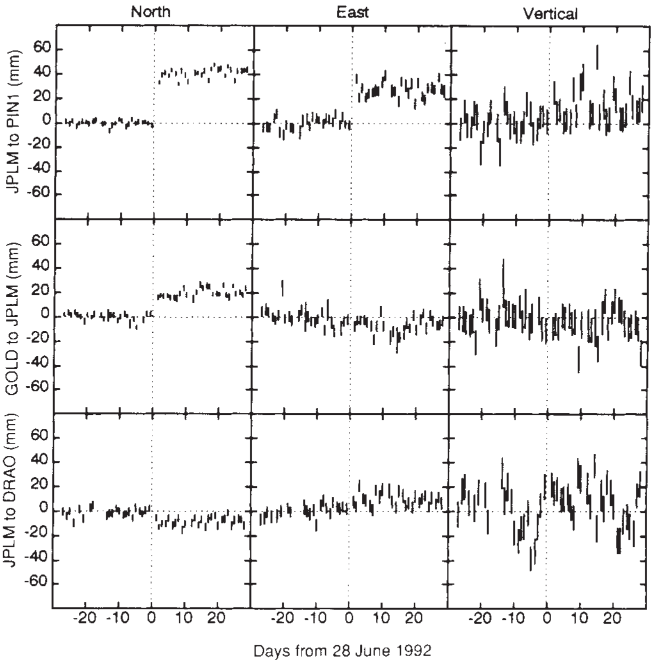

FIG. 2 Daily estimated coordinates of Goldstone (GOLD) and Pinyon Flat (PIN1) relative to Pasadena (JPLM) shown in local components (north, east and vertical), with their one-standard deviation error bars. The lowest three plots show the displacement of JPLM relative to Penticton (DRAO), British Columbia, over 1,700 km away. Despite the long distance, the step function in the north component is clearly evident (in this plot, DRAO appears to move south relative to JPLM). These plots are for illustration only; the actual displacement estimates in Table 1 are based on a step-function model for stations in California, and are absolutely determined with respect to a consistently defined Earth-fixed, corotating reference frame.

Forward modelling using a homogeneous elastic half-space and perturbations to a fault model derived from TERRAscope inversion[16] and measured surface offsets[6] was used to calculate displacements of the four stations JPLM, PIN1, GOLD and DEAD. The model includes eight fault planes for the Landers quake and one fault plane for the Big Bear quake. Details of the fault plane locations and slips are given in Table 2. To allow the modelled displacements to come close to the observed displacements, the moment release from the northern end of the Landers quake must be small. In view of the measured surface offsets in this region, the small moment in turn requires the depth of rupture to be shallow, as seismic moment is

TABLE 1 Absolute displacements of California GPS stations

Station	Approx. coordinates Latitude	Approx. coordinates Longitude	Estimates (mm) East	Estimates (mm) North	Estimates (mm) Vertical	Model (mm) East	Model (mm) North	Model (mm) Vertical
Pasadena (JPLM)	34° 12′	241° 50′	−9 ± 2	7 ± 1	−8 ± 5	−13	6	−4
Goldstone (GOLD)	35° 26′	243° 07′	−5 ± 2	−11 ± 1	−4 ± 5	−13	−10	2
Pinyon Flat (PIN1)	33° 37′	243° 32′	19 ± 2	46 ± 1	8 ± 5	24	39	10
Deadman (DEAD)	34° 15′	243° 43′	384 ± 35	−302 ± 34	100 ± 31	397	−280	27

TABLE 2 Details of fault-plane assumptions for elastic half-space model

Faults*	Dip (deg)	Rake (deg)	Width (km)	Length (km)	Depth (km)	Slip (m)	Starting longitude (deg)	Starting latitude (deg)	Ending longitude (deg)	Ending latitude (deg)
EP	90.0	180.0	15.0	15.24	0.0	0.5	−116.376	34.083	−116.439	34.210
JVs	90.0	180.0	12.0	18.63	0.0	4.2	−116.447	34.124	−116.432	34.292
JVn	90.0	180.0	15.0	7.93	0.0	3.5	−116.434	34.291	−116.485	34.349
Kik	90.0	180.0	15.0	5.38	0.0	2.5	−116.455	34.310	−116.447	34.358
HVs	90.0	180.0	8.0	10.30	0.0	3.5	−116.425	34.315	−116.470	34.400
HVn	90.0	180.0	8.0	15.72	0.0	3.3	−116.470	34.400	−116.549	34.526
E	90.0	180.0	5.0	12.75	0.0	5.5	−116.551	34.524	−116.633	34.617
CR	90.0	180.0	3.0	13.03	0.0	1.0	−116.634	34.616	−116.733	34.701
BB	90.0	0.0	15.0	35.07	2.0	0.8	−116.632	34.316	−116.901	34.093

