Long-period surface wave inversion for source parameters of the 18 October 1989 Loma Prieta earthquake

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ABSTRACT


We performed simultaneous seismic moment tensor inversions of long-period (157—288 s) fundamental mode Rayleigh and Love waves from the 1989 Loma Prieta earthquake to further constrain the source process of the event. Utilizing a two-step spectral inversion technique, we explored the model dependence and centroid location sensitivity of the long-period surface wave analysis to assess the confidence bounds on the results. We found that estimates of the source duration and depth are highly dependent on the choice of propagation, attenuation and source velocity structure models. Including centroid location parameters in the inversion stabilizes moment tensor estimates but yields a biased location away from the epicenter due to model inaccuracies. Our source duration estimate is 11 ± 5 s using a recent velocity model, MPA, with the centroid time of 6 s being significantly less than earlier surface wave studies (centroids of 10—22 s) and hence more compatible with both body wave and strong motion duration estimates. An unconstrained moment tensor inversion at the optimum centroid location yields a stable major double-couple solution (strike = 124 ± 6°; dip = 67 ± 6°; rake = 126 ± 7°) and a seismic moment estimate (3.0 ± 0.2 x 10^19 Nm; M_w = 6.9) similar to earlier long-period studies and body wave and geodetic results. The surface wave centroid depth estimate is 22 ± 11 km, which overlaps the body wave estimates (13 ± 5 km). Thus, surface wave source parameters for the Loma Prieta event, allowing for plausible model dependence, are fully compatible with body wave determinations, and there is no evidence for any anomalous coseismic long-period source process.

1. Introduction

The Loma Prieta earthquake, which took place on 18 October 1989, is perhaps the best instrumentally recorded earthquake to date, with high quality ground motion data ranging from short-period strong ground motions (0.3—5.0 Hz signals) to static offsets (ground deformation). This unusually complete data set allows a detailed analysis of the earthquake rupture process through the utilization of the various signals, each of which has a different sensitivity to the source process. This, in turn, provides an excellent opportunity to explore the compatibility and resolution of the different data sets and the associated seismic inversion techniques. Ideally, earthquake source models should be independent of inversion technique, but may depend on data type and frequency. For many large earthquakes, the results obtained using short-period waves differ from those using long-period waves or geodetic measurements, and similar discrepancies have been reported for the Loma Prieta event (Wallace et al., 1991).

The epicentral location (NEIC) and the approximately 40 km long rupture area (e.g. Wald et al., 1991) of the Loma Prieta earthquake are plotted in Fig. 1, along with the best double-cou-
Fig. 1. Map showing the epicentral location (filled circle) (NEIC) and approximate rupture area (e.g. Wald et al., 1991) of the 1989 Loma Prieta earthquake. Major double-couple focal mechanisms from P-wave first-motions (Oppenheimer, 1990), averaged teleseismic body wave solutions (Barker and Salzberg, 1990; Choy and Boatwright, 1990; Kanamori and Satake, 1990; Langston et al., 1990; Nábelek, 1990; Romanowicz and Lyon-Caen, 1990; Ruff and Tichelaar, 1990; Wallace and Lay, 1990; Wallace et al., 1991), averaged surface wave results (Kanamori and Satake, 1990; Romanowicz and Lyon-Caen, 1990; Zhang and Lay, 1990a; Wallace et al., 1991), and a Centroid Moment Tensor (CMT) solution (Dziewonski et al., 1990). The focal mechanisms are virtually identical, suggesting negligible frequency dependence or faulting complexity. Furthermore, estimates of seismic moment, centroid depth, and rupture duration obtained from local, regional and teleseismic body wave studies are generally consistent with each other (Wallace et al., 1991). However, long-period surface wave results have tended to give larger moments, deeper centroid depths, and longer rupture durations than body wave studies. These systematic discrepancies are suggestive of a complex source phenomenon, such as deep, slow rupture propagating into the mantle (Wallace et al., 1991). Before accepting the possibility of such a complex source process, the reliability of the long-period results must be tested, and this study will demonstrate that no anomalous source process is resolved by the long-period signals.

The various published investigations of long-period seismic waves for the Loma Prieta event have yielded consistent focal mechanisms and seismic moment estimates, as shown in Table 1. However, due to the limited resolution of long-period waves, several of these studies have necessarily constrained some aspect of the inversions.

### TABLE 1

<table>
<thead>
<tr>
<th>Strike (°)</th>
<th>Dip (°)</th>
<th>Rake (°)</th>
<th>Depth (km)</th>
<th>$M_0$ ($\times 10^{17}$ Nm)</th>
<th>Duration (s)</th>
<th>Ref.</th>
<th>Comm.</th>
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<td>124 ± 6</td>
<td>67 ± 6</td>
<td>126 ± 7</td>
<td>22 ± 11</td>
<td>3.0 ± 0.2</td>
<td>11 ± 5</td>
<td>This st.</td>
<td>R, G</td>
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<td>129 ± 2</td>
<td>69 ± 3</td>
<td>134 ± 4</td>
<td>15–23</td>
<td>3.3 ± 0.5</td>
<td>18 ± 5</td>
<td>Wetal</td>
<td>R, G</td>
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<tr>
<td>123</td>
<td>71</td>
<td>128</td>
<td>19 *</td>
<td>2.7</td>
<td>40.0</td>
<td>Detal</td>
<td>CMT</td>
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<tr>
<td>128</td>
<td>70</td>
<td>137</td>
<td>15</td>
<td>2.5</td>
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<td>KS</td>
<td>CMT</td>
</tr>
<tr>
<td>129</td>
<td>70 *</td>
<td>144</td>
<td>15</td>
<td>2.8</td>
<td></td>
<td>KS</td>
<td>R, G</td>
</tr>
<tr>
<td>127 ± 5</td>
<td>66 ± 5</td>
<td>132 ± 5</td>
<td>20 ± 5</td>
<td>3.3 ± 0.5</td>
<td>36.0–44.0</td>
<td>RL–C</td>
<td>R</td>
</tr>
<tr>
<td>130 ± 5</td>
<td>70 ± 5</td>
<td>135 ± 5</td>
<td>19 ± 3</td>
<td>3.4 ± 0.5</td>
<td>20.0–22.0</td>
<td>ZL</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.2 ± 0.4</td>
<td>16–54</td>
<td>J</td>
<td>FO **</td>
</tr>
</tbody>
</table>

