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Stability of coda wave attenuation during the Loma Prieta, California, earthquake sequence

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Abstract. The Loma Prieta, California, earthquake occurred in a densely instrumented region with a history of microearthquake recording beginning more than a decade before the October 1989 mainshock. This affords an unprecedented opportunity to detect changes in seismic wave propagation in the Earth's crust associated with a major earthquake. In this study we use pairs of nearly identical earthquakes (doublets) to search for temporal changes of coda attenuation in the vicinity of the Loma Prieta earthquake. We analyze 21 earthquake doublets recorded from 1978 to 1991 that span the preseismic, coseismic, and postseismic intervals and measure the change in coda Q using a running window ratio of the doublet spectral amplitudes in three frequency bands from 2 to 15 Hz. This method provides an estimate of changes in coda Q that is insensitive to other factors that influence coda amplitudes. Our observations place an upper bound of about 5% on preseismic, coseismic, and postseismic changes of coda Q in the epicentral region of the Loma Prieta earthquake. Even at this low level, the changes are neither spatially coherent nor correlated between adjacent frequency bands. The only hint of a signal is in the preseismic data where there is a possible precursory increase in coda Q of approximately 5% in the two years before the mainshock. The stability of coda Q throughout the Loma Prieta sequence is in sharp contrast to other studies that have reported much larger precursory changes in coda Q for other earthquakes.

Introduction

The possibility that changes in properties of crustal wave propagation precede major earthquakes has generated a multitude of research into possible precursory phenomena. Studies in the late 1960s and early 1970s focused on apparent changes in P and S wave velocities [e.g., *Semenov*, 1969]. Precursory effects reported in these studies were quite large, but subsequent investigations of earthquakes in well-instrumented areas found no evidence for such dramatic changes [*Kanamori and Fuis*, 1976; *Wesson et al.*, 1977]. Since that time, attention has shifted to the possibility that there are changes in other properties of crustal wave propagation. In particular, many studies have found evidence for large changes in the decay rate of the S wave coda prior to large earthquakes.

The S wave coda is the ground motion that occurs after the arrival of the initial S wave for local earthquakes [*Aki*, 1969]. It is thought to consist primarily of S waves that have been scattered from crustal heterogeneity into body or surface waves [*Aki and Chouet*, 1975]. Coda Q is a measure of the component of the temporal decay of the coda wave amplitude that is attributable to either intrinsic or scattering attenuation. It is observed to vary geographically [e.g., *Phillips and Aki*, 1986], but the idea that there might be temporal changes in coda Q was introduced by *Chouet* [1979]. Since that time there have been many studies citing temporal changes in coda Q as an earthquake precursor. An increase in coda Q by as much as 50% has been cited as a precursor to large earthquakes [*Gusev and Lemzikov*, 1985; *Novelo-Casanova et al.*, 1985; *Sato*, 1986; *Jin and Aki*, 1986]; however, a decrease was cited as a precursor by *Tsukuda* [1988]. In some cases changes of coda Q by as much as 50% have been reported even in the absence of a large event [*Jin and Aki*, 1989]. *Sato* [1988] has reviewed evidence for large temporal changes in coda Q and its possible relation to earthquake activity.

Estimates of coda Q are sensitive to a number of factors including source finiteness, geometric spreading, earthquake mechanism, and earthquake location. To address possible effects due to these factors most authors estimate coda Q from the late coda, which is defined to be the part of the coda arriving after twice the direct S wave arrival time. The relatively long paths taken by waves in the late coda are thought to sample a large volume of the crust and a variety of takeoff angles from the source. This sampling is assumed to average coda wave excitation over many takeoff angles and to remove the sensitivity to the focal mechanism. Possible systematic effects due to source location are also reduced by averaging over multiple earthquakes. Finally, the effects of geometric spreading, which are different for body and surface waves, are accounted for by simultaneously solving for geometric spreading and coda Q. This is a difficult task because both geometric spreading and attenuation cause the amplitude to decay in a similar manner. The sensitivity of coda wave amplitudes to these factors motivates the search for an alternate way of estimating changes in coda Q.

Earthquake doublets are naturally recurring seismic events that represent repeated slip of the same segment of a fault with the same focal mechanism. Doublets provide a method for

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measuring coda Q that is insensitive to assumptions of geometric spreading, location, and source mechanism because these factors are common to the two events. Adopting a technique similar to that of *Got et al.* [1990] we fit a line to the natural logarithm of a running-window spectral ratio of the doublet amplitudes to measure the change in coda Q over the time interval between the two earthquakes. This measurement is insensitive to the other factors that may contaminate estimates of coda Q because they are canceled in forming the spectral ratio. The doublet method also allows us to use both the early and late coda, unlike other studies that are forced to avoid the early coda due to its sensitivity to focal mechanism.

In this study we use doublets to search for temporal changes of coda Q associated with the October 18, 1989, Loma Prieta, California, earthquake (M_w = 6.9). This event occurred within the dense U.S. Geological Survey Calnet network, which has recorded digitizable waveforms since 1978, 10 years before the Loma Prieta mainshock. This data set provides an unprecedented opportunity to study possible temporal evolution of coda Q before a major earthquake. Moreover, the earthquake itself might be expected to have a strong effect on coda Q because its stress drop appears to have been nearly total [*Beroza and Zoback*, 1993]. Finally, since to some extent we know the stress change in the mainshock, we could use any observed changes to help constrain the underlying mechanism.

In our study of the Loma Prieta sequence we find no evidence for either a preseismic or a postseismic change in coda Q at the level of about 5% over the frequency range 2-15 Hz. We do not even detect a coseismic change in coda Q at the same threshold despite the occurrence of a major earthquake. What small changes we observe are neither spatially coherent nor correlated between frequency bands. The only possible signal we observe is an increase in coda Q by about 5% in the two years before the mainshock. The stability of coda Q in the region of the Loma Prieta earthquake contrasts sharply with previous reports of large changes in coda Q associated with other earthquakes.

In the next section we detail our method for measuring changes in coda Q and demonstrate it using seismograms from a doublet on the Calaveras fault. We then apply the method to doublets that span the preseismic, coseismic, and postseismic intervals. We use these measurements to constrain changes in coda Q associated with the Loma Prieta earthquake. We then analyze the observed temporal and spatial changes in coda Q and discuss the implications of our observations for possible mechanisms of temporal variations in coda Q and for the utility of coda Q as an earthquake precursor.

Earthquake Doublets

We define an earthquake doublet as a pair of earthquakes that occur at the same location, with the same mechanism, and that rupture the same segment of fault, but at two different times. This is an idealized definition, since no two earthquakes can be exactly identical. Thus it is important to validate that the two earthquakes are similar enough so that any changes in the signal we observe are not attributable to subtle differences in the constituent events.

The search for candidate doublets starts with routine earthquake locations determined by the U.S. Geological Survey from Calnet data. These locations typically have standard location errors of about 1/2 km, and they are used to select a subset of events in a small area of interest. Potential doublets are screened further by visual inspection for waveform similarity. If they appear sufficiently similar, i.e., if the seismograms are virtually identical from the first arrivals through the coda (Figure 1), we then undertake a cross-spectral analysis for all stations observing both events to determine the relative arrival times of the P and S waves. Visual similarity, however, merely guarantees that the events lie within a common first Fresnel zone ($\lambda/4$ rule [*Geller and Mueller*, 1980]) or at not more than a few hundred meters separation, and have nearly identical radiation patterns.

