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Seismological evidence for the brittle-ductile interaction hypothesis on earthquake loading

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We extended the analyses of temporal variation of coda Q^{-1} and seismicity by Jin and Aki (1989, 1993) for central and southern California to year 2003. We use the relative frequency $N(M_c)$ of earthquakes in a certain magnitude range around M_c characteristic to a seismic region to quantify the seismicity. The cross-correlation function between coda Q^{-1} and $N(M_c)$ is calculated using a 10-year moving time window . The correlation coefficient for the entire period of about 60 years is peaked at the zero-time shift with the value close to 0.8 for both regions. We found, however, the simultaneous correlation is disturbed before major earthquakes. The disturbance is, consistently, a delay in the change of coda Q^{-1} relative to that of $N(M_c)$ before the occurrence of a major earthquake. We attribute the temporal change in coda Q^{-1} to fractures in the ductile part of the lithosphere and that in $N(M_c)$ to the response of the brittle part to the ductile fracture. We believe that M_c characteristic to a seismic region is originated from a characteristic size of fractures in the ductile zone of the lithosphere. The observed delay of coda Q^{-1} change relative to $N(M_c)$ before a major earthquake can be explained simply by the strain energy stored in the brittle part of lithosphere reaching a saturation limit and starting to flow back to the ductile part.

Key words: Coda Q, characteristic magnitude M_c, seismogenic zone, plate driving earthquake loading, brittle-ductile transition zone.

1. Introduction

This paper is a companion to the one by Aki (2004) in this issue, in which a model of earthquake loading process by plate-driving forces is proposed. We shall call this model the "brittle-ductile interaction hypothesis". As explained in the companion paper, this hypothesis is in harmony with the conclusion of Zoback and Zoback (2002) reached after an extensive global survey of the tectonic stress. Our idea, however, was originated from Jin and Aki (1989, 1993) in which a model of interaction between the brittle part and the ductile part of lithosphere was proposed to explain the remarkable correlation between the temporal change in coda Q^{-1} and the frequency of earthquakes in a specific magnitude range for central and southern California.

As explained in detail in the companion paper, in this hypothesis, the coda Q^{-1} represents the density of fractures in the ductile part of the lithosphere, and the frequency of earthquakes $N(M_c)$ with the characteristic magnitude M_c represents the response of the brittle part of the lithosphere to the ductile fractures. In the normal period of the loading process by the plate driving forces, the correlation between the temporal change in coda Q^{-1} and $N(M_c)$ is simultaneous, but as recognized by Aki (2004), the simultaneous correlation was disturbed for a few years before the Kern County earthquake of 1952 and the Loma Prieta earthquake of 1989. We shall describe additional observations supporting the hypothesis.

2. Data Analyses

Figure 1 represents the study region in California. The solid triangles are the stations at which the seismograms are used to measure the coda Q^{-1} for central (Mt. Hamilton) and southern (Riverside) California, respectively. The red solid circles indicate the location of the earthquakes with $M > 6$ occurred during the study time period.

For a seismogram of a local earthquake, the coda amplitude, $A(t \mid f)$, at lapse time t with frequency f can be expressed as

$$A(t \mid f) = A_0(f) t^{-1} \exp(-Bt) \tag{1}$$

where $A_0(f)$ is the source term, and t^{-1} represents the geometrical spreading for body waves, t is the lapse time measured from the origin time of the event. B is the coda decay rate and

$$B = \pi f Q_c^{-1} \tag{2}$$

where Q_c^{-1} is called coda Q^{-1}, and f is the frequency of the corresponding seismic waves.

We shall first summarize, briefly, the previous measurements on coda Q^{-1} and $N(M_c)$ in California. Jin and Aki (1989, 1993) used the vertical component records of the Wood-Anderson seismometer of which the amplitude response is peaked around 1.5 Hz. They selected the station Riverside for southern California and Mt. Hamilton for central California. The earthquakes with magnitude 2.8–3.5 used for measuring coda Q^{-1} are located within 60 km around the station. The seismograms are first enveloped visually, and then digitized at a sampling rate of 20/sec. The lapse time window is from twice the S-wave travel time to 80