* Constrained in inversion; ** FO: Free Oscillations.

or used only limited surface wave data sets. Romanowicz and Lyon-Caen (1990) and Zhang and Lay (1990a) used only Rayleigh wave data (R1 and R2 arrivals) from 15 and 25 stations, respectively, in a spectral inversion for the source parameters (duration, depth and moment tensor). The only significant difference in the results of these two studies is the source duration estimate modeled in terms of a boxcar or trapezoidal duration (Table 1), for which Romanowicz and Lyon-Caen obtained a total duration of 36–44 s, while Zhang and Lay estimated a duration of 20–22 s. This difference is mainly due to the choice of phase velocity model used to correct for propagation delay, with Romanowicz and Lyon-Caen preferring the PREM model (Dziewonski and Anderson, 1981), while Zhang and Lay prefer aspherical model M84C (Woodhouse and Dziewonski, 1984). This indicates the model dependence of the long-period source parameter determinations, and raises questions about the true uncertainties of the estimates.

Kanamori and Satake (1990) applied both CMT and spectral inversion methods to a small set of R1 and G1 arrivals from 10 stations. They constrained the source depth and rupture duration in their inversions, as well as the fault dip in the spectral inversion, which used only data at a period of 256 s. Their results (Table 1) are similar to other long-period investigations, although they find the largest (most strike-slip) values for the rake (137–144°) and among the smallest seismic moment estimates \(2.5–2.8 \times 10^{19} \text{Nm}\) of the published values. Dziewonski et al. (1990) performed a CMT inversion of long-period body waves and surface waves with a more extensive data set, including the effects of aspherical model M84C, and they find a lower value for the rake (128°) but a comparable moment \(2.7 \times 10^{19} \text{Nm}\) to that of Kanamori and Satake (1990) (Table 1).

Wallace et al. (1991) inverted a very large data set of fundamental mode Rayleigh waves (R1 and R2) and Love waves (G1 and G2) for the moment tensor using a spectral technique for periods from 150 to 300 s. Their data were from 31 globally distributed stations in the Global Seismic Network (GSN), International Deployment of Accelerometers (IDA) and GEOSCOPE (Institut de Physique du Globe de Paris, France) networks. In the moment tensor inversion, Wallace et al. (1991) did not use the Love wave estimate of the \(M_{yz}\) term of the moment tensor due to instability of the inversion relative to the Rayleigh wave \(M_{yz}\) determination. Love waves were also not used in solving for centroid depth, since the excitation functions calculated for various source structures varied little with depth and the uncertainties in the source velocity structure caused problems in simultaneous modeling of Rayleigh and Love wave excitation.

Jordan (1991) analyzed free oscillations with periods from 400 to 67 s from nine vertical component IDA accelerograms to determine a centroid time of \(12.6 \pm 2.8 \text{s}\), and a characteristic duration \(\tau_c\) of \(20 \pm 11 \text{s}\). The latter characteristic duration value corresponds to a boxcar source function duration of about 35 s, while the centroid time would suggest a boxcar of 25 s duration. Jordan did not report results for the source depth or focal mechanism, but does give a seismic moment estimate of \(3.2 \pm 0.4 \times 10^{19} \text{Nm}\). In his analysis, Jordan found no evidence for a statistically significant precursory long-period radiation from the source.

The small differences in the results of long-period analyses of the Loma Prieta event are largely attributable to different model assumptions. Wallace et al. (1991) explicitly explored the model dependence of surface wave spectral inversions to assess the resolution of the source parameters and to determine whether they could resolve any anomalous long-period source process. They found that the choice of propagation model, global Q model, and source velocity structure directly affect the determinations of depth, moment and duration. By comparing their body wave and surface wave results, Wallace et al. (1991) concluded that deep, slow slip for the Loma Prieta earthquake may have occurred. However, the long-period surface wave inversions were shown to have sufficient model dependence that this hypothesis could not be confirmed, and Wallace et al. (1991) speculate that improved model corrections may eliminate any evidence for anomalous radiation.

In this paper, we further explore the model
dependence of the long-period inversions by utilizing a variety of global $Q$, phase velocity and source velocity models. The introduction of new propagation models that have better resolution of earth structure is a continuing process, and we apply one of the latest models which was not considered by Wallace et al. (1991), finding that it gives more stable results than either PREM or M84C, particularly for the duration determination. We also investigate the sensitivity of long-period spectral inversions to the source centroid location, which has not been done previously for very long-period analyses. This is motivated by the work of Zhang and Lay (1990b), who have demonstrated the effects of incorrect source location on such inversions, and by the parameterization of the CMT procedure, which allows for a pseudo-source location in the form of an optimal centroid location. Finally, we compare our resulting long-period source models with previous investigations to assess whether we can detect any anomalous long-period radiation for the Loma Prieta earthquake.

2. Data

The long-period data for the Loma Prieta earthquake are of high quality, allowing us to pursue a complete investigation of long-period source parameter determinations. Figure 2 illustrates some of the data, with well-defined Rayleigh wave arrivals (R1, R2 and R3) observed at stations of three global seismic networks (GSN, IDA and GEOSCOPE). The R1 and R2 signals have high signal-to-noise ratios. With the on-going global deployment of very broadband stations in the late 1980s, there were fortunately a large number of on-scale R1 arrivals, as shown, which have not been available for many previous events in such quantity. These on-scale R1 arrivals are desirable because the effects of inaccuracies in

![Fig. 2. A seismic profile of filtered (125–500 s) vertical component velocity seismograms for long-period channels of three seismic networks (GSN, IDA, GEOSCOPE). Amplitudes for all traces are scaled equally, and the three- and four-letter codes are station names. Multiple great circle Rayleigh waves, R1 and R2, show good signal-to-noise ratios. Many broadband instruments recorded on-scale R1 phases for the Loma Prieta event. However, due to the moderate magnitude of the earthquake, R3 arrivals are noisy and thus were not used in our analysis.]
the propagation models become greater as the distance traveled by the waves increases. The Loma Prieta earthquake was a bit too small to generate high quality long-period waves traveling more than one orbit on the surface, and the signal-to-noise ratio decreases significantly for the R3 arrivals. Zhang and Lay (1990a) found that existing propagation models have too much uncertainty to reliably estimate the short source duration of the Loma Prieta event using the R3 observations. Thus R3 and G3 arrivals are not used in this analysis other than to confirm the quality of the associated R1 and G1 spectra.