To determine if the events share a common location, we perform a relative event relocation by fixing one hypocenter and locating the other with respect to it. Arrival times of the P wave can be routinely measured to a sub-sample accuracy of about 10% or 1 ms for 100 samples/s data using the cross-spectral method (see *Poupinet et al.* [1984] and *Frémont and Malone* [1987] for a description of the method). For S waves, the errors are about twice as large. With this level of measurement precision, the spatial separation of the two events can be determined to a precision of about 20-30 m, approximately equal to the source dimension of a M 1.0 earthquake. *Frémont and Malone* [1987] also achieved this level of precision in their study of earthquake multiplets at Mount St. Helens.

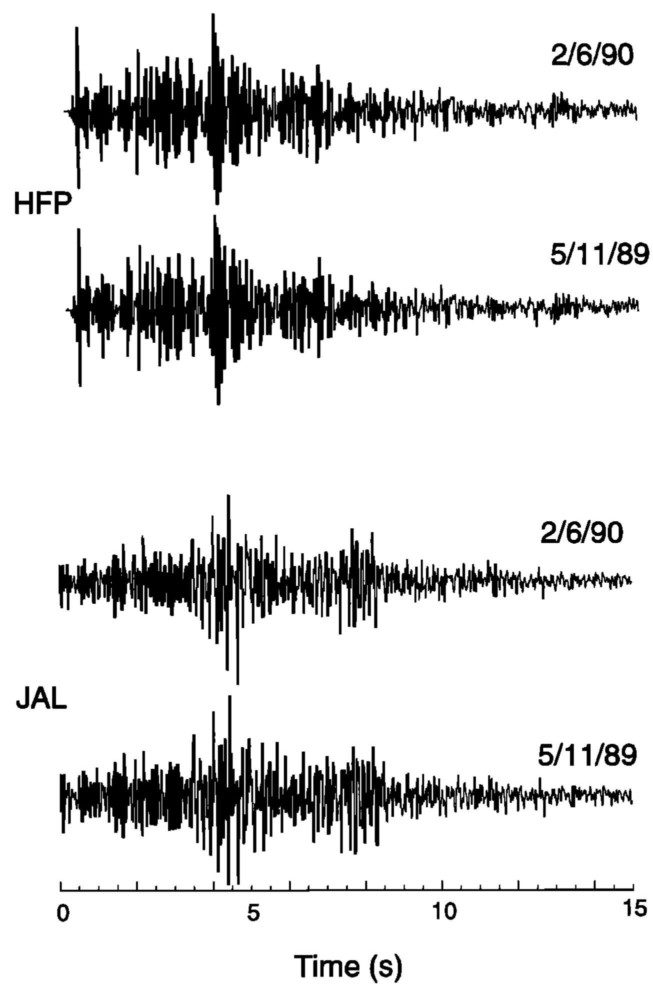

Figure 1. Seismograms for two of the events of the m1 multiplet on the San Andreas fault. These events were located at the southern end of the Loma Prieta aftershock zone (Figure 2). Seismograms for the May 11, 989, and February 6, 1990, events are shown. The first of these occurred before and the second one occurred after the Loma Prieta mainshock. The stations JAL and HFP are at quite different azimuths from the doublet, yet each station recorded essentially identical waveforms for each event.

We compute the location differences, actually the separation of the centroids, using the joint hypocenter determination (JHD) method, independently applying it to the P, S-P, and S travel time differences, respectively. A candidate doublet is accepted for further analysis when the centroid separation would require 50% overlap of the sources, for a stress drop of 3 MPa or less. For a pair of M 1.5 events, this corresponds to a centroid separation of about 25 m. Given our location accuracy above, the accepted doublets might represent repeated failure of identical areas on the fault, or they might represent partially overlapping ruptures, assuming that stress drops are less than about 100 bars and that source dimensions are more-or-less equidimensional.

A possible disadvantage of using doublets to measure coda Q is that we must limit our analysis to areas and time intervals where doublets occur. In the Loma Prieta region this has not been a problem. We have found many doublets that span the preseismic, coseismic, and postseismic intervals allowing us to search for changes in coda Q for all these periods. Other areas, e.g. the Anza region [*Aster and Scott*, 1993], may not have such an abundance of doublets, rendering this type of analysis more difficult.

Applying our doublet identification method to a small subset of the total seismicity in the Loma Prieta region, we identified 21 multiplets (Figure 2 and Table 1). Of these 21, six are triplets and one is a quadruplet. They include events on the San Andreas fault to the south of the Loma Prieta rupture zone, on the Calaveras fault to the southeast, east, and northeast of the rupture zone, and on the nearby Sargent fault. The combination of a rich set of doublets that span the time periods of interest with a dense station spacing and a wide range of azimuths with respect to the rupture zone of the Loma Prieta earthquake ensures that any substantial change in coda Q related to the Loma Prieta earthquake should be detected.

Measuring Changes in Coda Q Using Earthquake Doublets

Coda Q is a measure that characterizes the rate of decay, due to either scattering or intrinsic attenuation, of the amplitude of coda waves following the arrival of the direct S wave (see *Sato* [1988] for a thorough review). The decay rate of the coda is sensitive to a number of factors other than coda Q, including geometric spreading, earthquake mechanism, and earthquake location. To address possible effects due to these factors most authors estimate coda Q from the late coda, which is defined to be any time after twice the direct shear wave arrival time. The relatively longer paths taken by waves in the late coda are assumed to sample a large volume and a great variety of takeoff angles from the source, which should minimize the sensitivity to the focal mechanism. Possible effects due to changes in earthquake location are minimized by averaging over multiple earthquakes. Finally, the effect of geometric spreading is addressed by modeling the temporal amplitude decay of the coda with a term that represents geometric spreading and a term that represents coda Q. In practice it is difficult to be certain that assumptions of averaging are valid and that the resulting estimates of coda Q are reliable. *Got and Fréchet* [1993] have used near doublets to demonstrate how these factors can interfere with measurements of coda Q.

Earthquake doublets provide an alternative method for analyzing changes in coda Q. The doublet method is insensitive to the effects of geometric spreading, location, and source mechanism and thus should readily detect small changes in coda Q. The doublet method also allows us to analyze both the early and late coda. We now review our method for estimating changes in coda Q. A very similar approach has been taken by *Got et al.* [1990] and, more recently, by *Aster et al.* [1993].

