When and where the aftershock activity was depressed:
Contrasting decay patterns of the proximate large earthquakes in southern California

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[1] Seismic quiescence has attracted attention as a possible precursor to a large earthquake. However, sensitive detection of quiescence requires accurate modeling of normal aftershock activity. We apply the epidemic-type aftershock sequence (ETAS) model that is a natural extension of the modified Omori formula for aftershock decay, allowing further clusters (secondary aftershocks) within an aftershock sequence. The Hector Mine aftershock activity has been normal, relative to the decay predicted by the ETAS model during the 14 months of available data. In contrast, although the aftershock sequence of the 1992 Landers earthquake (\(M = 7.3\)), including the 1992 Big Bear earthquake (\(M = 6.4\)) and its aftershocks, fits very well to the ETAS up until about 6 months after the main shock, the activity showed clear lowering relative to the modeled rate (relative quiescence) and lasted nearly 7 years, leading up to the Hector Mine earthquake (\(M = 7.1\)) in 1999. Specifically, the relative quiescence occurred only in the shallow aftershock activity, down to depths of 5–6 km. The sequence of deeper events showed clear, normal aftershock activity well fitted to the ETAS throughout the whole period. We argue several physical explanations for these results. Among them, we strongly suspect aseismic slips within the Hector Mine rupture source that could inhibit the crustal relaxation process within “shadow zones” of the Coulomb’s failure stress change. Furthermore, the aftershock activity of the 1992 Joshua Tree earthquake (\(M = 6.1\)) sharply lowered in the same day of the main shock, which can be explained by a similar scenario.

INDEX TERMS: 7223 Seismology: Seismic hazard assessment and prediction; 7230 Seismology: Seismicity and seismotectonics; 8164 Tectonophysics: Stresses—crust and lithosphere;

KEYWORDS: aseismic slip, anomalous aftershock decay, Coulomb stress shadow, ETAS model, modified Omori formula, spatial pattern of aftershock decay


1. Introduction

[2] The 16 October 1999 \(M = 7.1\) Hector Mine earthquake occurred about 20 km northeast of the Landers earthquake (\(M = 7.3\)) which occurred on 28 June 1992 in southern California. The 28 June 1992 Big Bear earthquake of \(M = 6.4\) followed the Landers main shock by three hours, about 35 km west of the Landers epicenter. Also, the 22 April 1992 Joshua Tree earthquake preceded the Landers event near the southern end of the future Landers aftershock zones (Figure 1). Detailed seismicity observations of these events and their aftershocks are described by Hauksson et al. [1993]. The proximity of these earthquakes has led to a number of studies suggesting possible physical mechanisms [King et al., 1994], especially with regard to the question of whether the time of the Hector Mine earthquake was advanced by the stress changes caused by the Landers event [U.S. Geological Survey, 2000; Parsons and Dreger, 2000; Gomberg et al., 2001; Freed and Lin, 2001].

[3] However, there have been only a few seismicity studies on the relationship, based on their well-recorded aftershock sequences. For example, change of seismicity patterns due to the Landers earthquake is argued by Wyss and Wiemer [2000] based upon the declustered data set that removes aftershocks and swarms from the original catalog.
We are concerned, however, with aftershocks themselves, which comprise a major portion of an earthquake catalog, and therefore should include rich information concerning stress changes [Dieterich, 1994].

The observed relaxation properties of aftershocks sequences are considered to be the result of some complex and not well defined combination of processes and physical properties [Mogi, 1967; Kisslinger and Jones, 1991; Guo and Ogata, 1997]. Extensive reviews on their possible mechanisms are given by Utsu [1970] and Kisslinger [1996]. In particular, the aftershock decay parameter $p$ of the modified Omori formula has been estimated to explore physical features of aftershocks, reflecting heterogeneity and complexity of fault zones including geothermal environment. For example, Wiemer and Katsumata [1999] present a spatial variability of decay rate for the Landers aftershocks, assuming that the $p$ value of the modified Omori formula depends on location but is invariant with time, since they are concerned with nontransient, environmental features of the crust, such as heat flow and viscoelastic properties, in the different subregions.