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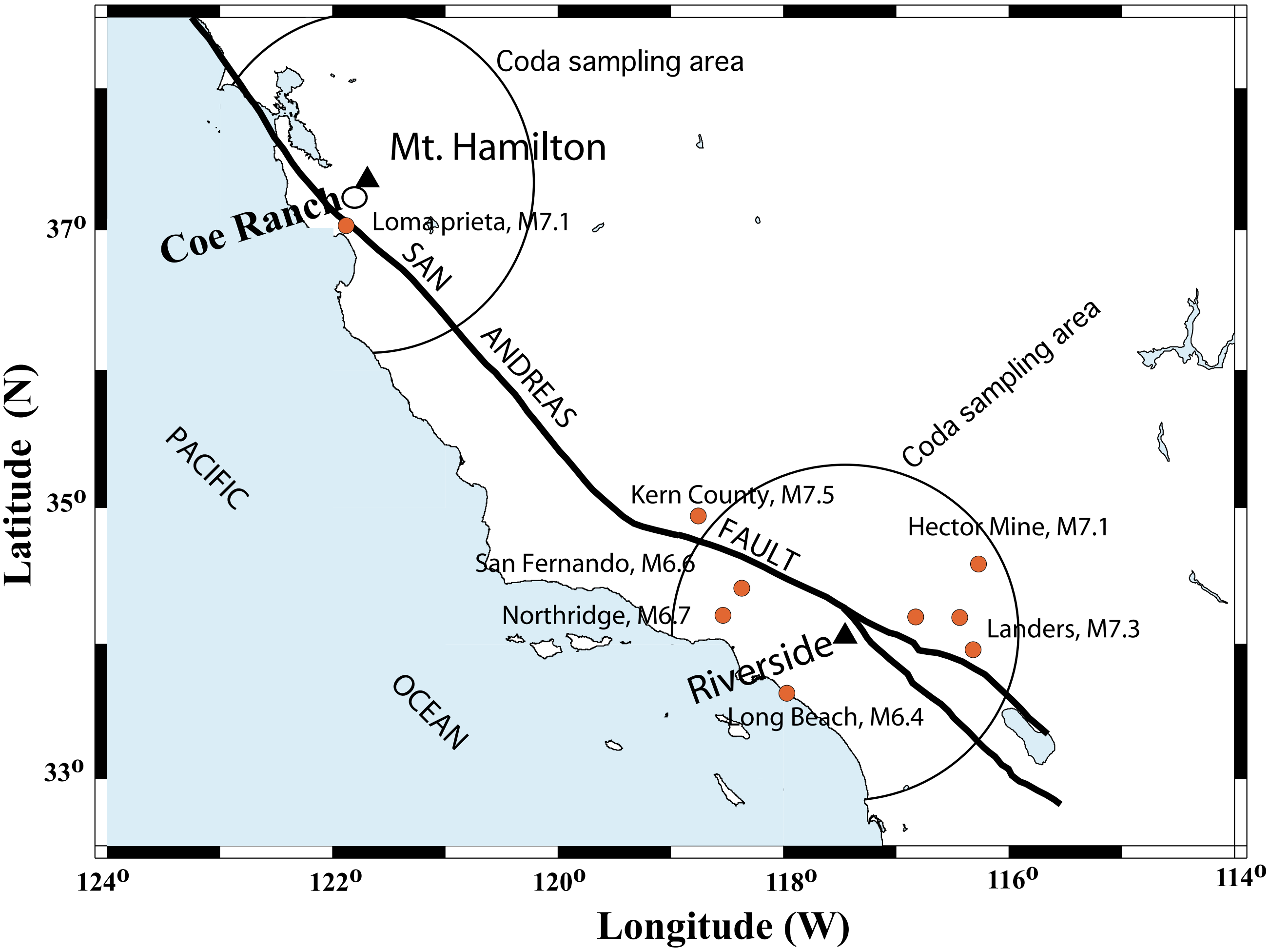

Fig. 1. A map of the study region. The large solid triangles indicate the location of the 2 seismic stations, Mt. Hamilton and Riverside, where the recorded seismograms are used for the coda Q^{-1} measurements. The small circle presents the location of station Coe Ranch (CCO) where the digital records are used to measure coda Q^{-1} and compared with that measured at station Mt. Hamilton. The red solid circles are the earthquakes with $M > 6$ occurred during the study time period. The thin line large circles indicate the 120 km in radius around the stations.

sec or the Signal/Noise = 2 whichever comes first. So, the coda wave sampling region is 120 km from the station, approximately, according to the single back-scattering theory of Aki and Chouet (1975).

Coda Q^{-1} was measured for a single station assuming that the coda decay rate is the same in a region. It requires 10–15 measurements in order to get a stable average coda Q^{-1}. To obtain a stable average with reasonable time resolution of the temporal change of the coda Q^{-1}, the individual measurements are averaged over 11 consecutive earthquakes with 4 overlapped with the neighbors. The corresponding time is the median time of the origin time of the 11 events.

The relative frequency of earthquakes with a certain magnitude M_i is defined as the number of earthquakes with magnitude of $(M_i \le M \le M_i + 0.5)$ among 100 consecutive earthquakes with magnitude $M \ge 3.0$, and located within 120 km from the station. The numbers were counted for $M_i = 3.0$, 3.5, 4.0, and 4.5, individually, using ANSS (Advanced National Seismic System) catalog for central California and the SCEC (Southern California Earthquake Center) catalog for southern California. The windows of 100 consecutive earthquakes are overlapped by 25 events with the neighbors. Each time series of $N(M_i)$ are used to calculate the cross-correlation with that of the coda Q^{-1}. They found that the cross-correlation coefficient reached higher than 0.85 with zero-time shift for $M_c = 3.0$ in southern California and $M_c = 4.0$ in central California; and it is significantly lower, even became negative sometimes, for other choices of M_c. Thus, the time series of $N(M_c$ 3.0–3.5)% and $N(M_c$ 4.0–4.5)% are taken to characterize the temporal variation of seismicity in southern and central California, respectively.

The time resolution of the constructed temporal change of coda Q^{-1} is 3 months, and that for the $N(M_c)$ is 5 months for central California and 3 months for southern California, approximately.

3. Extending Measurement on Coda Q^{-1} and $N(M_c)$

Vertical component digital High Broad Band seismograms recorded at station Mt. Hamilton (MHC) for earthquakes occurred within 60 km around the station are used to estimate coda Q^{-1} for the period from 1991–2003. The sampling rate of the digital records is 80/sec. The original records are first band-pass filtered for the frequency range of 0.75–3 Hz. For each filtered seismogram, the coda amplitude $A(t)$ is measured using a 5-sec moving lapse time window (with 2.5 sec

(a)