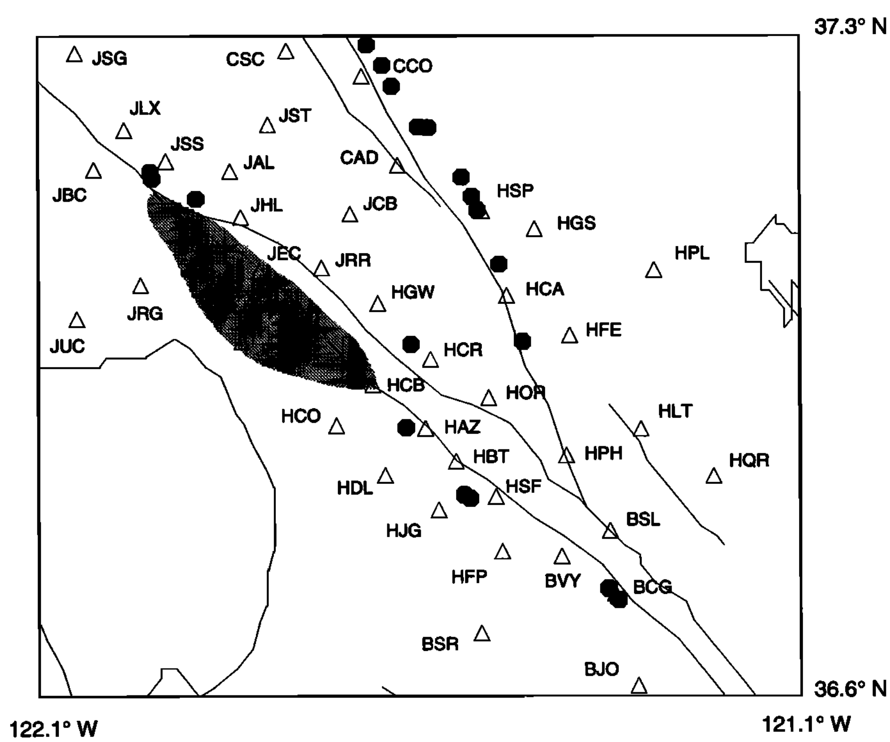

Figure 2. The locations of the 21 doublets listed in Table 1 are shown as solid octagons; the approximate rupture zone of the 1989 Loma Prieta mainshock is shown as the stippled region. Stations of the Calnet array are shown as triangles. The m1 doublet is the octagon near HCB at the southern end of the aftershock zone.

Table 1. Doublet Hypocenters

	Date	Time UTC	Latitude °N	Longitude °W	Depth km	M
m6	Oct. 13, 1984	1732	37.2908	121.6662	5.72	1.9
	Aug. 1, 1987	0140	37.2910	121.6668	6.11	1.9
	Oct. 1, 1989	1821	37.2913	121.6670	5.95	1.8
c2	June 15, 1978	1248	36.9763	121.4630	3.54	1.8
	Feb. 28, 1980	1231	36.9765	121.4602	3.82	2.1
	Dec. 12, 1988	0232	36.9743	121.4617	2.43	1.7
m1	Nov. 5, 1989	0057	36.9352	121.6812	12.17	1.6
	June 2, 1990	0050	36.9370	121.6800	11.89	1.6
	June 4, 1990	2006	36.9357	121.6802	12.27	1.4
	Aug. 19, 1990	1933	36.9353	121.6825	12.49	1.5
m2	June 17, 1984	1626	37.2035	121.5860	8.44	1.9
	Aug. 25, 1986	2232	37.2047	121.5858	8.97	1.8
	May 2, 1990	1235	37.2045	121.5865	8.82	1.6
m3	April 22, 1981	0024	36.9357	121.6833	11.01	1.8
	June 22, 1987	1955	36.9377	121.6830	10.35	1.7
	Oct. 26, 1989	0243	36.9387	121.6825	9.90	1.6
m4	June 28, 1984	1011	36.7022	121.3382	4.54	2.1
	Oct. 7, 1989	0252	36.7030	121.3368	4.83	2.1
m4a	June 21, 1984	0713	36.7145	121.3515	3.13	2.4
	Oct. 6, 1989	0914	36.7150	121.3495	2.60	2.3
m5	July 17, 1987	1603	37.1512	121.5425	7.53	2.2
	Oct. 13, 1989	2333	37.1522	121.5427	7.09	2.0
m7	April 25, 1984	1009	37.2043	121.5990	3.02	1.7
	Dec. 14, 1988	1053	37.2042	121.6003	3.53	1.4
	Feb. 15, 1990	1118	37.2040	121.5998	3.47	1.5
m8	Feb. 14, 1987	2344	37.0583	121.4937	4.24	2.3
	May 17, 1981	2256	37.0588	121.4942	4.34	2.6
m9	Feb. 15, 1986	0953	37.1158	121.5220	7.54	2.7
	Feb. 22, 1990	1352	37.1163	121.5220	7.26	2.6
m10	July 10, 1984	2301	37.2472	121.6337	3.63	2.8
	Dec. 21, 1990	0709	37.2477	121.6342	3.60	2.6
m11	Nov. 26, 1984	1512	37.2692	121.6458	6.87	2.1
	Nov. 11, 1991	0843	37.2692	121.6453	7.00	2.4
m12	Feb. 19, 1988	0413	37.1305	121.5293	7.34	1.8
	April 18, 1990	0325	37.1307	121.5305	7.34	1.7
sar	Oct. 25, 1987	2049	36.9735	121.6097	2.58	1.3
	May 9, 1991	1233	36.9730	121.6082	2.69	1.0
l1	Aug. 8, 1989	2215	37.1573	121.9515	13.94	1.6
	Sep. 4, 1989	2121	37.1558	121.9405	13.65	1.6
l2	Aug. 8, 1989	1525	37.1505	121.9493	13.60	1.6
	Aug. 9, 1989	0642	37.1510	121.9482	13.68	1.6
l3	Sep. 3, 1989	2313	37.1285	121.8917	11.85	1.0
	Oct. 10, 1989	0210	37.1267	121.8928	12.47	1.3
s4	June 9, 1979	0031	36.8143	121.5407	6.46	2.1
	June 15, 1981	1429	36.8127	121.5373	6.43	2.0
	Aug. 10, 1987	1853	36.8142	121.5397	6.56	1.8
s4a	Jan. 31, 1985	2203	36.8100	121.5330	6.53	2.0
	Dec. 30, 1989	2103	36.8095	121.5340	6.97	2.0
s7	Aug. 28, 1978	0533	36.8855	121.6162	7.06	1.8
	May 23, 1981	0026	36.8788	121.6187	7.92	2.0
	Oct. 29, 1989	1038	36.8802	121.6192	6.37	1.7

We assume that amplitude A_i of the S wave coda for event i as a function of angular frequency ω and time t, can be described by an expression of the form

$$A_i(\omega,t) = C_i t^{-\alpha_i} e^{-\omega t/2Q_i} \tag{1}$$

[*Aki and Chouet*, 1975] where C_i describes the initial amplitude, α_i describes the decay due to geometric spreading, and Q_i is the coda Q. If we make the simplifying assumption that the codas of two elements, i and j, of a doublet recorded at the same station are comprised of the same type of seismic wave, then α_i is the same for both i and j, and we can write the spectral ratio of the two events as

$$\frac{A_i(\omega,t)}{A_j(\omega,t)} = \frac{C_i}{C_j} e^{-\frac{\omega t}{2}(Q_i^{-1} - Q_j^{-1})} \tag{2}$$

If we now take the natural logarithm of both sides of this equation, we obtain a simple expression relating the observed amplitude ratio to coda Q.

$$\ln\left(\frac{A_i(\omega,t)}{A_j(\omega,t)}\right) = \ln\left(\frac{C_i}{C_j}\right) + \left[\frac{\omega}{2}(Q_j^{-1} - Q_i^{-1})\right] t \tag{3}$$

For a given frequency, this is an expression for a straight line with t as the independent variable. The intercept is related to the relative size of the two events and is given by the first term on the right-hand side. The slope is related to the differential of the inverse of coda Q.