In contrast, we are concerned with the detailed complex features of aftershocks such as interactively triggered aftershocks including those among off-fault regions within the wide aftershock regions of the Landers earthquake, as discussed by Felzer et al. [2002]. We will then analyze whether the model can be the same throughout the whole period or if the model needs to be modified to incorporate different parameter values after some time during the period, before we examine the regional patterns. That is to say, in this paper, we seek to apply good fitting models for normal aftershock occurrences to the Landers aftershock sequence, so as to examine whether an anomalous change to the aftershock decay rate took place or not. If such a change occurred, then perhaps the seismic change is somehow related to changes in stress in the crust, as described in Dieterich et al. [2000]. We also investigate the aftershock sequence of the 1992 $M = 6.1$ Joshua Tree earthquake leading up to the Landers earthquake.

2. Data

We use the earthquake catalog that has been relocated with a three-dimensional velocity model [Hauksson, 2000] based on data from the Southern California Seismic Network (SCSN) and the new TriNet stations [Mori et al., 1998]. Thus the depths and locations of the earthquakes in our analyses are very well constrained. For the study of the Hector Mine aftershocks, we use the available data for the period from the main shock through to 23 December 2000. The locations of these aftershocks are indicated in Figure 1 by red circles. For the study of the Landers aftershocks, we use events for the period until the occurrence of the 1999 Hector Mine earthquake, and a sequence includes the 28 June 1992 Big Bear earthquake of $M = 6.4$ which followed the main shock by three hours on the same day. These aftershocks can be considered as off-fault secondary aftershocks of the Landers earthquake, as well as the aftershocks in the Barstow region (region A). The Joshua Tree aftershocks before the Landers rupture are given by dark blue disks in region D, which are overlaid on the Landers aftershocks.

3. Model Fitting to the Aftershock Sequences

3.1. ETAS Model

The typical aftershock decay is represented by the Modified Omori function,

$$v(t) = K(t + c)^{-p}, \quad (K, c, p: \text{parameters}),$$

initiated by the main shock at time origin $t = 0$. This formula was proposed by Utsu [1961] from fits to many data sets as a modification of the Omori law [Omori, 1894]. This
formulas remains the most widely used model for typical aftershock rate decay. To estimate the coefficients, Ogata [1983] proposes the method which maximizes the log likelihood function

\[
\ln L(K, c, p; S, T) = \sum_{i=1}^{N} \ln v(t_i) - \int_{T}^{S} v(t)dt, \tag{1}
\]

with respect to \( K, c, \) and \( p, \) where \( \{t_i, i = 1, 2, \ldots, N\} \) is a series of occurrence times of aftershocks in the time interval \((S, T).\) Typically, equation (1) holds for quite a long period in the order of some tens of years or more, depending on the background seismicity rate in the neighboring area. See Utsu et al. [1995] and Ogata and Shimazaki [1984].

As we consider small aftershocks, however, clustering within the sequence becomes apparent. Thus aftershock activity is not always best predicted by the single modified Omori function [Guo and Ogata, 1997], especially when it includes remarkable secondary aftershock activities of large aftershocks. Therefore we assume that every aftershock can trigger its further aftershocks or remote events, and that the occurrence rate at time \( t \) is given by a (weighted) superposition of the modified Omori functions shifted in time

\[
\lambda(t) = \mu + \sum_{j} e^{\alpha(M_j-M)} v(t-t_j),
\]

where \( \mu \) represents the rate of the background seismicity, and the summation is taken over every \( j \)th aftershock occurred before time \( t, \) including the main shock at time origin \( t_0 = 0. \) The weighted size of its aftershocks is made as the exponential function of its magnitude \( M_j \) in accordance with the study by Utsu [1970], where \( M_c \) represents the cutoff magnitude of the fitted data. We call this the epidemic-type aftershock sequence (ETAS) model [Ogata, 1988], which was originally proposed for the general seismic activity in a region. For a single aftershock sequence, we usually expect very low background seismic rate (i.e., \( \mu = 0 \)) relative to the aftershock rate. For a sequence of occurrence times associated with magnitudes, we can estimate the parameters \( \theta = (\mu, K, c, \alpha, p) \) of the ETAS model that are common to all \( i, \) by maximizing the log likelihood function of \( \theta, \) which is of the same form as the one in equation (1) with the exception that the Modified Omori intensity function \( v(t) \) is replaced by the ETAS intensity \( \lambda(t). \) Here we note that in contrast to the Modified Omori intensity function, calculation of the log likelihood has to take account of the fact that the ETAS intensity \( \lambda(t) \) is conditional on the past history of occurrence since the main shock, in the sense that the intensity includes the events’ occurrence times and associated magnitudes in the time span \([0, t).\) See Utsu and Ogata [1997] for computational codes and useful manuals and Helmstetter and Sornette [2002], for example, for some discussions of statistical features of the ETAS model.