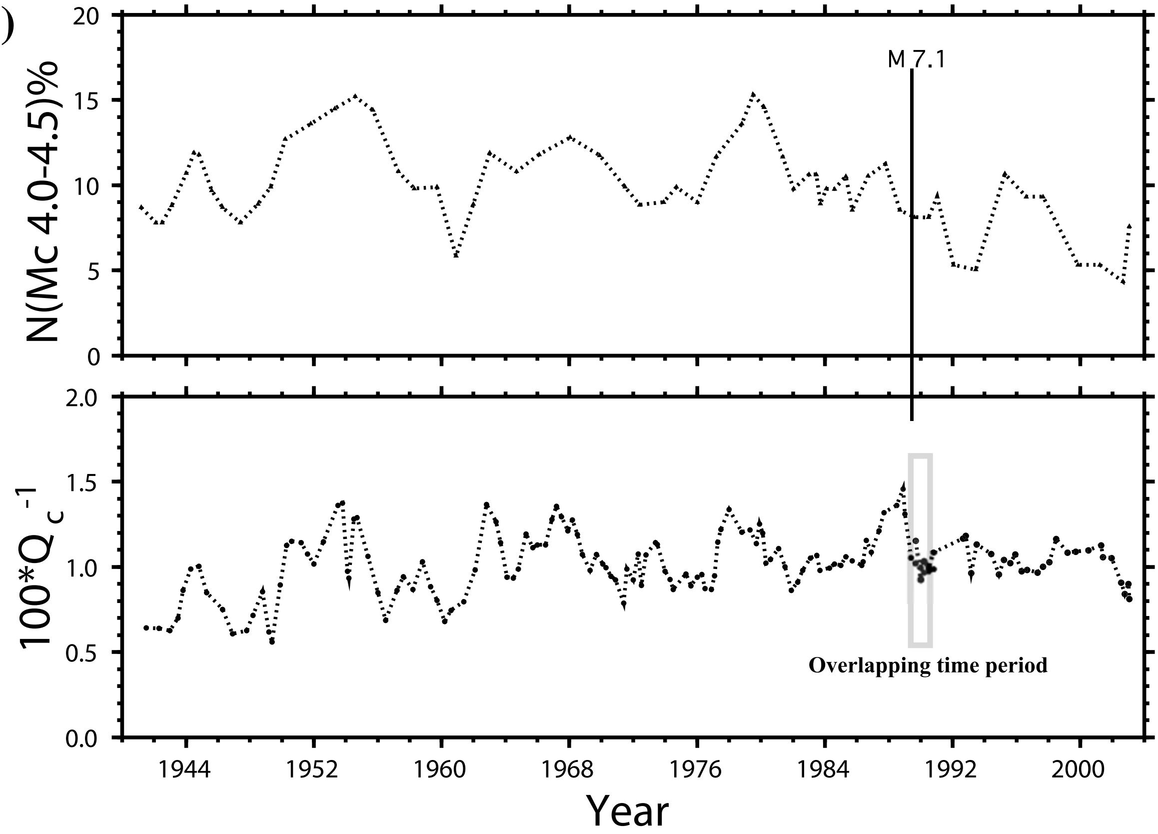

Fig. 2(a). The temporal change in coda Q^{-1} and that in $N(M_c)\%$ for central California. The vertical line indicates the occurrence time of the Loma Prieta earthquake, 1989 that was the only $M \geq 7$ event occurred within the region during the study time period. The rectangle represents the time period while the paper recording and digital data are both used.

(b)

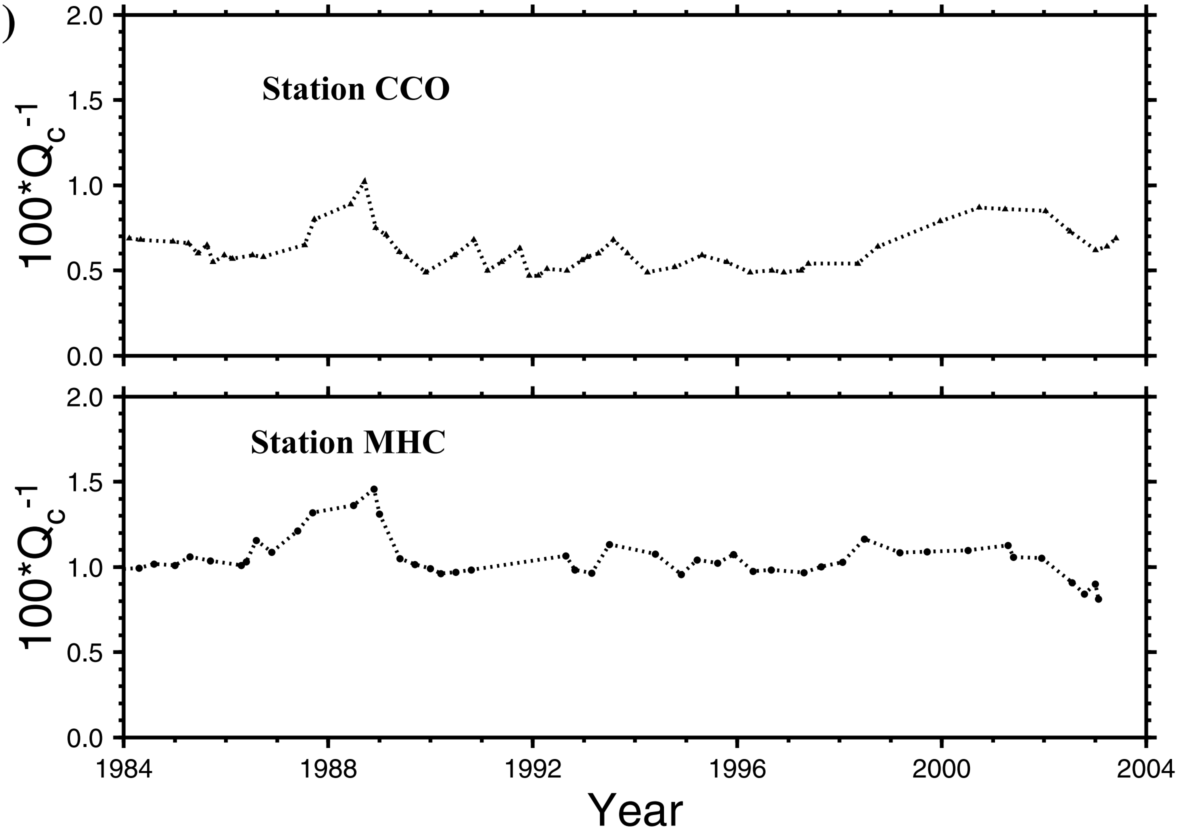

Fig. 2(b). The comparison between the temporal change in coda Q^{-1} or Q_c^{-1} measured at station Mt. Hamilton (MHC) and station Ceo Ranch (CCO).