Our data set is moderately increased over that used by Wallace et al. (1991). A total of 38 stations with 88 separate arrivals comprise our data set, with the phases used being listed in Table 2. Given the high signal-to-noise ratio and the good azimuthal coverage, these signals comprise an excellent long-period data set for constraining the source parameters.

### 3. Method

We analyze long-period (157–288 s) Rayleigh waves and Love waves utilizing a moment tensor spectral inversion method developed by Kanamori and Given (1981), modified to a two-step procedure which separates source finiteness effects from the determination of the centroid depth and moment tensor (Romanowicz and Guillemant, 1984). The simultaneous Love and Rayleigh wave inversion procedure is further described by Zhang and Kanamori (1988b). The complex source spectrum of surface waves excited by a point source is a linear function of the frequency-independent moment tensor \(M_{xx}, M_{yy}, M_{zz}, M_{xy}, M_{xz}, M_{yz}\). Our linear inversion method uses the complex spectra of multiple surface wave arrivals at several discrete periods. We group velocity window each fundamental mode Rayleigh wave (R1 and R2) and Love wave (G1 and G2) arrival and calculate amplitude and phase spectra, from which we choose seven different periods (157, 175, 200, 225, 256, 275 and 288 s) for our analysis. The observed surface wave spectra must be corrected for instrument response, propagation effects and source finiteness effects, and it is these corrections that affect the duration, depth and moment tensor estimates.

Before the duration determination, we must correct the phase for propagation delay assuming a phase velocity model. We assume great-circle paths in calculating the phase propagation corrections and neglect focussing and defocussing.
since these have been shown to have only second-order effects on waves for our period range for existing smooth earth models (Schwartz and Lay, 1988).

In the first-step inversion, the source finiteness correction (eqn. 9 in Zhang and Kanamori, 1988a) is calculated for a range of trapezoid source durations. The source is assumed to be a point source since none of the previous analyses have resolved any source directivity affecting the long-period signals. A trapezoidal source model is used for convenience since the long wavelength signals studied cannot resolve any fine structure in the short source time function. Since the rise time appears to be approximately 10% of the observed rupture time for many earthquakes (Kanamori and Anderson, 1975), we assume a trapezoid rise-time equal to 10% of the duration. We measure the misfit between data and the modeled source phase using a weighted RMS error, $\sigma$ (Zhang and Lay, 1989). The duration which yields the minimum $\sigma$ is our estimate. The error is a function of the source-process time and the propagation corrections, making the duration estimate dependent on the propagation model used for correcting the phase back to the source.

In the second-step inversion, we determine the point source depth and moment tensor, where the moment tensor solution depends on the surface wave excitation functions used in the inversion. To proceed, we must account for attenuation of the surface wave arrivals when correcting observed spectral amplitudes back to the source. Thus, we must assume a global attenuation, or Q model. The excitation functions, given by Kanamori and Stewart (1976), depend on the elastic properties in the source region and the source depth, making the moment tensor solution dependent on the assumed source structure. Global Q and source velocity structure thus affect moment tensor and depth estimates. For a range of trial depths and using the optimal source finiteness corrections obtained from the first step, we measure the misfit between data and the model spectra using a weighted RMS error, $\rho$, for this second step (Zhang and Lay, 1989). The depth at which we obtain the minimum $\rho$ gives the best depth and moment tensor estimates.

The decision to use the spectral method is largely based on the ease with which various models can be used in correcting for propagation effects, in contrast to normal mode based waveform procedures such as the CMT inversion. However, we do lose the advantage of including information from overtones or long-period body waves, which become a source of noise in this fundamental mode analysis. Another advantage of the spectral inversion technique is that it allows for a separation of source time function determination from depth and moment tensor estimation, making it an ideal method for studying the effects of various models on the inversions.

In performing a simultaneous inversion of Love and Rayleigh waves, it is possible to either jointly estimate the moment tensor terms with both data types, usually with some variance-based weighting functions, or to estimate separate combinations of moment tensor terms for each data type and then merge the estimates. One advantage of determining the Rayleigh and Love wave moment tensor elements separately is that inconsistencies can easily be identified. For example, an inconsistency between the $M_{yz}$ estimates for Rayleigh and Love waves for the Loma Prieta earthquake prompted Wallace et al. (1991) not to use the $M_{yz}$ estimate from the Love waves (this was more stable than any simple averaging strategy implicit in the joint estimation approach). Wallace et al. (1991) attributed the instability of the Love wave estimation of $M_{yz}$ to the shallow depth of the earthquake in combination with the noise in the data, which is usually somewhat greater for Love waves than for Rayleigh waves. In general, the uncertainties in $M_{yz}$ and $M_{xz}$ moment tensor terms for both Rayleigh and Love waves are greatest for fundamental mode surface waves from shallow events, making it necessary to identify such inconsistencies to assess the reliability of the solutions. Furthermore, the characteristic signal quality between Love and Rayleigh wave data differs from event to event. Thus, we prefer to estimate moment tensor terms separately for each data type and then combine the estimates.

The assumed source location also affects the moment tensor inversion of long-period surface
waves, as demonstrated by Zhang and Lay (1990b), and may be an alternative explanation for the $M_{0z}$ inconsistency found by Wallace et al. (1991). Wallace et al. (1991) assumed the source location given by the NEIC determination, forcing any residual phase anomalies into the moment tensor inversion. Inaccuracies in the propagation models, particularly when anomalous relative results between Rayleigh and Love waves exist, may be reduced by determining an optimal centroid location, following the strategy of the CMT inversion procedure. Zhang and Lay (1990b) found that an optimal centroid location determined using Rayleigh waves alone may not give a good source model because of direct trade-offs between location and source mechanism. A search for centroid location is more stable when simultaneously inverting both Rayleigh and Love waves because they have different radiation patterns, and most effective when including body wave trains and overtones as done in the CMT inversion. We explore whether centroid location optimization affects the source depth, duration and moment tensor solutions for the Loma Prieta event in the following analysis.