### 3.2. Model Comparison and Change Point Analysis


\[
\text{AIC} = (-2) \max_{\theta} \{ \log \text{likelihood} \}
+ 2 \{ \text{number of adjusted parameters} \}
+ (\text{number of events}) \]

is useful to compare the goodness of fit of the competing models to a given data set. The model with a smaller AIC value shows a better fit (see also Akaike [1987] for relation to the likelihood ratio statistics). For example, Guo and Ogata [1997] compared the goodness of fit between the modified Omori formula (three parameters) and the ETAS model (four or five parameters) applied to 34 aftershock sequences of the latest 20 years in the last century, in Japan and its vicinity. The results were that for two thirds of the sequences, the ETAS model fitted better than the modified Omori formula. In such a case, the \( p \) value of the modified Omori formula is usually smaller than the \( p \) value of the ETAS model. This shows a heavier tailed decay in trend, owing to the effect of further clusters within the sequence. For the remaining one third of the sequences where the modified Omori model is a (slightly) better fit than the ETAS, its \( p \) value almost coincided with that of the ETAS. In general, the ETAS tends to fit better as the cutoff magnitude of the sequence lowers, as the clusters within it become apparent. This demonstrates that ETAS is a natural extension of the modified Omori model for studying various types of aftershock sequences, including nonvolcanic swarms [Utsu et al., 1995].

[10] In order to examine whether or not the temporal aftershock pattern changed at a suspected time \( t \) on a time interval \((S, T)\) in a given data set, we consider a two-stage ETAS model applied to the occurrence data sets on the separated subintervals \((S, t)\) and \((t, T),\) respectively, to calculate the corresponding AICs:

\[
\text{AIC}_1 = (-2) \max_{\theta_1} \ln L(0_1; S, t) + 2 \dim(\theta_1)
\]

\[
\text{AIC}_2 = (-2) \max_{\theta_2} \ln L(0_2; T, t) + 2 \dim(\theta_2),
\]

and search \( t \) that minimize \( \text{AIC}_1 + \text{AIC}_2, \) where, as noted in paragraph (8), \( L(0_1; S, t) \) and \( L(0_2; t, T) \) include the event data not only in the time span \((S, t)\) and \((t, T),\) but also those in the former time span \((0, S)\) and \((0, t),\) respectively, for the history of occurrence times and magnitudes since the main shock. Then, to validate the significance of the change point, the single ETAS model is applied to the whole data for the period \((S, T),\) so as to examine whether

\[
\text{AIC}_0 = (-2) \max_{\theta_0} \ln L(0_3; S, T) + 2 \dim(\theta)
\]

is greater than \( \text{AIC}_1 + \text{AIC}_2 + 2q(N). \) If it is not greater, then it is not significant and we deem there to be no change in activity. Here the function \( q(N) \) of the number of events in the interval \((S, T)\) is a further penalty value in the search for minimizing \( t: \) see Ogata [1999] for the explicit form of \( q(N). \) The criteria for this comparison take account of the overfitting bias due to the greater complexity of the two-stage models, and also the freedom in searching for a change point [Ogata, 1992, 1999].

### 3.3. Graphical Examination by the Time Transformation

[11] The AIC is useful in the comparison of competing models. However, having obtained the best model among proposed ones, there is still the possibility of the existence of a better model. We can see precisely how well or poorly
Thus it can be seen from Figure 2 that the aftershock rate of the Hector Mine earthquake has decayed as predicted by the models. The linearity of the cumulative functions holds for all the shown threshold magnitudes. This indicates that the ratio of small to large aftershocks is almost the same at any time except for the first period immediately after the main shock, which indicates the same $b$ value in Gutenberg-Richter’s magnitude frequency in time [Utsu, 1962].

2.4. Landers Aftershock Sequence

[15] The clustering feature within the Landers aftershock sequence is conspicuous. This is not only because it includes the Big Bear aftershocks but also because of the clusters due to large aftershocks. For example, the kinks in the plots of the cumulative curve in Figure 3a are due to the $M_{5.3}$ and $M_{5.4}$ event of 27 November and 4 December 1992, respectively, in the Big Bear region (region E in Figure 1). Table 2 shows that the ETAS model (ETAS0) is a far better fit than the Modified Omori model (M-Omori1), with the AIC difference being 1087.2 for the whole period until the 1999 Hector Mine event. Here, the background effect $\mu$ is added to the Modified Omori intensity function.