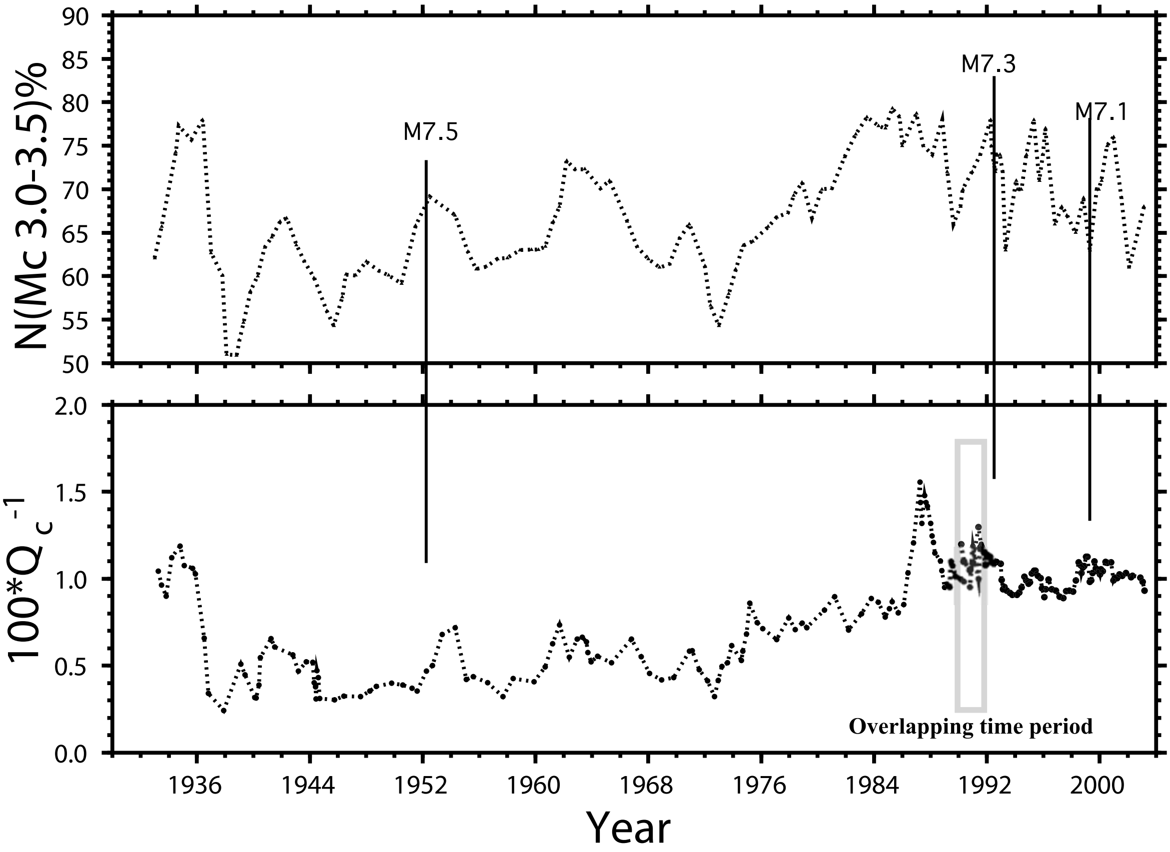

Fig. 3. The temporal change in coda Q^{-1} and that in $N(M_c)\%$ for southern California. The vertical lines indicate the occurrence time of all $M \geq 7$ events within the region during the study time period. The rectangle represents the time period while the paper recording and digital data are both used.

overlap from the neighbors) started at lapse time t = twice S-travel time and ended at the time when signal = 2*noise-level or 80 sec at the maximum, that corresponds to 120 km radius of the coda sampling area around the station, approximately. Then the coda decay rate and coda Q^{-1} are estimated by fitting equation (1) and (2). Again, the coda Q^{-1} for each individual seismogram is averaged over 11 successive earthquakes with 4 overlapped with the neighbors. The resultant coda Q^{-1} is plotted against time (the median of origin times of the 11 events) from 1940 to 2003 in Fig. 2(a). The results from the analog data and that from the digital data appear to be connected smoothly as indicated in Fig. 2(a).

To confirm the validity of the temporal change in coda Q^{-1} found at station MHC, we apply the same procedure to the seismograms recorded at station COE RANCH (CCO) located at 37.2582 N; 121.6735 W, about 10 km southwest of station MHC. The digital recording started in 1984 at CCO, 7 years earlier than at MHC. Figure 2(b) shows the comparison between the temporal changes in coda Q^{-1} measured at these 2 stations. Their absolute values are different, but the temporal change is remarkably similar between the two stations, supporting our basic assumption that the temporal change in coda Q^{-1} reflects the change in the physical condition of Earth's interior.

For southern California, we measure coda Q^{-1} by the use of the short period vertical component (VHZ) digital seismograms recorded at station Riverside, with sampling rate of 100/sec, started from 1986. The procedure is the same as for the MHC data. The results are plotted as shown in Fig. 3. There are 2-year overlapping time between the analog records and digital records. Again the results from the digital data connect smoothly to the earlier results from the analog data.

As mentioned earlier, we follow Jin and Aki (1989, 1993) and use $M_c = 3.0$ and 4.0 for southern and central California, respectively. The number of earthquakes with magnitude $4.0 \leq M \leq 4.5$ among 100 successive (25 overlapped with the neighbors) $M \geq 3.0$ earthquakes occurred within 120 km around the MHC station are counted using the ANSS catalog. The median time of each 100 consecutive events is taken to construct the time series of $N(M_c)$. In the same way, we constructed the time series of $N(M_c)$ for earthquakes with $M \geq 3.0$ and occurred within 120 km from station Riverside for $M_c = 3.0$. The temporal changes of $N(M_c)$ are shown in Figs. 2(a) and 3 for central and southern California, respectively.

