JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. B9, PAGES 20,137–20,140, SEPTEMBER 10, 1996

Reply

Thóra Árnadóttir
Department of Geological and Geophysical Sciences, Princeton University, Princeton, New Jersey

Paul Segall
Department of Geophysics, Stanford University, Stanford, California

In the paper by *Árnadóttir and Segall* [1994] (hereinafter referred to as AS94) we argued that there was no reason to reject the hypothesis that the aftershocks of the Loma Prieta earthquake occurred on, or very near, the rupture surface estimated from inversion of geodetic data. Subsequent relocation of the aftershocks [e.g., *Pujol*, 1995; *Dietz and Ellsworth*, 1996] only strengthens this conclusion.

To put the AS94 results into context, one must recall that previous analyses of geodetic data [*Lisowski et al.*, 1990; *Marshall et al.*, 1991] had inferred that the dislocation surface was offset up to 3 km southwest of the aftershock zone defined by preliminary U. S. Geological Survey (USGS) locations. *Marshall et al.* [1991] suggested that this was evidence that the rupture surface might be distinct from the aftershock zone. *Eberhart-Phillips and Stuart* [1992] pointed out that three-dimensional variations in elastic properties across the fault plane could bias the geodetic inversions. *Árnadóttir et al.* [1992], however, showed that the discrepancy in location found by *Marshall et al.* [1991] could be largely eliminated by accounting for correlations in the leveling data they analyzed. *Marshall and Stein* [1996] subsequently concluded that the discrepancy between aftershock locations and geodetic fault models was insignificant when they included the data correlations and used a more realistic Earth model. The discrepancy between aftershock locations and the dislocation surface inferred by *Lisowski et al.* [1990], who analyzed Global Positioning System (GPS) and trilateration data, was less pronounced than that of *Marshall et al.* [1991]. *Árnadóttir et al.* [1992] found a more consistent result using a nonlinear inversion method to estimate fault geometry from these data, as opposed to the trial-and-error approach of *Lisowski et al.* [1990].

The objective of AS94 was to estimate the geometry and slip distribution of the 1989 earthquake using all the available geodetic data [*Clark et al.*, 1990; *Lisowski et al.*, 1990; *Marshall et al.*, 1991; *Williams et al.*, 1993]. We estimated the geometry of the best fitting uniform slip dislocation using a nonlinear, quasi-Newton method and determined confidence intervals for the dislocation parameters using bootstrap resampling (AS94). We illustrated the uncertainty in the location of the dislocation plane by plotting the "density" of bootstrap estimated fault models that are within the 95% confidence level (see AS94). Figure 1a (identical to Figure 6 of AS94) shows a SW-NE cross section roughly corresponding to the combined cross sections AA' – DD' shown by *Pujol* [this issue]. The location of the main shock and $M \geq 3.0$ aftershocks recorded from October 18 to October 31, 1989, shown on Figure 1a are preliminary USGS locations (provided by D. Oppenheimer, personal communication, 1992). We were aware of the possibility of systematic biases in these preliminary aftershock locations due to local velocity structure, but detailed studies of the aftershock locations ongoing at the time, implied these biases were small. The extent of the shaded region in Figure 1a demonstrates the range in uniform slip dislocation models that fit the geodetic data at the 95% confidence level. Notice that there is a ±2-km uncertainty in the across-strike position of the fault surface and that this range includes most of the aftershock zone. This was the basis of our conclusion that there was not a significantly discrepancy between the aftershock locations and the estimated dislocation surface.

In Figure 1b we show the same cross section as in Figure 1a but with the aftershocks relocated by *Pujol* [1995], again plotting only aftershocks with $M \geq 3.0$ recorded from October 18 to October 31, 1989. Comparing Figures 1a and 1b, we see that the aftershock locations determined by Pujol tend to lie southwest of the preliminary USGS locations. *Dietz and Ellsworth* [1996] also observe the same systematic bias in aftershock locations. Their relocations are shown in Figure 1c for the same magnitude range and time period as Figures 1a and 1b. The relocated aftershocks are in slightly better agreement with our geodetically determined dislocation surface than are the preliminary USGS locations, as *Pujol* [this issue] points out. This reinforces our conclusion that there is not a significant discrepancy between the aftershock locations and the fault model we obtained from geodetic data.