[16] The plot of the cumulative number of Landers aftershocks ($M \geq 3$) against the transformed time by the ETAS model for the whole period, deviates systematically from a straight line (Figure 3b). This indicates that the observed aftershocks are not well modeled by the single ETAS model (Figure 3a). To examine this anomaly, we hypothesize that the aftershock activity pattern changed at some point during the period. Indeed, in Figure 3b, the cumulative function appears to have a break in the straight line.

[17] We therefore applied the change point analysis as described in paragraph [10]. The most likely time for the candidate of the change point is sought by minimizing $AIC_1 + AIC_2$ of the two-stage ETAS model for the subintervals divided at the time. Further, to validate this as the change point, it is necessary to confirm whether the two-stage ETAS model on the subintervals divided at a suspected change point, fits significantly better than the single ETAS model on the whole interval. Table 2 indicates that the two-stage ETAS model (ETAS1 + ETAS2) with the most likely change point (190.59 days), fits significantly better than the single ETAS model (ETAS0) used in Figures 3a and 3b, with an AIC difference of 15.3.

[18] Consequently, we see that the ETAS model (ETAS1) can be fitted quite accurately to the Landers aftershock sequence, including its conspicuous clusters, up until the change point for the first 6 months. Indeed, we have confirmed no further significant change point in the sequence for the period of (0.75, 190.59) days. Namely, the smallest AIC value among the two-stage ETAS models was larger than the AIC value of the single ETAS model (ETAS1). Incidentally, ETAS1 is a far better fit than the M-Omori1, with an AIC difference of 1719.0.

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Table 1. Estimated Parameters for Hector Mine Aftershocks $M \geq 3$*

<table>
<thead>
<tr>
<th>Models</th>
<th>Fitted Period, days</th>
<th>( \hat{\mu} ), events d(^{-1} )</th>
<th>( \hat{K} ), events d(^{-1} )</th>
<th>( \hat{c} ), days</th>
<th>( \hat{\delta} ), magnitude(^{-1} )</th>
<th>( \hat{\rho} )</th>
<th>AIC</th>
<th>(-2q(N))</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-Omori</td>
<td>(0.25, 409.2)</td>
<td>–</td>
<td>103.84</td>
<td>0.1344</td>
<td>–</td>
<td>1.18</td>
<td>– 1466.6</td>
<td>–</td>
</tr>
<tr>
<td>ETAS</td>
<td>(0.25, 409.2)</td>
<td>–</td>
<td>60.74</td>
<td>0.00087</td>
<td>2.44</td>
<td>1.13</td>
<td>– 1526.1</td>
<td>– 6.30</td>
</tr>
</tbody>
</table>

*The penalty for change point significance $q(N)$ is calculated from the equation of Ogata [1999, section 4.2], where $N$ is the number of events in the fitted interval.
Thus we eventually obtained Figures 3c and 3d which clearly show that aftershock activity changed around 190.6 days after the main shock occurrence. There, in particular, we extrapolated the theoretical cumulative number \( C_q(t) \) using the parameter estimates of ETAS1 in the Table 2. The predicted theoretical cumulative curve for the remaining interval of nearly 7 years leading up to the Hector Mine rupture, however, shows substantially fewer events than expected. We call this lowered activity the relative quiescence. Here one may question whether the longer period of the quiescence can be considered following only half a year of normal activity. However, we should note that though the first period has a shorter duration in this case, it accounts for more than 80% of all the aftershocks. Moreover, as we will see in the next section, only some spatial subsets of the aftershocks deviate from the first rate.

5. Spatial Pattern of the Landers Aftershock Decay

The depths of events of the relocated catalog [Hauksson, 2000] are very well constrained, with the Landers aftershocks ranging from 0 to 15 km in depth. To examine the spatial distribution of the relative quiescence in more detail, the cumulative curve of the Landers aftershocks is separated into two cumulative curves for the events, above and below a depth of 5.5 km (Figure 4). From these curves, we clearly see that the lowering (relative quiescence) took place in the shallower part, while the deeper part follows the decay pattern set in the first 6 months. The boundary in depth between the two behaviors is not sharp. A difference in behavior can be seen by dividing the seismicity anywhere between 4 and 8 km depth. The depth of 5.5 km was chosen mainly to provide the same cumulative number of aftershocks at the time of change point.