4. Temporal Correlation between Coda Q^{-1} and $N(M_c)$

The time series of coda Q^{-1} and $N(M_c)$ are constructed at uneven sampling interval because of the nature of the data and they are non-coincidently sampled. Therefore, before calculating the cross-correlation function using conventional method, we needed to interpolate the time series first. Both the interpolating and computing on cross-correlation sequence are done by using the software in MATLAB (version 6.3).

The cross-correlation functions between the time series of

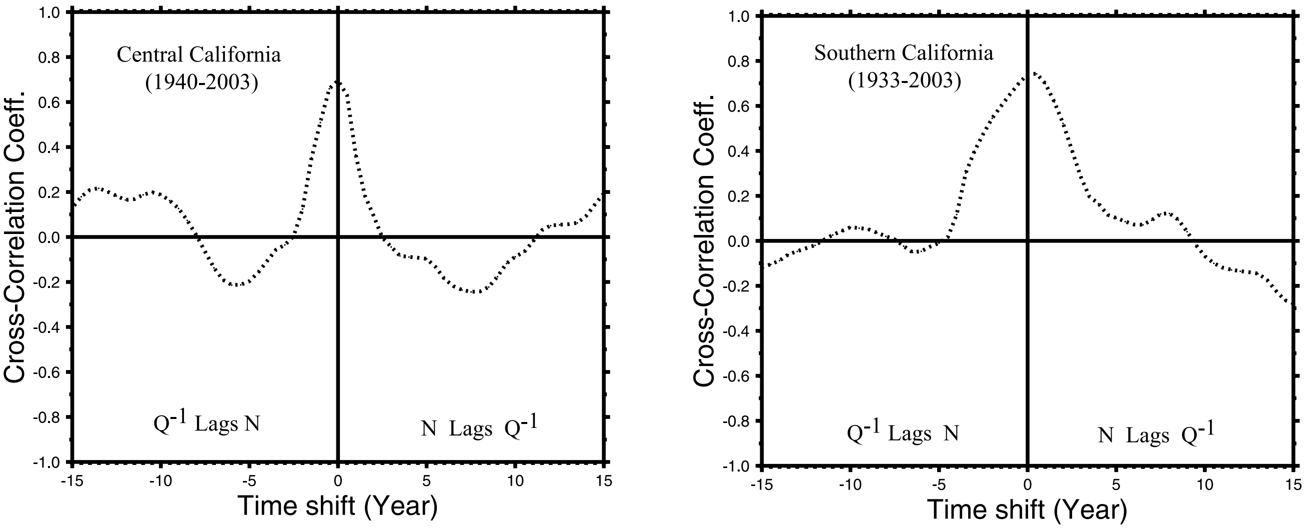

Fig. 4. The overall temporal cross-correlation function between the changes of coda Q^{-1} and $N(M_c)\%$ for central (left) and southern (right) California.