We measured the spectral ratio on the left-hand side of (3) using a 2.56-s Hanning-tapered window and shifted the time by 1.28 s between adjacent windows. We began the analysis 2 s after the theoretical S wave arrival time and continued for nine additional windows covering a total of 14 s of the coda. At the short source-receiver distances used in this study, this window usually included both the early and the late coda. For the 1589 pairs, the median S time was 10.8 s with inner quartiles of 7.7-14.9 s so that with the analysis of a 14-s window we reached the late coda for nearly 75% of the seismograms.

We applied a simple five-point spectral smoothing operator to the data to avoid instabilities due to spectral holes and determined the least squares estimate of $\Delta Q_{ij}^{-1} = Q_j^{-1} - Q_i^{-1}$ for each of the doublets and each of the stations. These estimates of ΔQ_{ij}^{-1} were interpreted in terms of a percentage change, q_{ij}, in coda Q by assuming a representative value of Q_i for central California [*Phillips and Aki*, 1986] in the formula

$$q_{ij} = \frac{Q_i \Delta Q_{ij}^{-1}}{1 - Q_i \Delta Q_{ij}^{-1}} \times 100\% \tag{4}$$

Rather than attempting to determine q_{ij} for each frequency, we used three frequency bands (2-5 Hz, 5-10 Hz, and 10-15 Hz) and estimated the percent change of coda Q in each band. The low-frequency cutoff at 2 Hz was applied because signal levels at lower frequencies are too low for earthquakes of this magnitude range. The 15-Hz upper limit on the frequency band is a conservative estimate of the highest frequency for which the response of the Calnet seismometers and recording systems were constant over the recording period. We found the most stable estimates of coda Q in the 5-10 Hz band due to a higher signal-to-noise ratio than at higher and lower frequencies.

Splitting the analysis into three adjacent frequency bands served several purposes. The finite bandwidth stabilized the estimate by removing the effect of spectral holes. Having several windows allowed us to determine the coherency of the estimated change in coda Q with frequency. We expect that real changes in coda Q will extend over each of these frequency bands. Previous estimates of coda Q indicate that it has a strong frequency dependence [*Phillips and Aki*, 1986]. We used reference values of coda Q = 200, 300, and 500 for the 2-5, 5-10, and 10-15 Hz frequency bands respectively, to account for the effect of the frequency dependence of coda Q.

Figure 3 shows an example for the station JEC and doublet m2 on the Calaveras Fault. The running window spectral ratio is shown together with the best fitting straight line fit to equation

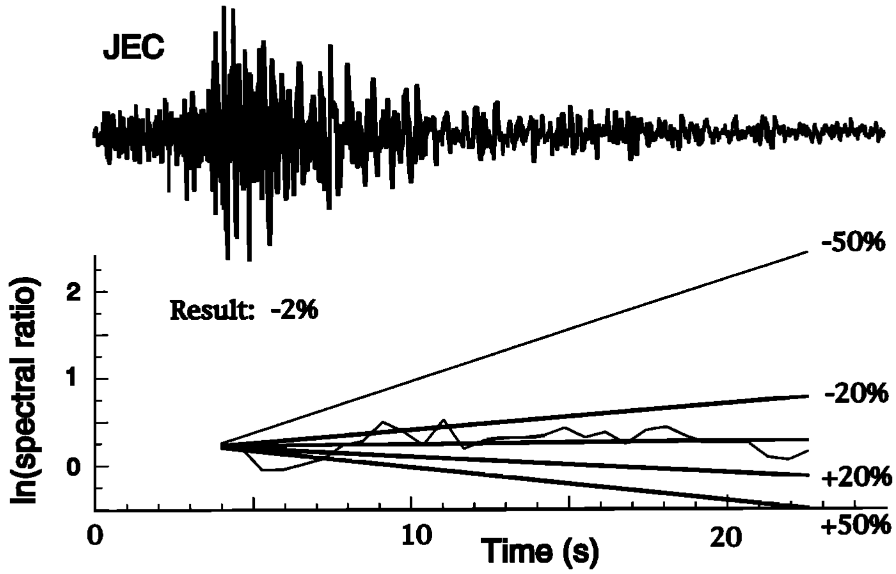

Figure 3. Seismograms recorded at JEC for the m2 doublet on the Calaveras fault. The measurement of change in coda Q by a fit of spectral ratios to a straight line is shown below. The estimated change is a decrease of 2% in coda Q. Also shown are predicted lines for ±20% and ±50% in coda Q.

(3). The fit of the spectral amplitudes indicates q_{ij} = -2%, i.e., a decrease of 2% in the nominal coda Q of 200. The other two lines show the predicted change in the spectral ratio amplitude for changes of ± 50%. Changes as large and substantially larger than 50% have been reported as precursors to large earthquakes [e.g., *Jin and Aki*, 1986] and have been reported even in the absence of large seismic events [*Jin and Aki*, 1989]. If such large changes occurred in the Loma Prieta region, they should be readily observed in our analysis.

Temporal Variation in Coda Q

We have measured changes in coda Q for each of the doublets at all Calnet stations that have signal-to-noise ratios large enough to provide a stable estimate. We used these measurements to search for temporal changes in coda Q associated with the 1989 Loma Prieta earthquake.

Coda Q is usually assumed to be characteristic of a large scattering volume. Thus we assumed in this study that coda Q for a particular station is independent of the location of the doublet being used to estimate it. We used measurements of the change in coda Q from all doublets recorded at a single station to reconstruct the temporal variation. That is, we reconstructed the function $Q(t)$ from measurements of its differences. This is a fundamentally underdetermined problem, and we explored a number of possible solutions. We settled on one of the simplest possible. We represent $Q(t)$ as a discrete function with 10 samples per year. We define the change in coda Q between each of the discrete time periods as

$$\Delta Q_k = Q_{k+1} - Q_k \tag{5}$$

Then our observed changes in coda Q are simply the sum of all the changes in coda Q between the two elements of the doublet. We write this relationship as

$$\sum_{k=i}^{j} \Delta Q_k = q_{ij} \tag{6}$$

We now can combine all the observations in the matrix equation:

$$\boldsymbol{W} \cdot \boldsymbol{\Delta Q} = \boldsymbol{q} \tag{7}$$

We solve equation (7) using least squares while simultaneously minimizing the second temporal derivative of Q, i.e.,

$$\min \left\{ \beta^2 \partial_t^2 Q \right\} \tag{8}$$

where β^2 is a factor that controls the relative importance of satisfying equations (7) and (8). To recover the discrete representation of the time evolution of coda Q, $Q(t)$, that we seek, we sum the differences,

$$Q(t_j) = Q_i + \sum_{k=1}^{j} \Delta Q_k \tag{9}$$

In this approach our discrete function, $Q(t)$, is a minimum gradient solution.