We also note that only some parts of the aftershock zone clearly reflect the relative quiescence. Figure 5 shows the cumulative numbers of aftershocks in each of five subregions of the aftershock zone as shown in Figure 1, for the same transformation of time as in Figure 3d, using the estimated ETAS coefficients (ETAS1) in Table 1. We find that the shallow regions B, D and E (the Emerson, Joshua Tree, and Big Bear segments) show relative quiescence, while the regions A and C (the Barstow and Landers regions) do not. There is a further suggestion that the shallow parts of A and C turn off at a later time, around 1996, as indicated by upward arrows.

There are not many \( M_5 \) class large aftershocks of the Landers earthquake besides the Big Bear event of \( M_5 = 6.4 \), which occurred mostly in the regions D and E. The Big Bear region (region E) has \( M_5.3 \) and \( M_5.2 \) (Mw 5.4) shallow (3–4 km depth) events that occurred on 27 November and 4 December 1992, respectively, in the same concentrated cluster around the northern boundary of region E. These are located before and after the steep rise of the cumulative function in Figure 5, region E, respectively.

The Landers earthquake also triggered three shallow clusters of events (\( M \geq 2.5 \)) within the source region of the Hector Mine rupture (Figure 1). First, the Landers rupture triggered a cluster of events, including an \( M_5.4 \) event near the Hector Mine epicenter (compare region F in Figure 1, Figure 11 of Hauksson et al. [1993], and Figure 12 of King et al. [1994]). This activity (\( M \geq 2.5 \)) ceased after 4 months, following which the relative quiescence of the Landers...
aftershock activity began. This quiescence lasted until the Hector Mine rupture (see M-T plot in Figure 5). This phenomenon led us to a speculation about possible precursory aseismic slip on the Hector Mine fault around asperities, which will be discussed in the next section. The second cluster (blue disks over the star, Figure 1, around the main shock epicenter) took place during 1994 at almost the same site as the Hector Mine epicenter (east of the first cluster). The third cluster took place during 1996, located in the northern off-fault region of the Hector Mine rupture (another cluster of blue disks in Figure 1).

The summarized space-time features of the Landers aftershocks are (1) the lowering of the Landers aftershock activity in the specified shallow volumes B, D, and E but not lowering in A and C; (2) turnoff of the shallow seismicity in regions A and C after 1996 up until the 1999 Hector Mine rupture, (3) the termination of the triggered activity in the western neighboring spot F of the Hector

Table 2. Estimated Parameters for Landers Aftershocks, Including Big Bear Secondary Aftershocks $M \geq 3.0$

<table>
<thead>
<tr>
<th>Models</th>
<th>Fitted Period, days</th>
<th>$\lambda$, events d$^{-1}$</th>
<th>$\lambda\ell$, events d$^{-1}$</th>
<th>$\ell$, days</th>
<th>$\delta$, magnitude$^{-1}$</th>
<th>$\phi$</th>
<th>AIC</th>
<th>$-2\eta(N)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-Omori0</td>
<td>(0.75, 2649.0)</td>
<td>0.0441</td>
<td>324.98</td>
<td>0.4194</td>
<td>1.16</td>
<td>-1184.4</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>ETAS0</td>
<td>(0.75, 2649.0)</td>
<td>0.0115</td>
<td>108.63</td>
<td>0.00751</td>
<td>2.32</td>
<td>1.10</td>
<td>-2271.6</td>
<td>-6.60</td>
</tr>
<tr>
<td>M-Omori1</td>
<td>(0.75, 190.59)</td>
<td>0.6332</td>
<td>243.72</td>
<td>0.0455</td>
<td>-</td>
<td>1.10</td>
<td>-2211.4</td>
<td>-</td>
</tr>
<tr>
<td>ETAS1</td>
<td>(0.75, 190.59)</td>
<td>0.0</td>
<td>91.58</td>
<td>0.00637</td>
<td>2.20</td>
<td>1.05</td>
<td>-3930.2</td>
<td>-6.52</td>
</tr>
<tr>
<td>ETAS2</td>
<td>(190.59, 2649.0)</td>
<td>0.0500</td>
<td>129.94</td>
<td>0.00605</td>
<td>2.60</td>
<td>1.19</td>
<td>1636.7</td>
<td>-</td>
</tr>
</tbody>
</table>
**Figure 4.** Cumulative curves of the aftershocks ($M \geq 3$) of the Landers event shallower (thin black) and deeper (thick gray) than 5.5 km depth, plotted against the ordinary and transformed occurrence times. The time marks in the axis of the transformed time are the same as in Figure 2. Note that the shallower and deeper parts of the fault produced about the same number of aftershocks in the first 6 months but that the shallower part shows a much slower rate of aftershocks after 1992.