4. Source duration estimation

For the Loma Prieta earthquake, Wallace et al. (1991) used a similar spectral inversion method to ours and explored the model dependence of the duration estimate associated with phase velocities for two models, PREM (Dziewonski and Anderson, 1981) and M84C (Woodhouse and Dziewonski, 1984). We include a new model, called MPA (Wong, 1989), which was derived using far more data than were used in the development of M84C. Figure 3 compares the spatial patterns of phase velocities for Love and Rayleigh waves for the M84C and MPA models for periods around 220 s. As can be seen, MPA has a somewhat more detailed picture of the earth than M84C, reflecting the fact that the spherical harmonic expansions of the heterogeneity are truncated at degrees 12 and 8, respectively. MPA appears to be a better match to the expectations of global tectonics, with better definition of slow regions near active oceanic ridges as well as in the tectonically active source region of the western United States, and with fast regions beneath continents being more closely related to shields. While these models are still of limited resolution, MPA represents progress in the last 5 years toward developing more accurate models for very long-period surface waves, and we will assess whether that affects our source models for the Loma Prieta event.

For a point source with the NEIC epicentral location and origin time, duration estimates for propagation models PREM, M84C and MPA demonstrate substantial model dependence (Fig. 4). Each curve in Fig. 4 shows the normalized, spectral amplitude weighted error, $\sigma$ (Zhang and Lay, 1989), as a function of assumed trapezoid source duration for Rayleigh and Love waves of a given period (157, 175, 200, 225, 256, 275, 288 s). The minimum of each curve is the best duration estimate from the corresponding period. The duration estimate is sensitive to the centroid time, and not the shape of the source time function. We assume a trapezoid parameterization for the source time function making the duration twice the centroid time, but the actual shape of the source time function is arbitrary as long as the centroid time does not change. Furthermore, the trapezoid duration estimate ($\tau$) is parameterized to be period-independent. Thus, some of the scatter between periods could reflect a more complex phenomena, such as slow slip, for which longer periods should give longer durations. Although there is a weak indication of a frequency-dependent trend for model MPA ($\tau_{150} = 12$ s; $\tau_{175} = 7$ s; $\tau_{200} = 9$ s; $\tau_{225} = 9$ s; $\tau_{256} = 17$ s; $\tau_{275} = 19$ s; $\tau_{288} = 18$ s), the scatter is more suggestive of uncertainties in the phase velocity model rather than a source phenomenon. The period range is rather small for confidently establishing any complex source model, but the greater range considered by Jordan (1991) in a free oscillation analysis also shows no indication of a strong frequency dependence of the centroid time in the phase spectra.

For each propagation model, we estimate the source duration ($\tau$) by averaging the duration estimates from the seven different periods. PREM
Fig. 3. Maps of aspherical phase velocity models used for phase propagation corrections. (a) M84C Rayleigh wave model (degree 8) at 225 s (Woodhouse and Dziewonski, 1984). (b) MPA Rayleigh wave model (degree 12) at 220 s (Wong, 1989). (c) M84C Love wave model at 225 sec. (d) MPA Love wave model at 220 s. The path anomalies are calculated by integrating along the great circle from source to receivers.
has the highest residual error $\tau$ and gives $\tau = 30$ s (Fig. 4). Model M84C significantly reduces the overall variances for all periods, and gives a shorter average duration ($\tau = 20$ s). This uniform improvement of the fit strongly indicates the need for aspherical propagation corrections for this event, as noted by Romanowicz and Lyon-Caen (1990) and Zhang and Lay (1990a). MPA further reduces the estimate of $\tau$ to approximately 11 s, but the overall variance reduction is comparable to that for M84C. In both cases the residual error is similar to that obtained using Rayleigh waves alone (Zhang and Lay, 1990a; Wallace et al., 1991), indicating that the Love and Rayleigh wave data are generally compatible in terms of a systematic source phase shift, and both wavetypes have comparable residual phase scatter after propagation correction. This is not the case in general, at least with the current generation of aspherical models. In detail, we find that the shorter durations found for MPA relative to M84C reflect small shifts of the average phase velocities at each period in the models rather than systematic improvement in path-specific corrections. The scatter between duration estimates at different periods is not reduced, and is most likely due to inadequacies of the models. M84C and MPA both reduce the normalized error relative to PREM, and thus appear to give better estimates of the duration, but choosing between the two is difficult. MPA does give a source duration which is virtually identical to durations estimated from shorter period studies, and additional evidence favoring this solution is described below.

To test the propagation models further, we explored the effects of assuming different source locations in the first-step inversion. If there are systematic errors in the models that can map into a source relocation, this procedure can reduce those errors and potentially may reduce any bias in the duration estimate. This process can be visualized as locating the effective source position with a 'best' point source trapezoidal source time function. Surface waves alone are not usually used for source location due to the limited resolution of the long wavelength waves, which lack sensitivity to small location perturbations. Because our data set is of unusually high quality, we proceed to search for the source location that minimizes the first-step error using a 112 km × 112 km grid centered about the NEIC location. The grid has 8 km spacing, and the spectra were corrected to each location assuming the NEIC origin time is unperturbed. We then invert for duration using the first-step inversion at each grid point. By contouring the normalized error, $\sigma$, given by the average residual error for a given source duration for the seven different periods, we identify the optimal source location consistent

![Fig. 4. Normalized error vs. assumed trapezoid source duration obtained in the first-step inversion. Each plot shows duration estimates for a given earth model (PREM, M84C and MPA) used to make propagation corrections in the combined inversion of Rayleigh and Love waves. The minimum of each curve is the duration estimate from the inversion of waves of that particular period. The estimates at each period are combined to determine the optimal mean duration over the period range. The mean duration estimates are 30, 20 and 11 s for PREM, M84C and MPA, respectively.](image-url)
with the corresponding propagation model and a trapezoidal representation of the source time function.