Paper number 96JB01913.
0148-0227/96/96JB-01913$09.00

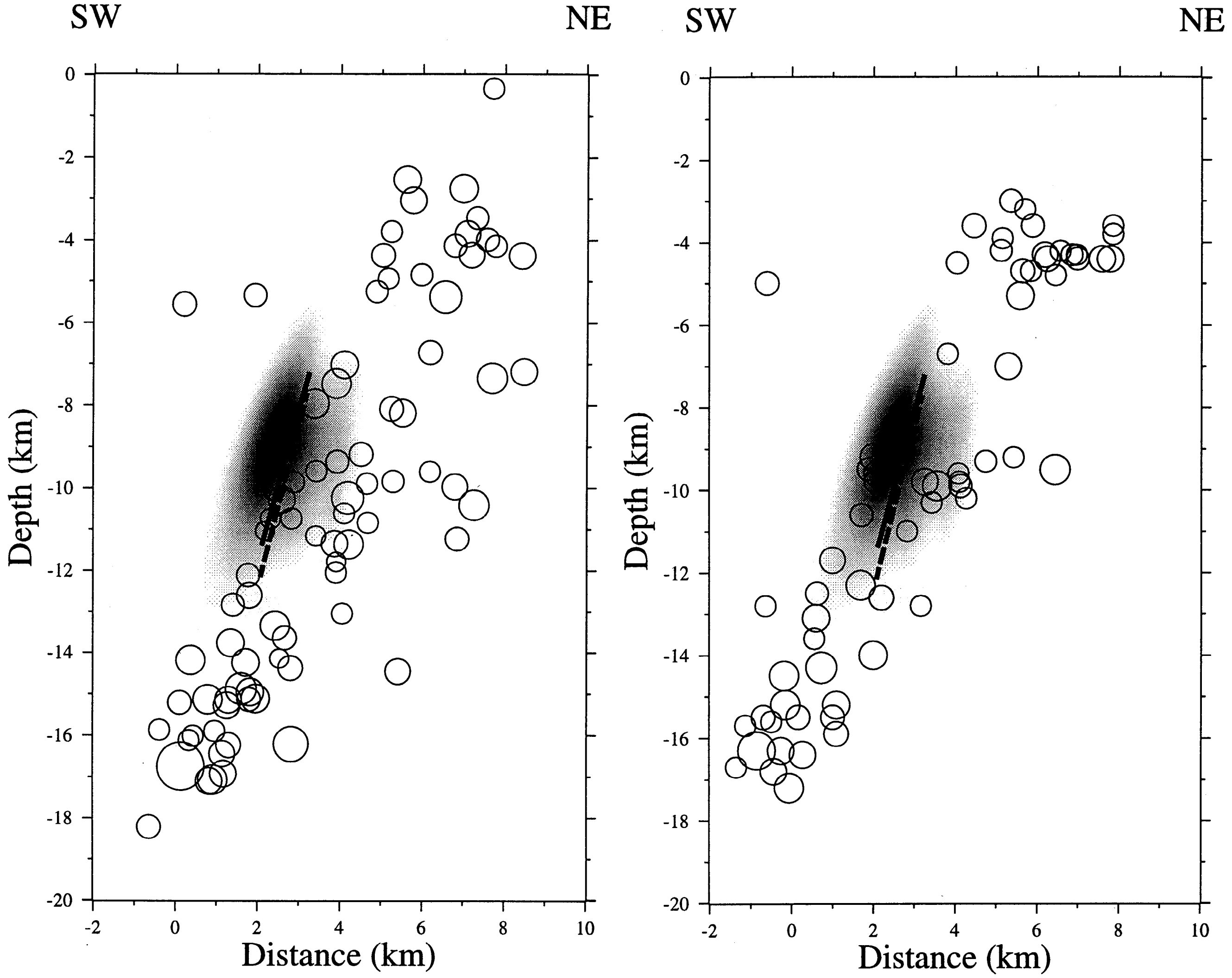

Figure 1. A SW-NE cross section along azimuth N41°E through the Loma Prieta main shock epicenter. The shaded region shows the location of bootstrap models within the 95% confidence limits of the fault parameters. The solid line is the mean of the 2000 bootstrap models, and the dashed line is the best fit model from all the data. The locations of earthquakes with $M \geq 3.0$ recorded from October 18 to October 31, 1989, are shown with circles. The size of the circles reflect the magnitudes of the earthquakes. (a) Preliminary USGS location of the main shock and aftershocks used by AS94 (Figure 6 from AS94). (b) Relocated main shock and aftershocks from *Pujol* [1995]. (c) Relocated main shock and aftershocks from *Dietz and Ellsworth* [1996].