**Figure 5.** Cumulative numbers of aftershocks ($M \geq 3$) in subregions A–E and magnitudes of events ($M \geq 2.5$) in region F, plotted against the frequency-linearized times. Thin black and thick gray lines represent shallow (= 5.5 km) and deep events, respectively. The lowering of shallow aftershock activity after about 6 months from the Landers event is seen in regions B, D, and E, and continues the 7 years up to the Hector Mine event. The activity in region F stopped at about the same time as this decrease in aftershock activity began. In regions A and C, in contrast, the rate is unchanged through 1992–1997 but does go down about 2 years before the Hector Mine rupture (see upward arrows). The numbers within each frame show total cumulative numbers of the corresponding curves.
Mine main shock; (4) the activation of the other two clusters in the Landers source during the period of the Landers aftershock quiescence (see Figure 1); and (5) the normal decay of the aftershocks in deep layer for all subregions A–E.

6. Discussions

6.1. Possible Mechanisms for the Features of Landers Aftershocks

[25] Wiemer and Katsumata [1999] showed that different parts of aftershock sequences in the Landers case, in particular, decayed in different ways. They interpreted this phenomenon as possible mechanical differences in the source subvolumes. Namely, near absence of stress in the shallow part, or the inability of the shallow part to build up and maintain significant stress, leads to a situation in which the pockets of stress created by the main shock are quickly eliminated by aftershocks, thus shallow aftershock activity stops essentially after 6 months. In contrast, the stress level in the deeper parts is higher; thus, aftershock activity can continue for a longer time. The idea that aftershocks may be controlled by fluid flow could be discussed in this context; special conditions of stress level or fluid flow could give rise to normal Omori decays in the two shallow volumes where this exception is observed.

[35] The regions B and D of relative quiescence in this paper correspond roughly to the regions of high \( p \) values in the Landers fault if the modified Omori formula is applied to each region. Nevertheless, we need to apply the ETAS model to analyze the complex, interactively triggered aftershocks among the subregions, rather than applying the differently modified Omori functions to separated regions. Indeed, the goodness of fit of the ETAS model was substantially better than the set of the differently modified Omori functions applied to corresponding divided data sets. Also, the identified change point of the Landers aftershock sequence is sharp in the sense that even the cumulative function for the whole period clearly shows two broken line segments as given in Figure 3b. This feature is hard to see from the cumulative function of the transformed time with the estimated modified Omori functions because the deviation of such a function should be gradual. Similarly, viscoelastic rebound effects from lower crust and upper mantle should exhibit a sort of gradual effect, making it difficult to explain the sudden stress change in the upper crust [cf. Freed and Lin, 2001].

[27] Another possible mechanism for the relative quiescence would be the stress changes resulting from the two large aftershocks mentioned in paragraph [15]. The two significant (shallow, 3–4 km depth) earthquakes in the Big Bear region (region E) occurred at 27 November and 4 December 1992 that are about the time of the change point. The lowering of the shallow events in regions E and C could be changes in the Coulomb failure stress (\( \Delta CFs \)) resulting from the mechanisms, which can be calculated by the first-motion mechanisms of these events listed in Table 2 of Hauksson et al. [1993]. For example, Harvard centroid moment tensor (CMT) solution for the December event corresponds to a 32 cm thrust slip in the 2–5 km depth, with a 6 km length and (strike, dip, rake) = (120, 54, 112). Interestingly, the quiescence (\( M \geq 3.0 \)) lasting for about 2 months before the two events is clearly seen in both the shallow and the deep regions in the sequence of region E (e.g., see Figure 5). Incidentally, the focal mechanism of the December event is a reverse fault type which can influence the change in deep seismicity more strongly than the strike-slip type does. This is consistent with the fact that the slope of the cumulative curve of deep events following the change point in region E, lowers a little relative to the one before the change point.

[28] With regards to aftershocks in the Joshua Tree region (region D), on the other hand, we could not find any \( M5 \) class events that could affect the broken-line-shaped cumulative curve of shallow events in Figure 5. Most of the \( M5 \) class events there occurred within several days following the main shock, with no conspicuously large aftershock occurring around the first knot of the broken-line-shaped cumulative function.