Figure 5 shows contours of $\sigma$ over the search grid obtained using models PREM, M84C and MPA (Figs. 5(a), 5(b) and 5(c), respectively). The contoured surfaces have well-defined minima with value $\sigma_{\text{min}}$ which are reasonably concentrated spatially. For PREM (Fig. 5(a)), $\sigma_{\text{min}} = 0.483$, which is larger than for the other models, and the minimum is located approximately 35 km north-east of the event epicenter. This result should not be confused with a centroid location, for we are not finding a best moment tensor in this search. Rather, we are finding how compatible the propagation models are with the travel times from the actual source location to the set of stations. The overall error reduction is only 15% over the grid for the PREM model. For M84C (Fig. 5(b)), $\sigma_{\text{min}} = 0.325$, the smallest value of the three models, and the apparent source location is just north of the epicenter. The area surrounding this minimum with less than 4% variation in $\sigma_{\text{min}}$ encompasses the epicentral region. The variance reduction for M84C as a function of position over the grid is 30%, which is twice as large as for PREM. The results for MPA (Fig. 5(c)) give $\sigma_{\text{min}} = 0.340$, a value slightly higher than that for M84C, with the spatial variance reduction in the grid being 30%, virtually identical to M84C. However, model MPA locates the optimal source position right at the actual epicenter, a remarkable demonstration of consistency of the propagation corrections with the independently known source location. This leads us to place additional confidence in the duration estimate using model MPA, complementing the consistency with the body wave analyses. For all three models, the actual duration

Fig. 5. Contours of the residual error in the first-step inversion using propagation models (a) PREM, (b) M84C and (c) MPA for different assumed source locations. A 112 km x 112 km grid of assumed epicentral locations, comprised of 225 points (triangles), was constructed around the epicenter. The spectra are corrected back to each source location, with the origin time held fixed at the NEIC origin. The residual error from the first-step inversion at each assumed source location is contoured. The minimum error gives the optimal epicentral location for a point source. For PREM, the minimum error is located northeast of the actual epicenter. M84C locates the minimum error slightly to the north of the epicenter, whereas MPA locates the minimum error directly on the epicenter. Duration estimates vary by only a few seconds over the grid for each model.
estimate varies by only a few seconds over the grid ($\tau = 10$–$13$ s for MPA), and the variations are less than 1 s within the region of the lowest contour, which includes the minimum. This result is important for the second-step inversion in which we specify the duration and then invert for depth and moment tensor. It is thus reasonable to use a single value for the duration associated with a given propagation model when searching over the same grid for an optimal centroid location which yields the best moment tensor fit to the data.

5. Depth, moment tensor and centroid location estimation

The second-step inversion depends on the choice of $Q$ model and source region velocity structure. Zhang and Lay (1990a) and Wallace et al. (1991) explored the effect of global $Q$ model on source depth determination using the three models shown in Fig. 6, which are from Masters and Gilbert (1983), Dziewonski and Steim (1982), and PREM (Dziewonski and Anderson, 1981) (subsequently referred to as MG, DS and PREM, respectively). Depth determinations varied by 10 km for the Loma Prieta earthquake depending on which model was assumed. We use the same global $Q$ models in the present analysis, since they represent a reasonable range of one-dimensional models. A new generation of aspherical $Q$ models is presently emerging, but correct utilization of these models requires simultaneously accounting for complex focussing and defocussing effects due to the velocity inhomogeneity. Such analysis is being undertaken, but has not been included in this paper.

The source velocity structure to be used for calculating the excitation functions is perhaps the least constrained set of model parameters required for the second-step inversion, given the complex tectonic history of the source region. Wallace et al. (1991) used the four source velocity models shown in Fig. 7, including the average and...
young ocean models of Regan and Anderson (1984), the average PREM structure, and an ad hoc model called LOMA, comprised of a P-velocity crustal model from Walter and Mooney (1982) the western US P-velocity mantle model GCA of Walck (1985) and the S-velocity mantle model TNA of Grand and Helmberger (1985) (subsequently these models are referred to as RA, RA-yo, PREM and LOMA, respectively). These models span a reasonable range of upper mantle structures expected for the tectonically active source region, but a localized lithospheric model specific to the area is not available. Thus, there will be intrinsic uncertainty in all of the source inversions. Since we have no new information regarding the appropriate structure, we utilize the same four models. Wallace et al. (1991) found that the centroid depth varied about 10 km depending on the choice of source excitation structure, but other parameters are not strongly affected.

5.1. Moment tensor and centroid location

The source location will affect the moment tensor through both the effects on the phase and minor amplitude effects due to propagation and attenuation, as demonstrated by Zhang and Lay (1990b). We proceed to use both Rayleigh and Love wave spectra to find the centroid location, depth and moment tensor by searching over the same 112 km x 112 km grid as used in the duration determination. Setting the source duration to be the optimum for each propagation model, a large number of inversions were performed to determine the moment tensor and depth at each grid point. Inversions were performed for the suite of global Q models (MG, DS, PREM), source velocity models (RA, RA-yo, PREM, LOMA) and propagation models (PREM, M84C, MPA) for each grid point. The \( \rho \) values for each grid point are then contoured over the grid, with the minimum giving an optimal centroid location, since \( \rho \) is a measure of how well the data are fit by the associated moment tensor for that source position. We find that for each grid point the depth resolution curves are relatively flat. However, the \( \rho \) values vary substantially over the grid, providing a fair estimate of the centroid location.

We first explore the effect of the propagation models on the second-step inversion by specifying the excitation structure to be RA-yo and the global Q model to be MG, and then inverting for depth and moment tensor at every grid point for PREM, M84C and MPA. Figure 8 shows resulting contours of \( \rho \) where the duration is fixed at 30 s for PREM, 20 s for M84C, and 11 s for MPA. In the moment tensor inversion, the spectra at each period are inversely weighted by the corresponding residual errors for the first-step inversion to accommodate the non-uniform spread of the travel-time scatter indicated in Fig. 4. Since there are significant differences in \( \rho_{\text{min}} \) between the phase velocity models, the contour plots have been separately normalized to their minimum \( \rho \), with the scale showing relative residual variance values ranging from 1.0 to 1.5. For PREM (Fig. 8(a)), the error reduction over the grid is only about 30%, with the minimum encompassing a broad region centered just north of the epicentral region. The smallest residual variance (\( \rho_{\text{min}} = 0.100 \)) is about 30% higher than that for M84C (Fig. 8(b), \( \rho_{\text{min}} = 0.0773 \)) and MPA (Fig. 8(c), \( \rho_{\text{min}} = 0.0724 \)). For M84C (Fig. 8(b)), the variation in \( \rho \) over the grid is approximately 50%, and the contours show a steep-sided well with a flat bottom encompassing the epicenter. Results for MPA (Fig. 8(c)) are comparable to M84C, although \( \rho_{\text{min}} \) is slightly lower than for M84C.

For the different propagation models, the position of \( \rho_{\text{min}} \) varies little in location. For PREM, M84C and MPA, the centroid location is shifted just offshore about 24 km west of the epicenter. However, using PREM propagation and excitation models shifts \( \rho_{\text{min}} \) 24 km northeast of the epicenter (Fig. 8(a)). These shifts are comparable to those found for the CMT centroid (Fig. 1), which is heavily influenced by the long-period body wave trains in the records rather than the fundamental mode arrivals. Thus, the choice of propagation model not only affects the second-step inversion residual variance, but it can also affect the centroid location.