We did feel it appropriate to point out that the best fitting dislocation surface was located toward the southwestern edge of the aftershock zone (AS94). This does not contradict our conclusion that "there is no significant discrepancy between the geodetic data and the aftershock locations." Our comment was simply meant to point out that systematic biases could still exist at the ±1-km level, but given our error estimates and uncertainties in the absolute aftershock locations, such a small bias is not statistically significant. When comparing the absolute location of a geodetic fault model and aftershock locations, it is important to note that both are sensitive to the Earth model used to obtain them. Even if relative earthquake locations determined from different velocity models appear consistent, the absolute location of these events can differ by up to several kilometers [e.g., *Reasenberg and Ellsworth*, 1982]. Similarly, the location of a dislocation model obtained from geodetic data can be sensitive to assumptions about elastic homogeneity and isotropy [*Eberhart-Phillips and Stuart*, 1992; *Du et al.*, 1994]. It is also worth noting that many aftershocks have very different focal mechanisms from the main shock [e.g., *Oppenheimer*, 1990; *Beroza and Zoback*, 1993; *Foxall et al.*, 1993; *Dietz and Ellsworth*, 1996] and thus are probably not occurring on a simple planar surface. This suggests that the finite thickness of the aftershock zone, observed in Figures 1a-1c, is probably real and not an artifact of mislocation.

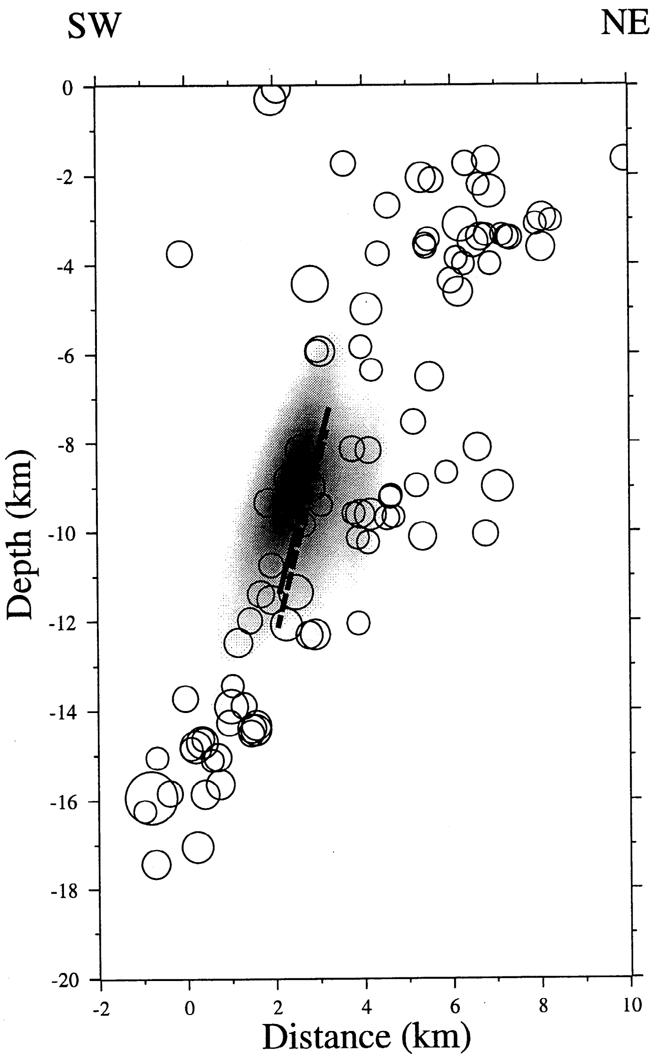

Figure 1. (continued)

Small biases due to all of these effects are undoubtedly present. The important point is that the ~1-km potential bias in aftershock locations is well within the ±2-km uncertainty in the geodetic fault location. There is thus no reason to reject the simplest interpretation that the aftershocks and the source of the static surface deformations were coincident.

We agree that a single rectangular dislocation in a homogeneous elastic half-space cannot represent all aspects of the Loma Prieta earthquake. As we previously noted [AS94], the variation in rake observed in distributed slip calculations could be explained by variations in fault dip of about 10° from northwest to southeast, as suggested by the aftershock locations. The geodetic data, however, do not allow us to resolve such details of the fault geometry. The one-sigma uncertainty in dip for a single dislocation surface is ±9° (AS94). We therefore chose to use the simplest dislocation model that fits the data, i.e., one fault with constant dip, rather than allowing the dip to vary along strike.

We are delighted that relocations of the Loma Prieta aftershocks provide somewhat better agreement with the dislocation surface estimated from geodetic data than do the preliminary USGS locations. In fact, both the preliminary USGS locations and the more recent aftershock relocations agree with the geodetic interpretation at the 95% confidence interval. There is therefore no reason to change our conclusion that the aftershocks show the location of the rupture surface, as we stated in our paper.