[25] Our last possible scenario for the mechanism is motivated by the sharp turning off of the seismicity at about the same time as the onset of the relative quiescence in region F, as shown in Figure 5. This led us to the speculation of a quiet slip within the Hector Mine Fault. Figure 6 shows this change in Coulomb’s failure stress around the Landers and Hector Mine aftershock regions, from an assumed 10 cm aseismic slip in the southern shallow parts of the Hector Mine rupture source. The similar stress pattern can be produced by assuming the slip occurs only in the two small subareas where the shallow aftershocks (\( M \geq 2.0 \)) are sparse along the above assumed fault segment. The receiver fault orientation is followed by King et al. [1994]. Majority of the Landers aftershocks are consistently distributed with this orientation [Hardebeck et al., 1998]. The \( M5.4 \) event in region F has consistent focal mechanism with the orientation [Hauksson et al., 1993], which we assume adopt the similar mechanism to the clustered events in region F. Therefore, if such a slip occurred at the end of 1992, the spatial pattern of the resulting stress changes almost explains the summarized items described in paragraph [24]. In particular, the stress change effect could decay rapidly with depth relative to the one with horizontal directions, because the assumed slip was strike-type in the shallow crust, and perhaps stronger confining pressure in the deep crust might further weaken the effect of the stress change there.

[36] Furthermore, if we assume a secondary aseismic slip within part of the northern fault segment (the west side one) from the future Hector Mine epicenter, this produces stress shadows in regions A and C, which could turn off the activities about two years before the main rupture (cf., arrows in Figure 5, regions A and C). The relative quiescence in the Big Bear region (subvolume E) is not easily explained by a precursory slip model, because the changes in the Coulomb failure stress (\( \Delta CFs \)) owing to the assumed slips in Figure 6 are neutral in that region. The change in this region may be better explained by what is described in paragraph [27].

[31] Compared to the relative quiescence, the relative activation is insensitive to the transformed time. This is because the times of triggered clusters are transformed into frequency-linearized time which is due to the ETAS model, unless the \( b \) value of the G-R magnitude frequency significantly increases (i.e., increase of the portion of the smaller
events). Also, equations (12) and (13) of Dieterich [1994] show that $R/t$ (ratio of future to past seismicity rates) is nonlinearly increasing with $\tau$ (change of shear stress, or the Coulomb failure increment) in a convex manner [Toda et al., 1998]. Therefore relative decreases of $R$ due to $\tau < 0$ should be more sensitive than the increases due to $\tau > 0$ for the same absolute increment. This should become more conspicuous for smaller values of $\lambda$, where $\lambda$ is the normal stress and $h$ is a fault constitutive parameter. The empirical evidence of the $R/t$ curve is seen, for example, in the studies by Reasenberg and Simpson [1992] and Toda et al. [1998] for the case $\tau > 0$, but is not clearly seen for the case $\tau < 0$. This is because their data is mostly from background seismicity and therefore the decrease of $R/t$ is seen only when the seismicity rate $t$ is high enough, while an increase of $R/t$ is easily seen, whether $t$ is large or small, by simply counting the earthquakes. On the other hand, aftershock activity usually occurs at a high rate, so that the relative quiescence can be sensitively observed.

6.2. Anomaly of Joshua Tree Aftershock Sequence and its Mechanisms

First, we note that the change in the lowering of the decaying rate of aftershocks is conspicuously seen regardless of threshold magnitude at the same time during the day of the Joshua Tree main shock (compare arrow in Figure 7). This makes the determination of which part of the sequence should be considered “normal” more problematic, although it is clear that a change happened. To model this change, we first speculate that aseismic slip in the southern fault segment of future Landers aftershock zone, including the Eureka Peak Fault, might be triggered by the Joshua Tree rupture. The stress changes as shown in Figure 9 of King et al. [1994] and Figure 7 of Hauksson et al. [1993] support the possibility of such triggering. Indeed, Behr et al. [1994] observed aseismic afterslip of the Landers event in the Eureka Peak Fault, and suggested that the slip was triggered by the Joshua Tree earthquake.

With this model, say, a 10 cm aseismic slip in the shallow fraction given in Figure 8 could, in turn, inhibit the Joshua Tree aftershock activity. This is because most of the Joshua Tree aftershocks, including off-fault ones, had right-lateral focal mechanisms with nodal planes either subparallel to the main shock plane, or auxiliary nodal planes striking at high angles [Hauksson et al., 1993].