The next model sensitivity that we test is the influence of the excitation structure, using models RA-yo, PREM and LOMA, where we specify
Fig. 8. Contours of the residual error in the second-step inversion for the full moment tensor as a function of source centroid location for propagation models (a) PREM, (b) M84C and (c) MPA. The second-step inversion is affected by the choice of propagation models for a given excitation structure (in this case, RA-vo: Regan and Anderson, young ocean model (1984)) and global Q model (in this case, MG: Masters and Gilbert (1983)). The minimum error (\( \rho_{\text{min}} \)) gives the optimal centroid location for a particular combination of models. For PREM, M84C and MPA, the centroid location (solid square) is shifted just offshore about 24 km west of the epicenter (solid triangle). The minimum second-step errors (\( \rho_{\text{min}} \)) are 0.1000, 0.0773 and 0.0724 for PREM, M84C and MPA, respectively. Using PREM propagation and excitation models results in a 20 km shift of the centroid northeast of the epicenter, as demonstrated in (a). In each case, the minima are broad and flat, and the epicenter is encompassed in the lowest contour level.
the propagation (MPA) and global Q (MG) models. Figure 9 shows contours of $\rho$ as a function of source location in the source grid. The contours are scaled over a 40% relative residual error variation to accentuate any differences that may exist. Model LOMA has a broad minimum (Fig. 9(a)), with $\rho_{\text{min}} = 0.0985$, while PREM (Fig. 9(b)) has a lower $\rho_{\text{min}} = 0.0872$. The result for RA-yo shown in Fig. 9(c) involves the same combination of models as in Fig. 8(c) but plotted on a slightly different scale for comparison. This model has $\rho_{\text{min}} = 0.0724$, which is the smallest for the three excitation structures considered. Although there is a baseline shift in the $\rho_{\text{min}}$ estimates depending on the excitation structure used, the minimum in each surface does not vary, and is located 24 km west of the actual epicenter. This is true for various propagation models combined with the different excitation structures. Thus, the centroid location is not affected significantly by the choice of source velocity structure.

Our final sensitivity test is with respect to the global Q model used in the inversion. We specify the propagation model (MPA) and the excitation model (RA-yo), and then invert for depth and the moment tensor using the three global Q models (PREM, DS and MG). Figures 10(a), 10(b) and 10(c) show the centroid location results for the PREM, DS and MG Q models, respectively. As can be seen, the choice of Q does not affect our centroid location or the shape of the minimum. The $\rho_{\text{min}}$ values are all virtually identical. The choice of global Q model does strongly influence the depth and moment tensor estimates, but not the centroid location. This result may change, however, with the advent of new aspherical global Q models that are currently under development.

The optimal centroid location estimates are shifted from the epicenter, as is the case for the CMT solution, but the location brings the Rayleigh and Love wave estimates of the $M_{Tz}$ moment tensor element into better agreement for the MPA and M84C propagation models, yielding unconstrained moment tensor inversions that are consistent with body wave studies. The location bias is most likely a result of errors in the models, since the source does not have significant spatial finiteness. Even though the value of $\rho$ at the epicenter is within a few percent of that at the optimal centroid location for any of the model combinations, we found that the results are generally significantly more stable if we use the centroid location. Even a few percent difference in variance reduction can destabilize the inversion for poorly constrained terms like $M_{zz}$ and $M_{xz}$. Inversions at the epicenter tend to give strikes and rakes that are 10° lower than the centroid results, which are less consistent with the body waves. Thus, centroid optimization gives improved results over the study of Wallace et al. (1991), who only considered sources at the epicenter.

The stability of the moment tensor inversions around the centroid location is illustrated in Fig. 11 for the particular model combination of MPA, RA-yo and MG. The best double-couple solutions for each moment tensor inversion are shown at nine source positions around the optimum centroid as well as at the epicenter. Since the nine source locations are within the region where $\rho$ is minimized (e.g. Fig. 10(c)), the mechanisms vary only slightly (4° in strike, 4° in dip, and 6° in rake). At the epicenter, which is slightly further from the minimum, the rake and strike vary by up to 10°, and the variations get stronger at larger distances from the optimum centroid. The results shown here are comparable to those using RA-yo and MG in combination with model M84C, while using PREM with these models gives greater stability with only a few degrees difference in mechanisms at the centroid and the epicenter. However, using PREM alone for propagation and excitation does not yield good results.

It is by no means obvious that using an effective source location that gives the best variance reduction for the moment tensor will necessarily give the 'best' moment tensor. This is also true for the CMT procedure. We find the encouraging result that no matter what phase velocity and attenuation model is used, and for most reasonable source excitation structures, the solutions for the simultaneous Love and Rayleigh wave inversion are essentially identical when we perform them at the optimal centroid location for the particular model combination. This stability suggests that the primary differences in the spectra
Fig. 9. Contours of the residual error in the second-step inversion for the full moment tensor as a function of point source location for excitation structures (a) LOMA, (b) PREM, and (c) RA-ye. The propagation model is MPA and the Q model is MG. The centroid location (solid square) is not very dependent upon the excitation models, although the RA-ye model has the lowest absolute error and the most spatially concentrated minimum.
Fig. 10. Contours of the residual error in the second-step inversion for the full moment tensor as a function of point source location for Q models: (a) PREM, (b) DS, and (c) MG. The propagation model is MPA and the excitation structure is RA-yo. The centroid location is not dependent upon the Q model.
corrected for the different models are small slowly-varying phase and amplitude patterns. This is apparent in the significant differences between moment tensor inversions for different model combinations when the epicenter location (or any other common source location) is assumed. The centroid location procedure projects most of these small, low-degree azimuthal patterns into the source relocation, finding in each case a comparable moment tensor fit to the Love and Rayleigh spectra. This is only stable due to the significant differences in the radiation patterns for these spectra, and the centroid optimization may not converge to the correct solution if only Rayleigh waves are used, as noted by Zhang and Lay (1990b). The CMT inversion is similarly stabilized by the differences in the radiation patterns of the body wave and surfaces wave arrivals in the wave trains that are inverted. Since the centroid optimization reduces to some extent the dependence on the model parameters, we are able to establish realistic confidence bounds on our source parameter estimates by comparing the suite of results for different model combinations.