An example of the application of this procedure to changes in coda Q measured at station JHL is shown in Figure 4. The solid line indicates the minimum-length solution. The dashed line is obtained by fitting the data with a smoothly varying function. For this station the observed variations in coda Q are of the order of 10% for both solutions. Although measurements at this and most other stations do not exhibit any dramatic changes in coda Q, it may be that relatively small changes, on the level of 10-20%, could occur and not be apparent in this analysis. Therefore we attempt to measure possible preseismic and coseismic changes in coda Q by restricting the analysis either to doublet pairs occurring before the mainshock or to pairs that span it.

Coseismic Changes

A coseismic change in coda Q is a reasonable expectation given that the Loma Prieta mainshock resulted in a substantial stress redistribution over a very large area [*Reasenberg and Simpson*, 1992] and that stress drop in the mainshock appears to have been nearly complete [*Beroza and Zoback*, 1993]. Many

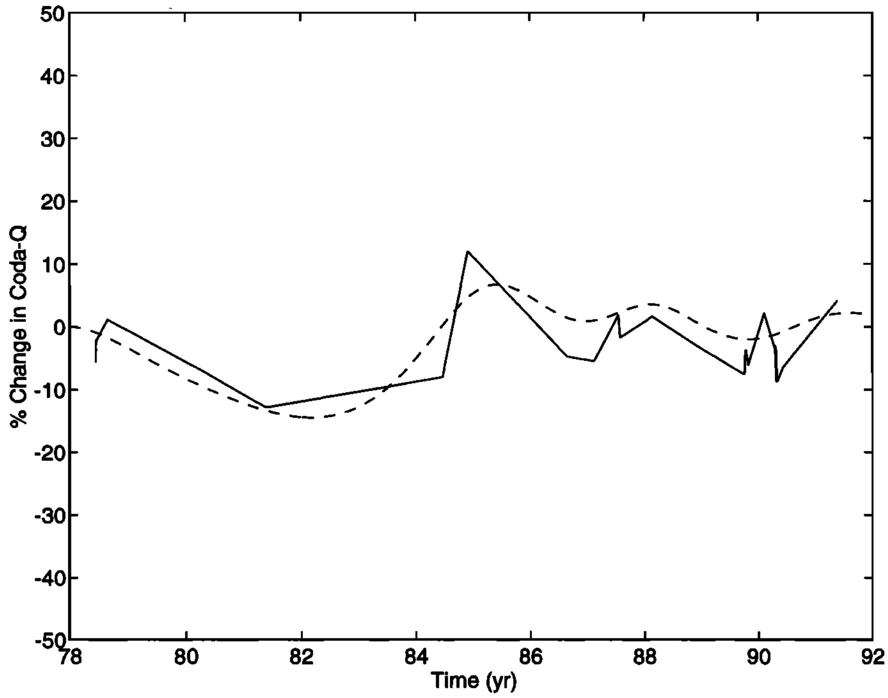

Figure 4. Measured changes in coda Q and reconstruction of $Q(t)$ from these measurements for the station JHL in the frequency band 5-10 Hz. The dashed line shows our smoothed solution. The solid line shows the minimum length solution. No large change in coda Q occurs before the Loma Prieta earthquake in October 1989. There is no apparent coseismic change either.

studies of temporal variations in coda Q have argued that coda Q is controlled by the opening and closing of cracks in the Earth's crust due to stress variations. If such a mechanism is responsible for these reported changes, the effect ought to be most apparent as a coseismic change in coda Q for all doublets that span the mainshock. The Loma Prieta earthquake is particularly convenient for testing this hypothesis because the slip distribution in the mainshock is well constrained by strong-motion data [*Beroza*, 1991] allowing regional stress changes to be calculated in some detail. However, the distribution of doublets that we have identified is not sufficient to identify both spatial and temporal variations simultaneously. In this study we simply try to identify or place bounds on the magnitude of coseismic and preseismic changes.

We can solve explicitly for a coseismic change in coda Q. We assume that the largest change in coda Q results from the coseismic change, and we solve directly for the difference. To do this, we fit a single coseismic offset in coda Q to all of the doublet pairs that span the mainshock at a particular station, that is, doublets with the first event before and the second event after the mainshock. In this analysis we require a minimum of three doublets to provide a stable estimate.

Figure 5 summarizes our results for the coseismic doublets over the three frequency bands for all of the stations by showing the coseismic change in coda Q as a function of distance from the Loma Prieta mainshock epicenter. Although there are a few stations with large changes, most stations show little coseismic change in coda Q; the mean change is essentially zero. Figure 6 shows the same information on a map with the major faults of the Loma Prieta mainshock region. The percentage change is quite small with the exception of a single station that shows a large change in the 10-15 Hz band. If this change were geophysically meaningful, it would require that the coda waves be generated from a very small fraction of the total scattering volume. We think it is more likely that the apparent large change is due to a low signal-to-noise ratio in the late coda for these small earthquakes. Measurements in the 10-15 Hz band are particularly sensitive to noise because the high reference value of 500 means that a small change in amplitude maps into a large estimated percentage change in coda Q (equation (4)).

The maps indicate a lack of spatial coherency for all frequencies. Thus we found no evidence for a systematic regional change in coda Q at a level of about 5% as a result of the Loma Prieta mainshock. Of course, the stress field of the Loma Prieta mainshock will have a complicated, though predictable, spatial distribution that might be expected to induce a more complicated distribution in coda Q change than just a simple offset in the regional average.

Another way to assess if the observed changes in coda Q are geophysically meaningful is to test whether they are correlated across the three frequency bands. It is reasonable to expect that actual changes in coda Q will be of the same sign over the frequency band 2-15 Hz. A simple test of this is whether the fraction of stations for which all estimates of the coseismic change in coda Q are of the same sign for the three frequency bands: 2-5, 5-10, and 10-15 Hz. We find that they are of the same sign for 10 out of the 43 stations for which we have estimates. The expectation for a random distribution (not correlated in frequency) is 25% of the samples. Thus the observations are consistent with random fluctuations in the amplitude measurements rather than a true change in coda Q.

Preseismic Changes

Although our attempts to find a coseismic change in coda Q were unsuccessful, it is important to search for preseismic changes in coda Q as well since these have been reported before many other large earthquakes.