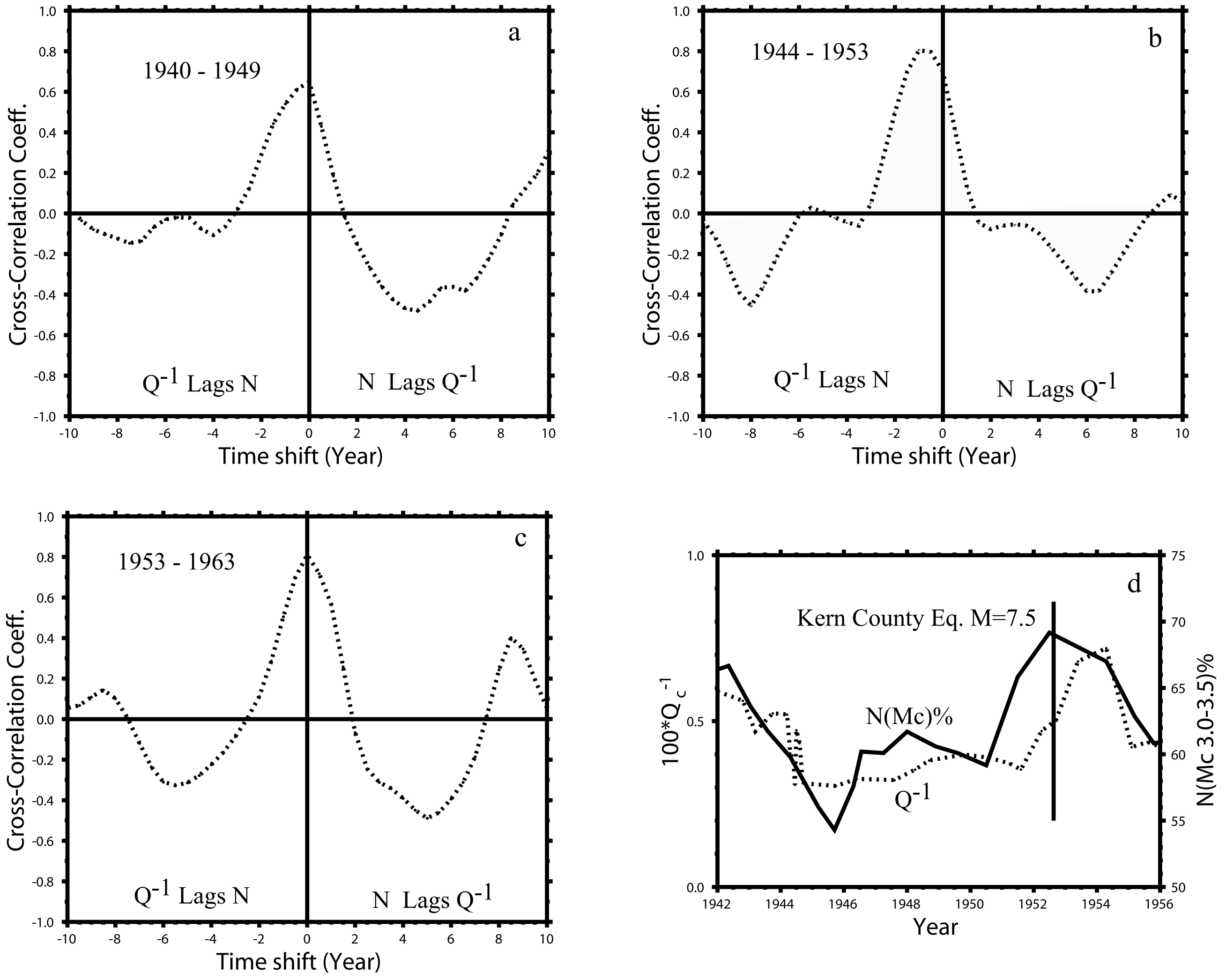

Fig. 5. The change in correlation between and $N(M_c)\%$ observed before and after the Kern County earthquake of 1952. An one year delay in the change of coda Q^{-1} relative to that of $N(M_c)\%$ is observed before the occurrence of the major event. The de-correlation can be seen clearly from the time series shown in panel d.

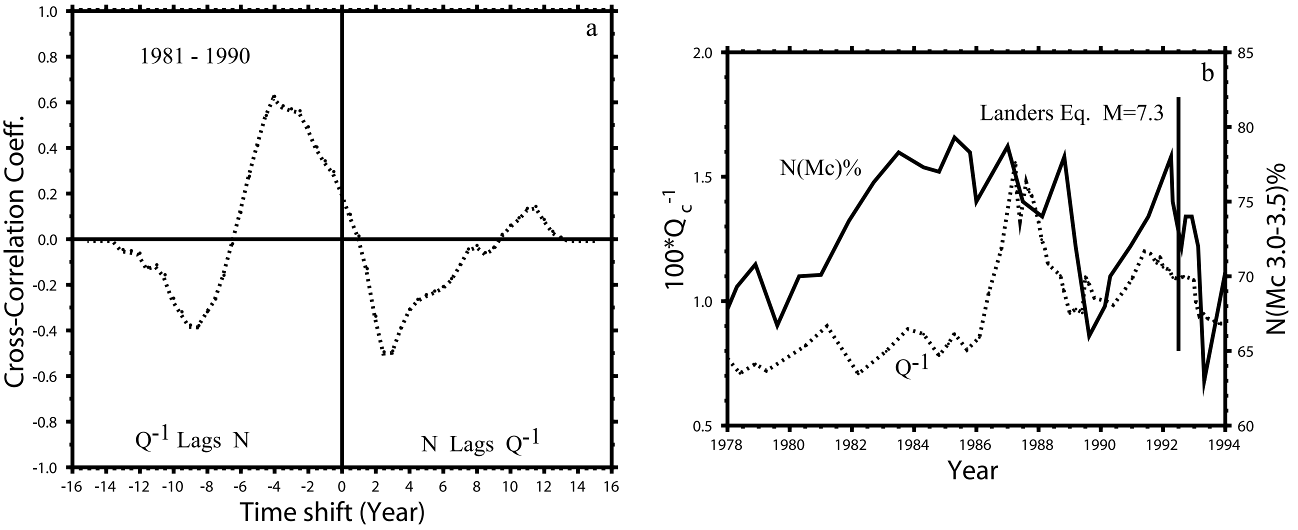

Fig. 6. The observed approximate 4-year delay in the change of coda Q^{-1} relative to that of $N(M_c)\%$ before the occurrence of the Landers earthquake of 1992.

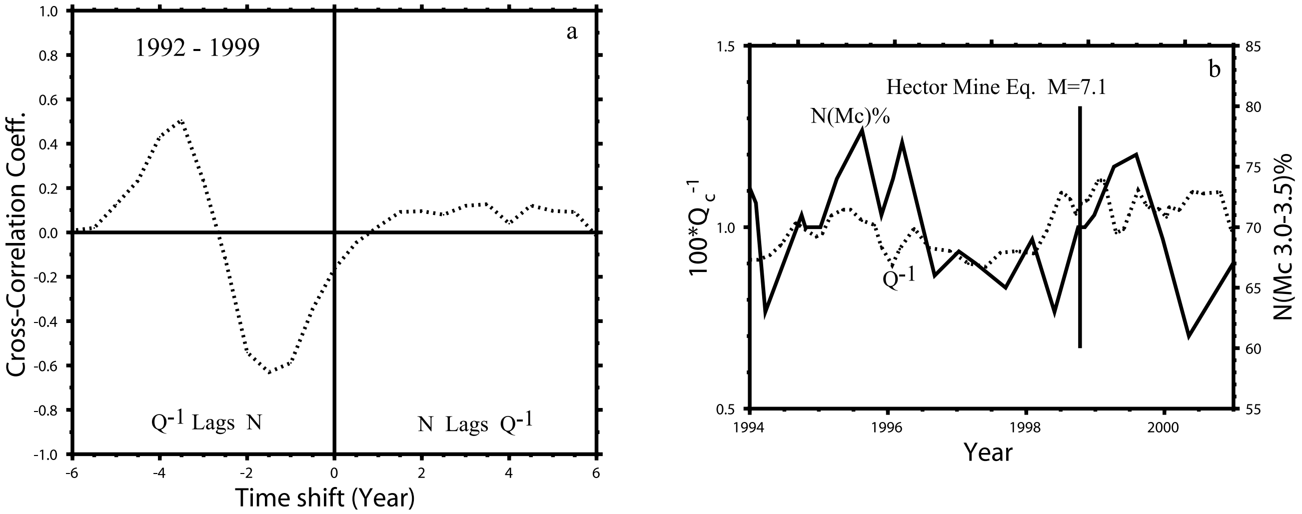

Fig. 7. Another 4-year delay in the change of coda Q^{-1} relative to that of $N(M_c)\%$ before the Hector Mine earthquake of 1999.

coda Q^{-1} and $N(M_c)$ for the entire time period are represented in Fig. 4. The left panel is for central California and the right one is for southern California. The cross-correlation functions for both regions are peaked at the zero-time shift. However, the shape of the cross-correlation function for southern California is somewhat different from that obtained by Jin and Aki (1989) using data during 1933 to 1988. There is an asymmetry in the curve toward pushing it to the delay of coda Q^{-1} relative to $N(M_c)$.