5.2. Depth

Associated with the moment tensor inversions is a search over point source depth at each source location. Depth resolution curves tend to have fairly well-defined minima for inversions that use only Rayleigh waves, while the simultaneous Love and Rayleigh wave inversions give flattened depth curves (Fig. 12), as noted by Wallace et al. (1991). This is largely due to the lack of depth dependence of the Love wave excitation functions, but
Fig. 13. Moment tensor inversion results from simultaneous inversions of Rayleigh and Love waves at periods of 157, 175, 200, 225, 256 and 275 seconds. The curves are the theoretical fits determined from the solution using the RA-yo excitation, MG global Q and MPA phase velocity models. Solid circles are amplitude data; solid squares are phase data. Note the excellent fit to the observed spectra over the period range investigated.
also reflects some source model incompatibility with the joint Love and Rayleigh wave data. For example, the top row in Fig. 12 shows inversions using MPA and MG models for different excitation structures. In both cases, the RA-yo model reduces the overall variance significantly and gives shallower depth estimates relative to the other source structures. The simultaneous inversions show greater sensitivity to the excitation models, and it appears that the ad hoc LOMA model does not fit the Love wave data very well relative to the other models, which accounts for some of the unstable solutions found using this model.

The choice of Q model also affects the depth estimate, as shown in the bottom row of Fig. 12, with shallower depths being found when using the MG model. The latter model gives a slightly lower residual variance for the Rayleigh wave inversion, but there is no significant difference for the simultaneous inversions. Clearly, there is substantial uncertainty in the depth estimates given both the flatness of these curves and our lack of a priori knowledge of which source velocity structure is most appropriate (the LOMA model is probably inadequate). As a result, we assign large uncertainties to our depth estimate. Taking into account the range in depth determinations for the different global Q models and source velocity structures, our final depth estimate is 22 ± 11 km. For the models with water layers (PREM and RA-yo) the depth into the solid crust is 5 km less, giving a centroid depth into the crust of about 17 ± 11 km. However, changing the crustal structure from oceanic to continental has little effect on the estimate of depth (Zhang and Lay, 1990a).

5.3. Preferred solution

In our final inversion, we use the MPA phase velocity model, RA-yo source structure and MG global Q model to demonstrate the fit to the data. Figure 13 compares the azimuthal patterns of observed amplitude (solid circles) and phase spectra (solid squares) with the theoretical moment tensor (solid curves) found in the simultaneous inversion of Rayleigh and Love waves for six of the seven periods used in the inversion (the 288 s data are not shown, but closely resemble the 275 s data). Each point is an observed spectral measurement of amplitude or phase for R1, R2, G1, or G2 arrivals. The high signal to noise ratio apparent in the time domain in Fig. 2 results in high quality spectral measurements that have very little scatter. Amplitude scatter increases for shorter periods, but the data are generally very well behaved, and clearly exhibit coherent radiation patterns. The moment tensor terms for this final solution are listed in Table 3, along with the moment tensor terms for the CMT inversion of Dziewonski et al. (1990). These results are generally quite compatible.

It is very encouraging to note that the new phase velocity model, MPA, yields a stable solution consistent with previous studies, without employing any constraints on the inversions. The duration estimate of 11 s and the consistency of the phase with the epicentral location for model MPA provides evidence that this model gives the most reliable results. However, we do find that for the simultaneous inversion of Love and Rayleigh waves, it is still important to determine an optimal centroid location to ensure a stable

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<td>Moment tensor solutions for the Loma Prieta earthquake (in units of 10^{19} Nm)</td>
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solution. Based on our preference for the MPA model, along with our consideration of the uncertainty in the source structure and Q model, our final duration is $\tau = 11 \pm 5$ s, and our depth estimate is $22 \pm 11$ km.

Taking into account the slight changes in mechanisms due to uncertainties in choosing a preferred earth model combination, we give as our preferred major double-couple representation for the Loma Prieta event a mechanism with strike = $124 \pm 6^\circ$, dip = $67 \pm 6^\circ$, rake = $126 \pm 7^\circ$, where the stated uncertainties include our subjective assessment of the model dependence. Seismic moment estimates vary little in the vicinity of the centroid, and for all model combinations that give reasonable solutions (some of the inversions with the LOMA excitation functions do not), we find a moment, $M_0 = 3.0 \pm 0.2 \times 10^{19}$ Nm. The non-double-couple component varies from 5 to 30% depending on source location, global Q model and source velocity model, with solutions near the centroid having about 10% minor double couples, which we deem to be noise effects. Comparison of these final parameters with other long-period results in Table 1 indicates good consistency, particularly with the CMT solution of Dziewonski et al. (1990).

6. Discussion

The Loma Prieta earthquake provides an excellent opportunity to test whether a single broadband seismic model can explain the entire

Fig. 14. Summary of moment, depth and duration estimates from this study and previous body wave studies by: (1) Wallace et al., 1991; (2) and (3) Kanamori and Satake, 1990; (4) Choy and Boatwright, 1990; (5) Ruff and Tichelaar, 1990; (6) Romanowicz and Lyon-Caen, 1990; (7) and (8) Langston et al., 1990; (9) Barker and Salzberg, 1990; (10) Wallace and Lay, 1990; (11) Nábělek, 1990; (12) Ammon, 1991; (13) Wald et al., 1991. Long-period surface wave studies are from: (14) this study; (15) Wallace et al., 1991; (16) Dziewonski et al., 1990; (17) and (18) Kanamori and Satake, 1990; (19) Romanowicz and Lyon-Caen, 1990; (20) Zhang and Lay, 1990a; (21) a free oscillation study by Jordan, 1991. Our estimates of moment and depth overlap with estimates from other investigations. Our duration results for the preferred MPA propagation model are consistent with those of body wave studies.
faulting process. Careful analysis of modeling assumptions, for both body and surface waves, is needed to assess the confidence bounds on source parameter estimates. We have demonstrated that propagation velocity model, global attenuation model, source velocity structure and assumed source location can have significant effects on the centroid depth, source duration and seismic moment tensor estimated by inversion of surface waves. Our analysis has explored a portion of the model space of the spectral inversion method, allowing us to assess the uncertainties in long-period source parameters.