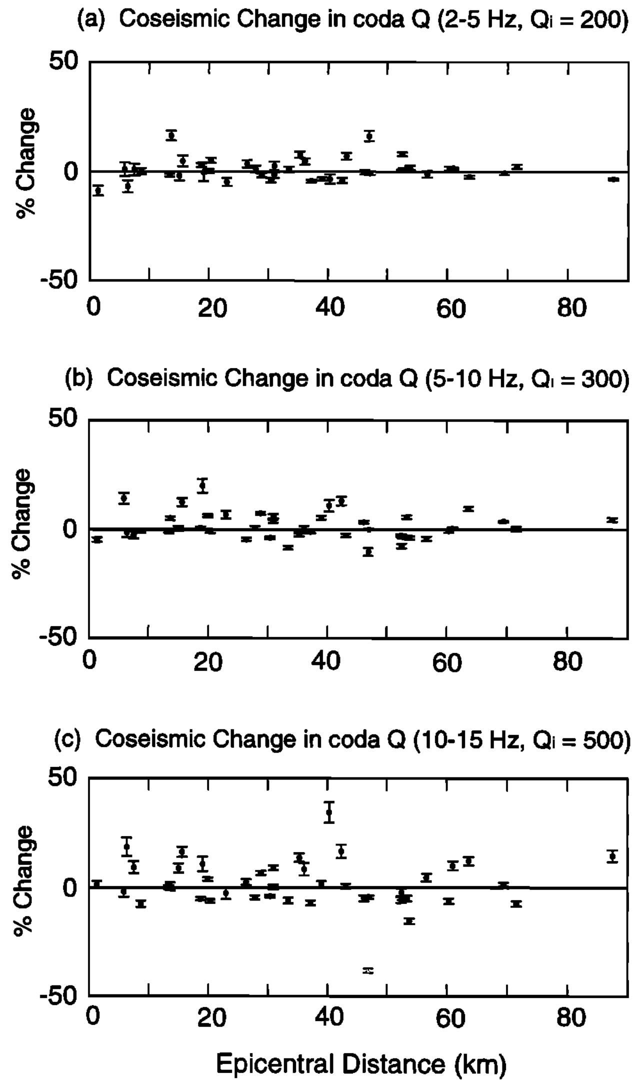

Figure 5. Coseismic offset in coda Q shown for the three frequency bands a) 2-5 Hz, b) 5-10 Hz and c) 10-15 Hz as a function of distance from the Loma Prieta epicenter. The error bars indicate the 1-σ confidence level. Although there is some variation, the change in coda Q is fairly small and not correlated across the three frequency bands.

To solve explicitly for a preseismic change in coda Q, we assume that the precursory change in coda Q is largest in the two years before the Loma Prieta mainshock. This interval was chosen because it provides a sufficient number of doublets for which the first event is before October 1987 and the second event is in the presumed precursory period. It also covers the time of the possible geodetic anomaly that initiated approximately 15 months before the Loma Prieta mainshock [*Lisowski et al.*, 1993]. To measure the preseismic change in coda Q, we fit a single preseismic offset to all of the doublet pairs that difference the immediate preseismic period, October 17, 1987, to October 17, 1989, with an event before October 17, 1987. The choice of a preseismic period is rather arbitrary; however, our results are not sensitive to the assumed preseismic interval because for most of the preseismic doublets, the second event occurs shortly before the mainshock. As with the coseismic analysis, we require at least three doublets to provide a stable estimate.

Figure 7 shows the preseismic changes in coda Q for each station as a function of distance for the three frequency bands. As in the case of possible coseismic changes, there is no convincing evidence for a strong preseismic change in coda Q. However, there is some evidence for a possible precursory increase in coda Q at the level of about 5% in the 5-10 Hz and 10-15 Hz bands. Nearly all of the stations within ~40 km of the epicenter show a positive change (increase in coda Q) in the 2-year interval before the mainshock at these frequencies. We emphasize that this possible change is approximately an order of magnitude smaller than previously proposed changes in coda Q.

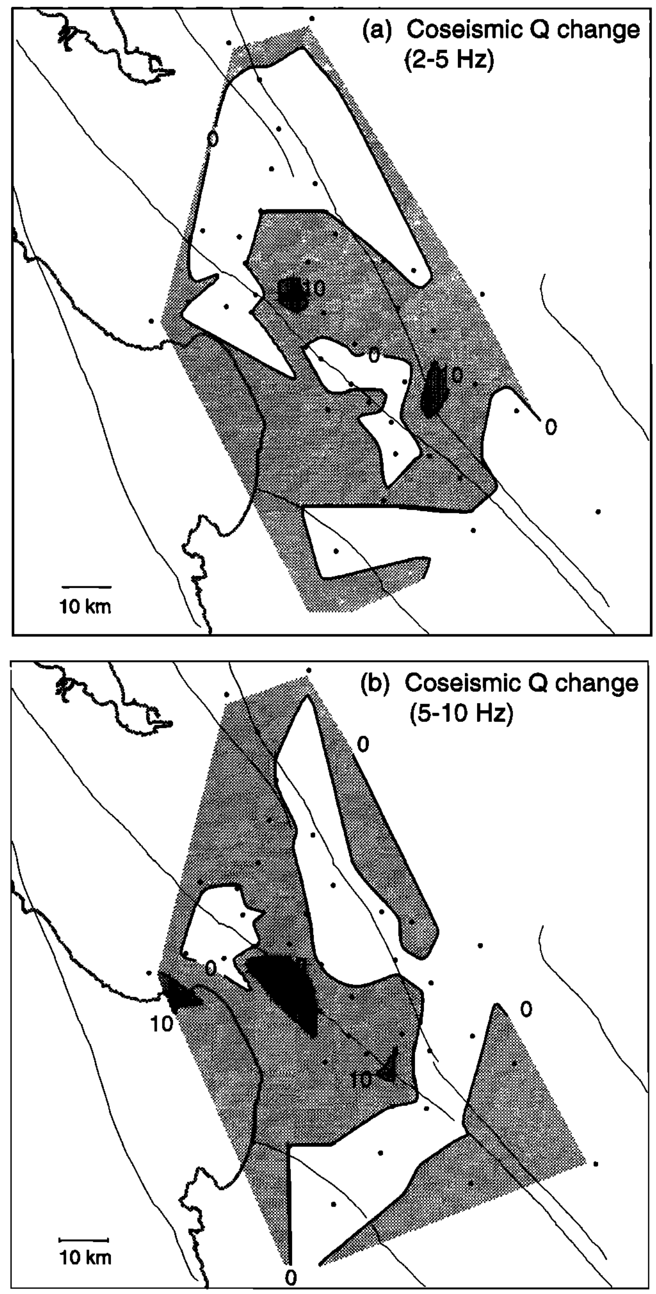

Figure 6. Geographical distribution of the same coseismic offset in coda Q for the three frequency bands a) 2-5 Hz, b) 5-10 Hz and c) 10-15 Hz as shown in Figure 5. The outline of the California coast and the major faults in the area are shown. Calnet stations are shown with solid circles. The values of coda Q change are interpolated between stations.