We apply a 10-year moving window to the time series to compute the cross-correlation in a short time period in order to study the temporal change of the cross-correlation function. We found 3 time periods for southern California and 2 time periods for central California during which the simultaneous correlation has been disturbed. Two characteristic features of these disturbances are that (i) All these disturbances appear to be a delay in the change of coda Q^{-1} relative to that of the $N(M_c)$; and (ii) All of these disturbances, except the current period for central California, are followed by earthquakes with magnitude greater than 7. There were no other earthquakes with magnitude greater than 7 during the study period in both regions.

Southern California

Case 1. 1944–1953. The cross-correlation was simultaneous for each consecutive 10-year time periods until 1940–1949. In the time period 1944–1953 we found an 1-year delay in the change of coda Q^{-1} relative to that in $N(M_c)$. Then the correlation became simultaneous after 1953. Figure 5 illustrates the change in the cross-correlation (panel a to c) and the corresponding time series (panel d). The $M = 7.5$ Kern County earthquake occurred in 1952 near the boarder of the study region.

Case 2. 1980–1991. The cross-correlation shows a 4-year delay in the change of coda Q^{-1} relative to the $N(M_c)$ change. Figure 6 shows the correlation function for 1980–1991 and the time series during the period. The $M = 7.3$ Landers earthquake took place in 1992.

Case 3. 1992–1999. Figure 7 represents the cross-

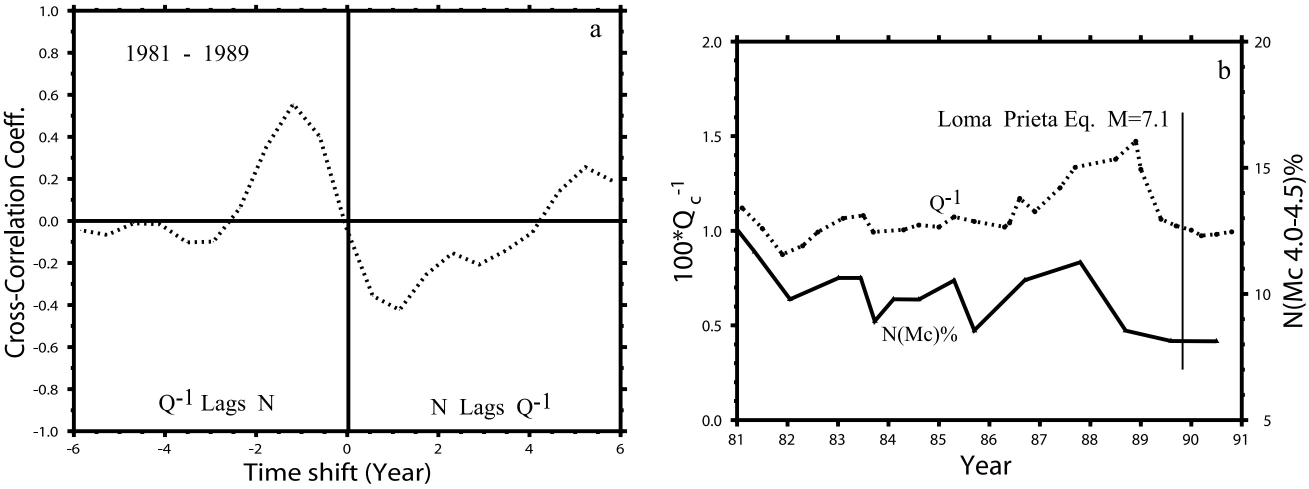

Fig. 8. The disturbed simultaneous correlation between the temporal change of coda Q^{-1} and that of $N(M_c)\%$ before the occurrence of the Loma Prieta earthquake in 1989. The delay time in coda Q^{-1} change is about 1.5 years.

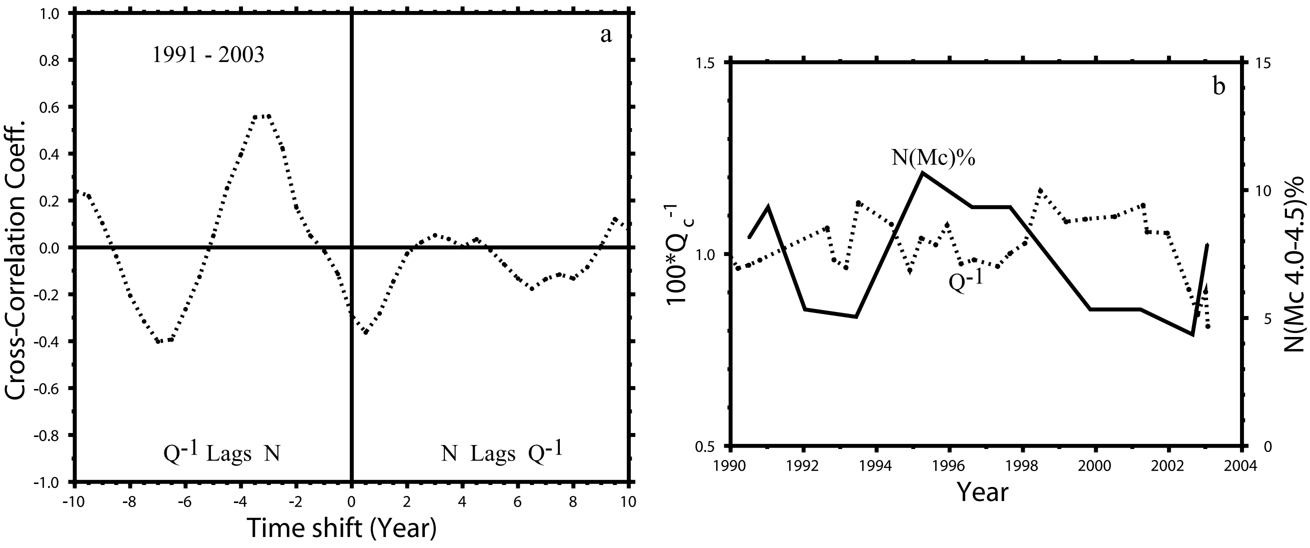

Fig. 9. The temporal change in and $N(M_c)\%$ for time period 1990 to 2003 observed at station MHC central California (right panel) and the corresponding cross-correlation sequence. A 3.5-year delay in the change of coda Q^{-1} relative to that of $N(M_c)\%$ has been found without $M > 7$ event occurred yet.