Acknowledgments. We thank Jose Pujol, Lynn Dietz, and Bill Ellsworth for supplying us with their relocated aftershock data.

References

Árnadóttir, T., and P. Segall, The 1989 Loma Prieta earthquake imaged from inversion of geodetic data, *J. Geophys. Res., 99*, 21,835–21,855, 1994.

Árnadóttir, T., P. Segall, and M. Matthews, Resolving the discrepancy between geodetic and seismic fault models for the 1989 Loma Prieta, California, earthquake, *Bull. Seismol. Soc. Am., 82*, 2248–2255, 1992.

Beroza, G. C., and M. D. Zoback, Mechanism diversity of the Loma Prieta aftershocks and the mechanics of mainshock-aftershock interaction, *Science, 259*, 210–213, 1993.

Clark, T. A., C. Ma, J. M. Sauber, J. W. Ryan, D. Gordon, D. B. Shaffer, D. S. Caprette, and N. R. Vandenberg, Geodetic measurement of deformation in the Loma Prieta, California earthquake with very long baseline interferometry, *Geophys. Res. Lett., 17*, 1215–1218, 1990.

Dietz, L. D., and W. L. Ellsworth, Aftershocks of the 1989 Loma Prieta earthquake and their tectonic implications, in *The Loma Prieta, California, Earthquake of October 17, 1989-Postseismic Effects, Aftershocks, and Other Phenomena*, edited by P. A. Reasenberg, *U.S. Geol. Surv. Prof. Pap., 1550-D*, in press, 1996.

Du, Y., P. Segall, and H. Gao, Dislocations in inhomogeneous media via a moduli-perturbation approach: General formulation and two-dimensional solutions, *J. Geophys. Res., 99*, 13,767-13,779, 1994.

Eberhart-Phillips, D., and W. Stuart, Material heterogeneity simplifies the picture: Loma Prieta, *Bull. Seismol. Soc. Am., 91*, 1964-1968, 1992.

Foxall, W., A. Michelini, and T. V. McEvilly, Earthquake travel time tomography of the southern Santa Cruz Mountains: Control of fault rupture by lithological heterogeneity of the San Andreas fault zone, *J. Geophys. Res., 98*, 17,691–17,710, 1993.

Lisowski, M., W. H. Prescott, J. C. Savage, and M. J. Johnston, Geodetic estimate of coseismic slip during the 1989 Loma Prieta, California, earthquake, *Geophys. Res. Lett., 17*, 1437–1440, 1990.

Marshall, G. A., and R. S. Stein, Elevation changes associated with the October 17, 1989, Loma Prieta earthquake and their use to infer fault slip geometry, in *The Loma Prieta, California Earthquake of October 17, 1989–Main Shock Characteristics*, edited by P. Spudich, *U.S. Geol. Surv. Prof. Pap., 1550-A*, in press, 1996.

Marshall, G. A., R. S. Stein, and W. Thatcher, Faulting geometry and slip from co-seismic elevation changes: The 18 October 1989, Loma Prieta, California, earthquake, *Bull. Seismol. Soc. Am., 81*, 1660–1693, 1991.

Oppenheimer, D. H., Aftershock slip behavior of the 1989 Loma Prieta, California earthquake, *Geophys. Res. Lett.*, *17*, 1199–1202, 1990.

Pujol, J., Application of the JHD technique to the Loma Prieta, California, mainshock-aftershock sequence and implications for earthquake location, *Bull. Seismol. Soc. Am.*, *85*, 129–150, 1995.

Pujol, J., Comment on "The 1989 Loma Prieta earthquake imaged from inversion of geodetic data" by Thóra Árnadóttir and Paul Segall, *J. Geophys. Res.*, this issue.

Reasenberg, P. A., and W. L. Ellsworth, Aftershocks of the Coyote Lake, California, earthquake of August 6, 1979: A detailed study, *J. Geophys. Res.*, *87*, 10,637–10,655, 1982.

Williams, C., T. Árnadóttir, and P. Segall, Coseismic deformation and dislocation models of the 1989 Loma Prieta earthquake derived from Global Positioning System measurements *J. Geophys. Res.*, *98*, 4567–4578, 1993.

T. Árnadóttir, Department of Geological and Geophysical Sciences, Guyot Hall, Princeton University, Princeton, NJ08544-1003. (e-mail: thora@geo.princeton.edu)

P. Segall, Department of Geophysics, Stanford University, Stanford, CA94305. (e-mail: segall@halape.stanford.edu)

(Received June 6, 1996; accepted June 13, 1996.)