6.3. Is the Relative Quiescence Precursor to Another Large Event?

Precursory seismic quiescences have been reported before a large earthquake (see Ohtake [1980] for a summary). The quiescence has been observed from seismic activity itself or has been statistically examined in the ‘background seismicity’ based on a declustered catalog [e.g., Kisslinger, 1996]. On the other hand, the relative quiescence is detected in comparison to the normal activity predicted by the ETAS model. The ‘conventional’ quiescence is therefore equivalent to the relative quiescence when the background seismicity data is tested against the stationary Poisson model instead of the ETAS model. Therefore we think the relative quiescence includes the conventional quiescence in the sense that quiescence can be more clearly seen by using a better model of normal aftershock activity or general seismicity.
There are a number of hypotheses of precursory quiescence to a large earthquake based on the heterogeneous strength (e.g., friction coefficients) of subfaults and heterogeneous stresses within a fault, which include a bimodal asperity model [Kanamori, 1981], stress weakening owing to a creep [Wyss et al., 1981], slip weakening [Cao and Aki, 1985] and others. Also, there are justifications for these hypotheses using computer simulations [Mikumo and Miyatake, 1983; Hainzl et al., 2000].

On the other hand, it is reported that seismic activity before a large earthquake can be quiet, not only in the seismic gap, but also in its wide neighborhood [Inouye, 1965; Ogata, 1992]. Moreover, even a short-term relative quiescence within an aftershock sequence is occasionally observed before a large aftershock whose rupture extends beyond the source of the main event [Matsu'ura, 1986]. As a relevant mechanism, Kato et al. [1997] discuss a model for the quiescence in an extended wider area using the simulation based on rate and state friction law, which also provides a useful scenario of geodetic changes in predicting interplate great earthquakes.

One of our scenarios for the relative quiescence in the present paper is similar to this and based on the asperity model in the sense that precursory slip around asperities applies more shear stress to the asperities, which in turn promotes the rupture of the main fault. However, on the other hand, aseismic slips in some region is not necessarily the direct precursor to a large event. Indeed, by the inversion analysis [e.g., Hirose et al., 2000] based on the records of strain and tilt meters or GPS time series in Japan, we have observed a number of aseismic slips (silent earthquakes; sometimes repeated in the same region) with no subsequent larger events in the last decades. This is consistent with some empirical results that the relative quiescence was not always followed by a large event [e.g., Wyss and Wiemer, 1999; Ogata, 2001]. Therefore distinguishing whether or not an aseismic slip leads to the rupture of asperity remains a further difficult research point in earthquake prediction.

At present, this issue can only be described in terms of probabilistic prediction. For example, the statistical results from Japan [Ogata, 2001] suggest that the probability of another large earthquake becomes greater if the aftershock activity of the first event shows the relative quiescence. Specifically, the occurrence rate within a range of 200 km is several times higher during the six years’ quiescence than would be the case if the aftershock activity continued normally.

Nevertheless, one of the major issues in this paper is to analyze seismicity using the ETAS which could provide sensitive detection of the stress changes in the analyzed region, including the inhibition of the crustal relaxation process due to a silent slip. We have been concerned with the lowering activity of aftershocks themselves which comprise a major portion of an earthquake catalog, and therefore should include valuable information concerning stress changes [Dieterich, 1994; Dieterich et al., 2000].

7. Conclusions

On the basis of the ETAS model, we have shown that the Hector Mine aftershock activity has been normal relative to the modeled decay. In contrast, although the aftershock sequence of the 1992 Landers earthquake ($M = 7.3$), including the 1992 Big Bear earthquake ($M = 6.4$) and its aftershocks, normally decayed up until about 6 months (the change point) after the main shock, the sequence showed clear relative quiescence during the rest of the period until the
Several possible mechanisms for the anomalous aftershock activity and the space-time features have been discussed. Among these, we are particularly concerned with the phenomenon that the substantial activity (including M5.4 event) near the Hector Mine epicenter that was triggered by the Landers event, which ceased closely before the onset of the relative quiescence of the Landers aftershocks. This could suggest inhibition of the crustal relaxation process presumably owing to an aseismic slip on the Hector Mine fault. Thus the speculative matching between the quiet volumes and the Coulomb stress shadows is applied to the aftershock activities of the Landers and Joshua Tree earthquakes by adjusting aseismic slip within the future rupture fault. The speculative slip ultimately needs to be confirmed by some geodetic records or more accumulation of matched examples elsewhere as examined in this paper.

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