We will now compare our results with other investigations of the Loma Prieta source, with an emphasis on assessing any systematic frequency-dependent differences. Understanding any discrepancies between short-period and long-period source models is essential for understanding fault rupture processes of large earthquakes. One physical explanation for frequency dependence of source properties may be variation in energy release along a fault rupture surface, with 'patches' of large displacement that fail with rapid rupture, producing high frequency body wave radiation while the surrounding regions slip slowly, having a predominantly long-period signature. Both teleseismic and strong motion investigations of the Loma Prieta event suggest some non-uniform slip on the fault, which would not be resolvable by our surface wave analysis, but could potentially give rise to some frequency dependence of the source parameters. Another possible cause of a discrepancy could be slow coseismic slip in the lower crust or uppermost mantle at the base of the aftershock zone. High strain rates during the mainshock rupture may induce coseismic failure on the down-dip extension of the fault, where grain size and thermal conditions may cause differences in rupture or particle velocities affecting the spectrum of seismic radiation (e.g. Das, 1982).

Figure 14 summarizes all available source parameter determinations for the Loma Prieta event, with the results from this study being indicated with the open circles (and number 14). Wallace et al. (1991) discussed the differences between their body and surface wave results. They found that the surface wave rupture duration and depth estimates were both larger than the body wave estimates, while the seismic moment at long-period was marginally larger than at least some body wave results, and thus suggested that deep, slow slip may have occurred during the Loma Prieta earthquake. With our further surface wave analysis, our seismic moment estimates is slightly reduced to $3.0 \pm 0.2 \times 10^{19}$ Nm. Other surface wave and free oscillation results give estimates between $2.5$ and $3.4 \times 10^{19}$ Nm. Body wave results (Fig. 14) for moment vary between $1.7$ to $3.0 \times 10^{19}$ Nm, with the most thorough body wave studies (e.g. Wald et al., 1991) giving the larger values. If the body wave values are not biased by the renormalization procedure used in scaling poorly matched strong-motion waveforms up to fit peak amplitudes, then we can conclude that there is no discrepancy in the moment estimates, suggesting a fairly high corner frequency for the source. Comparing depth estimates (Fig. 14), we see that our depth estimate has a larger uncertainty than other long-period estimates. This in part reflects our inversion of both Rayleigh and Love waves, which increases our sensitivity to poorly known source structure, but also includes our awareness of the strong model dependence. Thus, our error bars overlap with previous body wave studies as well as surface wave and free oscillation studies (Fig. 14). Thus, there appears to be no resolvable discrepancy between long- and short-period depth estimates at the present.

Finally, our results for source duration vary from $30$ s for PREM to $11$ s for MPA. We prefer the latter results for the reasons stated above. Thus, the centroid time of the moment release is $6.1$ s after the onset of rupture (recall that we include a $10\%$ rise time). The surface waves we use are only sensitive to the centroid time and not to the shape of the source function. To compare this with the body wave results, we must ensure a common origin time for reference. Wald et al. (1991) discovered a $1.6$ s precursor to the main rupture, which cannot be seen seismically, but appears to correspond to the origin time of the local array trigger, given by Dietz and Ellsworth (1990). Since we use this origin time for our analysis ($0004:15.21$ UTC on 18 October 1991), our time function must be shifted slightly...
Fig. 15. Comparisons of our surface wave source time function, a deconvolved body wave source time function (Wallace et al., 1991), and local and teleseismic data (after Wald et al., 1991) for the Loma Prieta event. BSR Z, TOL Z, SAR Z and SAO Z are vertical component displacement seismograms recorded at local or teleseismic distances. Labels 1, 2 and 3 on TOL Z represent identified pulses of energy corresponding to subevents. A 1.6 s time shift of the strong motions and teleseismic signals relative to the local array-triggering arrival was identified by Wald et al. (1991), caused by a small precursory radiation. Note the consistency in the centroid time of the moment release between the surface wave and body wave source time functions.
from those obtained from teleseismic body wave results (Fig. 15). The source time function from our study and the source time function from teleseismic broadband body wave deconvolutions (Wallace et al., 1991) have very consistent centroid times. Given our preference for the MPA model results, we find no duration discrepancy. Thus, we do not find any evidence supporting the hypothesis of significant frequency dependence of the source parameters, and hence no evidence for deep, slow slip or other anomalous long-period radiation.

While our procedure provided an optimal centroid location for each model combination, we do not attach any significance to the centroid position, for it is probably a manifestation of model inadequacies. Comparing our centroid location from the second-step inversions with the CMT solution, we find that our centroid is shifted to the west, while the CMT procedure shifts the centroid to the east of the epicenter. This difference is probably a result of the different types of data used. If we use the CMT centroid location in the surface wave inversion we do not get acceptable results, which suggests that the CMT inversion and centroid determination primarily fit the body wave portion of the seismograms. We did demonstrate that global Q and source velocity models had little affect on the centroid location. Furthermore, it is interesting to note that the phase velocity propagation models affect the centroid location in the second-step inversion, despite use of the optimal source durations for the different models. This indicates that the residual phase anomalies from the first-stage inversion can be suppressed in the second-stage inversion which uses the complex number representation of the spectra. We find that by minimizing the second-stage error, $p$, we stabilize the estimation of source parameters, regardless of which propagation model is utilized, as long as the excitation and Q structures are compatible with the data.

7. Conclusions

In this study, we have extended the analysis of long-period fundamental mode Rayleigh and Love waves for periods ranging from 157 to 288 s for the Loma Prieta earthquake, and further explored the stability of the focal mechanism, seismic moment, centroid depth, source duration and centroid location determinations. Duration and centroid location are both influenced by the choice of propagation model. By including a recent spherical harmonic degree 12 phase velocity model, MPA, the long-period analysis gives duration and source location results consistent with other studies. Attenuation and source velocity structure models mainly affect depth and moment tensor estimates. We introduce a procedure for searching for an optimal centroid location that appears to significantly stabilize focal mechanism determinations for simultaneous inversions of Love and Rayleigh waves. While significant model uncertainty increases our confidence bounds on our source parameter estimates, we find no significant discrepancies in the long-period parameters relative to results from shorter period waves. Thus, we conclude that there is no evidence for anomalous long-period radiation from the mainshock. Better resolution of frequency-dependent source phenomena will require improved propagation and attenuation models, many of which are currently being developed. Application of these new models to the excellent Loma Prieta data set in the future is well justified given the large confidence bounds in the present work, and the value of this event to calibrate methodologies.

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