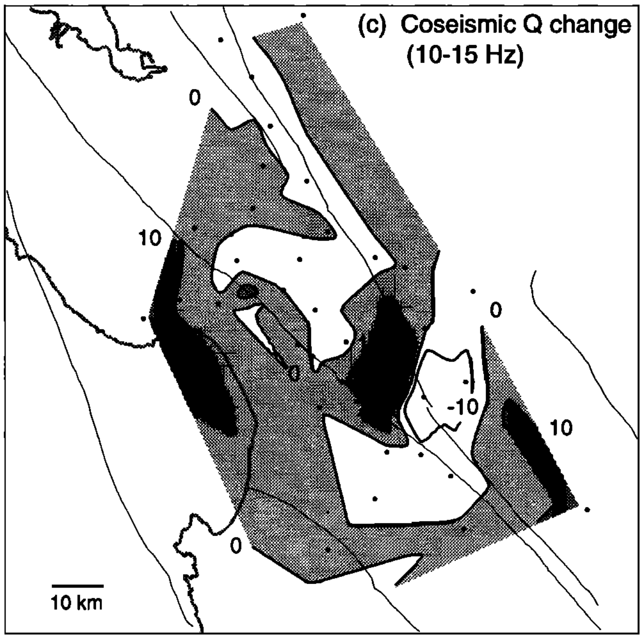

Figure 6. (continued)

Attempts to detect such a small change by "averaging" estimates of coda Q over many earthquakes would likely prove futile. Only by using doublets can such accurate measurements be made. While this change is intriguing, the level is quite small and it depends on the measurements of a small set of doublets. There are at most six doublets that can be used in this analysis for any station; a more typical number is 3. A follow-up study using a much larger set of doublets is required to attach geophysical significance to this observation.

Figure 8 shows the geographical distribution of the preseismic changes. Again, the measured changes are small and spatially incoherent, though in the 5-10 Hz and 10-15 Hz bands there is a tendency for an increase in coda Q in the preseismic period at stations near the epicenter. One station shows large changes in the 10-15 Hz band; however, this is probably attributable to noise in the observations rather than a true change in coda Q as discussed previously. For the preseismic observations, we found that the change in coda Q is of the same sign for each of the three frequency bands at 15 of the 31 stations, which is much larger than the expectation of 25% if the estimates vary randomly, indicating a substantial correlation across the three frequency bands. This correlation is primarily due to the systematic increases in the 5-10 Hz and 10-15 bands.

Discussion

Comparison With Other Coda Q Studies

With the notable exception of *Got et al.* [1990], previous studies of coda Q have estimated it as a function of time by modeling the amplitude decay of the S wave coda. These studies attempt to eliminate other factors that affect seismic amplitudes by averaging over many earthquakes and working with the late coda. By using running spectral amplitudes of microearthquake doublets, we are able to eliminate factors other than coda Q, that might contaminate coda Q estimates. Our results for the Loma Prieta earthquake indicate that there are no changes in coda Q at a level of about 5% during the entire Loma Prieta earthquake sequence.

In a study of six doublets occurring during the period 1978-1981, i.e. before and after the 1979 Coyote Lake earthquake, *Got et al.* [1990] found that coda Q was quite stable and that temporal variations of coda Q were no more than 5%. The Coyote Lake earthquake is located directly across the Santa Clara Valley from the 1989 Loma Prieta earthquake and many of the stations used in our study were also used in the *Got et al.* [1990] study. Combining the results of our study with those of *Got et al.* [1990], we conclude that temporal variations in coda Q in this region have been small for more than 13 years, despite the occurrence of the 1979 Coyote Lake ($M = 5.9$), 1984 Morgan Hill ($M = 6.2$), and 1989 Loma Prieta ($M = 6.9$) earthquakes.

There are many studies of temporal changes in coda Q. Many of these find large temporal variations in coda Q precursory to earthquakes similar in size to the Loma Prieta earthquake. We believe that the doublet method is a much more reliable way of detecting changes in coda Q than methods that rely on

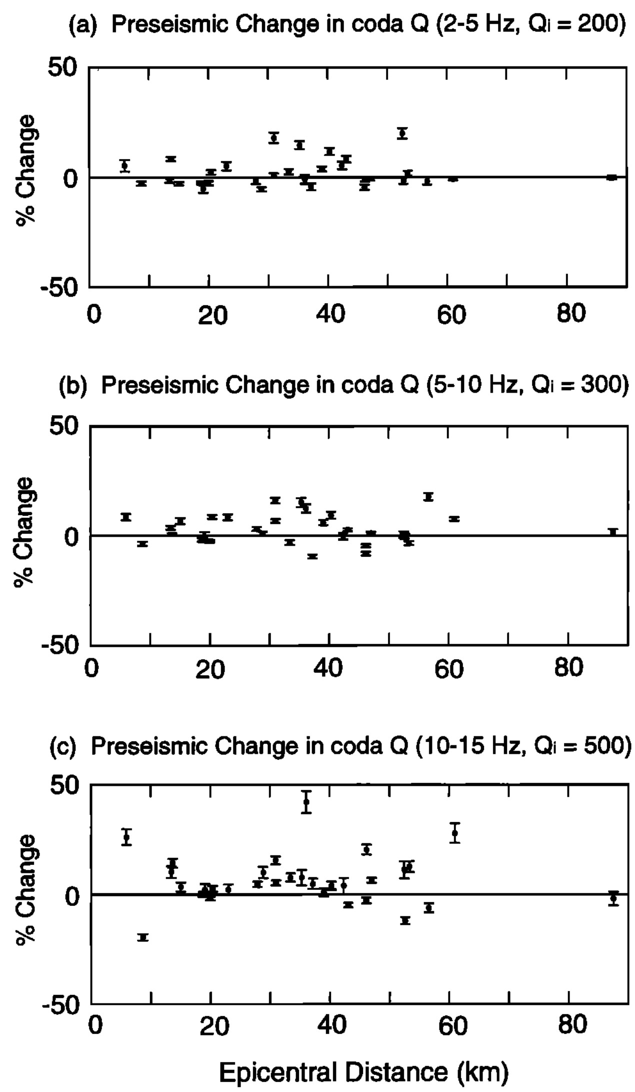

Figure 7. As Figure 5 for preseismic changes in coda Q. The preseismic period is defined as the 2 years preceding the Loma Prieta mainshock. The signals in this case are also quite small and uncertainties are large, but there is a suggestion of a preseismic increase in coda Q of about 5% for stations within 30 km of the mainshock. Unlike the coseismic offset, the preseismic change shows some correlation between frequencies.