* EP: Eureka Peak; JVs: Johnson Valley (south); JVn: Johnson Valley (north); Kik: Kikapoo; HVs: Homestead Valley (south); HVn: Homestead Valley (north); E: Emerson; CR: Camp Rock; BB: Big Bear

proportional to the product of slip and rupture area. In our model the Homestead Valley (north), Emerson and Camp Rock faults have a maximum depth of faulting of 8.0, 5.0 and 3.0 km respectively. To fit the observed displacements of DEAD, we have modelled the southern end of the Johnson Valley (south) fault to be ~8 km south of the recognized surface rupture. This extension may more properly coincide with the Burnt Mountain fault[6,17].

For the Landers earthquake only, teleseismic data yield a moment of 1.1×10^{20} N m^{-1} (ref. 6); inversions of TERRAscope data yield 0.8×10^{20} N m^{-1} (ref. 6); geological observations yield 0.9×10^{20} N m^{-1} (ref. 6); and our model has a moment of 0.9×10^{20} N m^{-1}.

The differences between our model and the observed displacements may be attributed to a combination of inaccuracies in our fault model and possibly inhomogeneous response of the crust. Our GPS results strongly suggest that rupture under the northernmost segment of the surface break is surprisingly shallow (extending ~3 km below the surface). This may explain the paucity of aftershocks on the Camp Rock fault. The displacements derived from our (symmetric rupture) model fall outside the 95% confidence ellipses at PIN1 and GOLD by 6% and 15% of the observed total displacement at the respective site. These discrepancies may be explained by some combination of asymmetric rupture, inhomogeneous material properties, and mismodelling of fault parameters. ☐

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Do virtual geomagnetic poles follow preferred paths during geomagnetic reversals?

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VIRTUAL geomagnetic poles (VGPs) recorded in sediments during reversals of the Earth's magnetic field show an apparent preference for two antipodal sectors of longitude[1–3], not only in records of the same reversal from different sites, but also in records of different reversals. If preferred bands really have persisted from one reversal to the next, this would imply that the mantle exerts a significant control over the reversal process[4]. Here we analyse the available database of reversal records from the past 12 Myr, using a statistical test specifically designed to test the hypothesis of two preferred antipodal longitudinal bands. Our analysis shows that the records, taken as a group of independent observations, do show an overall preference for two antipodal longitudinal bands. However, the site longitudes are also strongly grouped[5], and a comparison of the transitional VGP longitudes with site longitudes shows an unlikely grouping under the hypothesis of a genuine geographical preference for transitional VGPs. We conclude that it is premature to accept the hypothesis of mantle control over the core during geomagnetic reversals.

Laj *et al.*[4] presented a visually compelling diagram showing all of the individual VGP positions, and linked the preferred longitudinal sectors to lateral inhomogeneities in the lower mantle. However, the hypothesis of preferred sectors was not based on an objective analysis of the data: it relied strongly on a visual perception which may have been biased by the presentation.

Valet *et al.*[5] have recently disputed the interpretation of preferred longitude sectors for the transitional VGPs, basing their conclusions on a χ^2 analysis of a parameter they refer to as the MVL (mean value of longitude) for each record. Given n VGP unit vectors $\mathbf{v}_i=(x_i, y_i, z_i)^t$ in a transitional record the MVL for that record is simply a weighted mean of the i longitudes, the weight for each $\mathbf{v}_i$ being the cosine of the latitude of $\mathbf{v}_i$. Thus

$$\mathrm{MVL}=\arctan\left(\sum_{i=1}^{n} y_i \Big/ \sum_{i=1}^{n} x_i\right)$$

Clearly it is necessary to use some form of central measure to categorize each record with a single parameter for analysis, and the MVL seems the most natural choice. Laj *et al.*[6], in a more