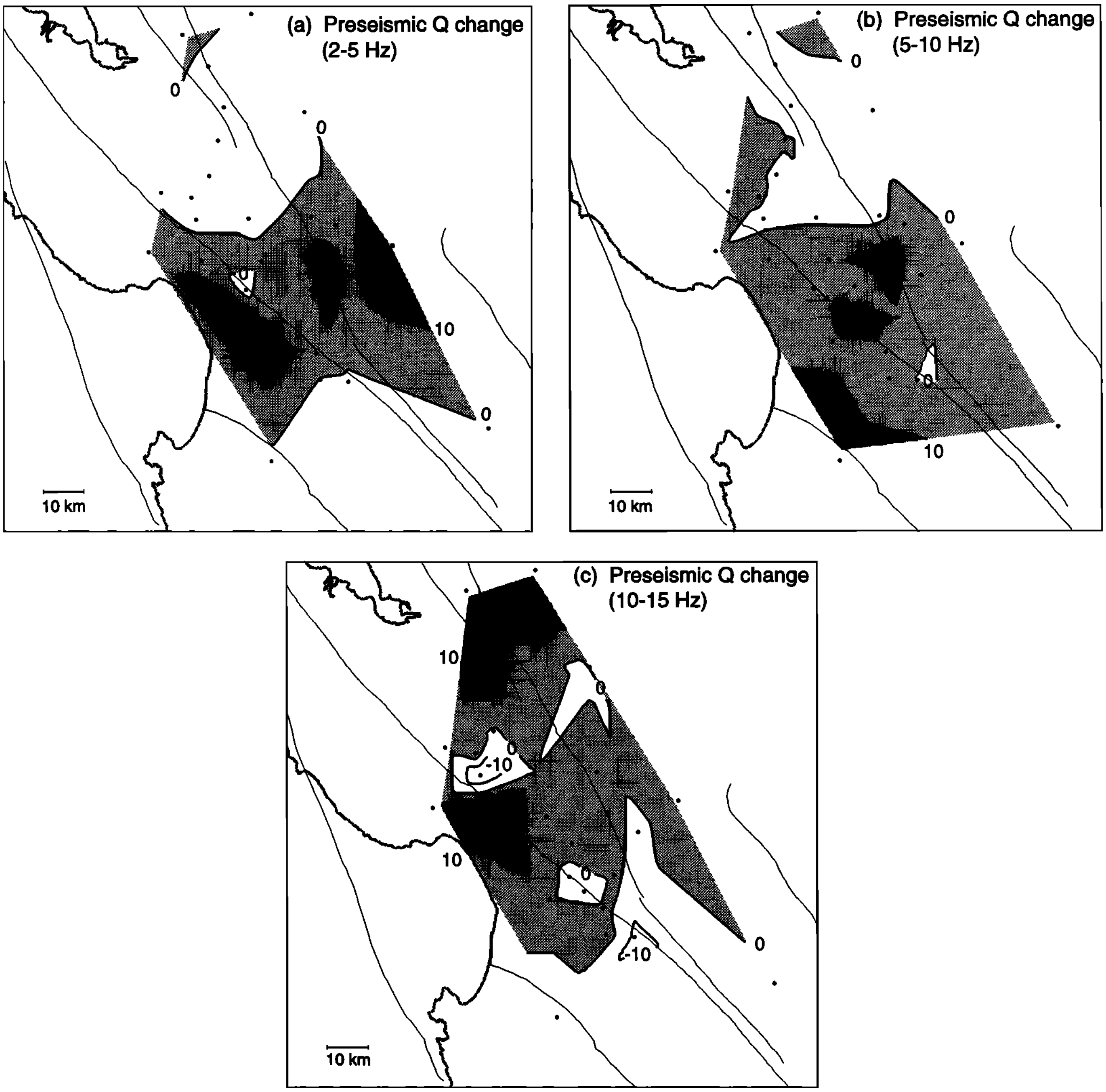

Figure 8. Geographical distribution of preseismic changes in coda Q for each of the three frequency bands as shown in Figure 6.

eliminating other factors influencing coda amplitudes by averaging. It is disappointing that we see no clearly detectable changes associated with the Loma Prieta earthquake. Although our observations are strictly relevant to the Loma Prieta earthquake only, it is surprising that we see no dramatic changes in coda Q for such a large earthquake. Our results suggest that previous measurements of large changes in coda Q may be artifacts due to other factors that influence the coda rather than a true change in the scattering or absorption properties of the Earth.

Applying our method to other earthquakes would allow us to confirm or refute this possibility. The 1992 Landers earthquake might be an interesting event to study. It occurred in an area of relatively good instrumentation, had a rupture length over twice as large as the Loma Prieta earthquake, and involved many meters of shallow slip. This last point may be important because the shallow crust is likely to show the strongest response to preseismic and postseismic strains due to the large magnitudes of the coseismic stress changes relative to the low overburden at shallow depths.

Temporal Variations in Coda Q and Seismic Velocities

Ellsworth et al. [1992] analyzed the same set of doublets used in this study to search for changes in seismic velocity. In contrast to our results, they find convincing evidence for a large coseismic change in velocity that amounts to up to 0.8% of the path-averaged slowness in the same S wave coda that we have analyzed for coda Q variations. In addition, they find evidence for a possible precursor at the level of approximately 0.2% of the path-averaged slowness. We think the difference in the results is attributable to the differing sensitivity of the two measurements. The measurements of travel time used in the velocity analysis are extremely accurate because they are a measure of phase. Measures of amplitude are much less accurate. Taken together the two studies indicate a change of velocities of the order of 0.5% but no change in attenuation any larger than 5%. Thus monitoring seismic travel times using doublets may be more promising than monitoring coda amplitudes.

The one promising aspect of this study for using coda Q in earthquake prediction is that there may have been a preseismic increase in coda Q at the level of about 5% for stations located within about 30 km of the epicenter in the 5-15 Hz frequency range. Interestingly, *Ellsworth et al.* [1992] find evidence for a possible slight increase in velocity of the early S wave coda over the same period. These two observations are consistent with a common mechanism wherein the crack distribution in the Earth's crust is altered prior to the mainshock. If the crack density decreases or the cracks themselves become smaller, seismic velocities will increase, and the attenuation and scattering of seismic waves will decrease. A more comprehensive study of doublets in the Loma Prieta region is needed to explore this possibility. There are likely to be at least an order of magnitude more doublets in Loma Prieta region than we have identified with our ad hoc approach.

Conclusions

We use earthquake doublets to measure changes in coda Q. Unlike other methods for studying coda Q, our method is insensitive to assumptions of geometric spreading, location, and source mechanism because these factors are common to the two events.

We searched for temporal changes of coda Q associated with the October 18, 1989, Loma Prieta, California, earthquake and found no evidence for a coseismic change in coda Q at a level of about 5%. All the coseismic changes we do observe are spatially incoherent and not correlated in frequency from 2 to 15 Hz. The preseismic observations indicate a possible precursive increase in coda Q of about 5% for stations within about 30 km of the mainshock. Despite the possible observation of a precursor, the modest size of the observed changes contrasts sharply with previous reports of much larger changes in coda Q associated with other earthquakes. We speculate that the difference is attributable to contamination of other estimates of coda Q by other factors that affect coda amplitudes.

We identified the doublets used in this study by searching through the Calnet seismicity catalog for events of similar location and then comparing plot of the seismograms. The Calnet waveform data are currently being brought on line on a mass storage system [*Romanowicz et al.*, 1994]. This will allow us to identify and process doublets in an automated way [*Aster and Scott*, 1993], which in turn will permit much better monitoring of properties of crustal wave propagation such as the coda decay. One of the most serious limitations of these data is the rapid decay in high frequencies. This is not an instrument effect but is attributable to the highly attenuating near-surface zone. Applying the same technique to seismograms recorded at borehole instruments should provide much more sensitive measurements [*Nadeau et al.*, 1994].

A possible disadvantage in our approach is that it relies on the occurrence of doublets. We are forced to limit our analysis to areas and time intervals where doublets occur. For the case of the Loma Prieta earthquake we found many doublets that span the intervals of interest and cover a wide range of azimuths with respect to the mainshock. If doublets are commonplace in other areas, then they will provide a powerful means of detecting temporal changes in properties of crustal wave propagation.

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