correlation function (a) and the corresponding time series (b) for this time period, again the $M = 7.1$ Hector Mine earthquake has happened at 1999.

Central California

Case 1. 1981–1989. As shown in Fig. 8, the change of coda Q^{-1} is delayed from that of the $N(M_c)$ before the occurrence of the $M = 7.1$ Loma Prieta earthquake in 1989.

Case 2. 1991–2003. We found that the cross-correlation is not simultaneous as shown in Fig. 9. It is similar to the situation in southern California before the Landers earthquake shown in Fig. 6.

5. Conclusions and Discussions

As mentioned above, the observed coda Q^{-1} and $N(M_c)$ time series are both irregular and sparse, the interpolating process may bring in new adjustable numerical parameters, increasing the danger of self-deception by possible data overfitting, specially for the short time correlation analyses. Recently, Zaliapin *et al.* (2003) introduced a formal statistic technique for detecting the temporal correlations between time series observed at irregular, not coincident grids. This technique allows one to work on the non-coincident time series without any data manipulation and the correlation is defined via the stable objects (trends) rather than noisy individual observations, hence it is highly robust, allowing one to work on different time scales. Zaliapin *et al.* (2004) applied this technique to study the temporal correlation between the coda Q^{-1} and $N(M_c)$ observed in central California. The result of their analyses agrees well with what we found in this paper.

The time series of coda Q^{-1} and $N(M_c)$ observed in both central and southern California are simultaneously correlated in the normal period during which the region is safe from a major earthquake. The simultaneous correlation is disturbed before major earthquakes with magnitude greater than 7 in the region. The disturbance, consistently, indicates a delay

Table 1. The parameters of the Brittle-Ductile interaction model.

Target Earthquake	Reference	Duration (year)	Delay Time (year)	M_c	fp (Hz)
Stone Canyon(M5)	Chouet(1979)	(Normal Period)		1-2	24
Misasa, Japan(M6.2)	Tsukuda(1988)	> 8	2 - 3	2-3	5-10
Loma Prieta(M7.1)	Jin & Aki(1993)	7	1	4-4.5	1-3
Kobe, Japan(M7.2)	Hiramatsu et al.(2000)	6	2	2.6-3.6	1.5-4
Kern County(M7.5)	Jin & Aki(1989)	8	1	3-3.5	1-3
Landers(M7.3)	Case 2 for S.CA in this paper	10	4	3-3.5	1-3
Hector Mine(M7.1)	Case 3 in S.CA in this paper	6	3.5	3-3.5	1-3
Tangshan(M7.8)	Jin & Aki(1986) Li & Chen(1981)	?	3	4.5-5	1-2

in the change of coda Q^{-1} relative to that of $N(M_c)$ with the delay time of 1–4 years.

A few other studies have reported correlations between the change of coda Q^{-1} and seismicity. We summarize those observations together with ours in Table 1. In this table, the duration is defined as the time length during which the simultaneous correlation between the two time series is disturbed. f_p is the dominant frequency at which the coda Q^{-1} change occurs. The model has 4 parameters: (i) duration of the abnormal period; (ii) delay time of the change of coda Q^{-1} and that of the $N(M_c)\%$; (iii) the characteristic magnitude M_c; and (iv) the frequency, f_p, at which the peak coda Q^{-1} change occurs. We find that M_c varies inversely with f_p in harmony with our brittle-ductile interaction model of earthquake loading as described in Aki (2003).

The first row of Table 1 is from the first report of temporal change in coda Q discovered at Stone Canyon by Chouet (1979). The Stone Canyon, California is located in the creeping zone of the San Andreas fault. The coda Q change observed in the Stone Canyon was very rapid (within a month or so) and change occurred at highest frequency. In fact, there was no major earthquake in the area during the time period of his study.

The observed coda Q decrease in high frequency, and its concurrence with the increase of seismicity for earthquakes with magnitude 1–2 indicates that the change represents the normal loading process according to our model.

According to this model, f_p corresponds to the fracture size in the ductile part of lithosphere that must be comparable to the size of earthquake with magnitude M_c. The data listed in Table 1 indicate that such requirement is at least qualitative met.

Modeling and monitoring the earthquake loading process in a seismic region is essential for earthquake prediction. One of the inherent difficulties in modeling the loading process is that the lithosphere involved in the process is not an isolated system for individual earthquake. A variety of interactions among the elements in the system appear to exist in a broad area. At each stage of the development of loading process, we expect numerous possible scenarios for the future course. Therefore, we need models that could be effectively constrained and adjusted by the monitored data. The brittle-ductile interaction hypothesis offers one of them. Of course earthquakes in nature are much more complicated than expected from one simple model. We need many such models that can be constrained by a variety of observations for a reliable prediction.

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References

Aki, K., Scale dependence in earthquake processes and seismogenic structure, *PAGEOPH*, **157**(2000), 2249–2258, 2000.

Aki, K., A new view of earthquake and volcano precursors, *Earth Planets Space*, **56**, this issue, 689–713, 2004.

Aki, K. and B. Chouet, Origin of coda waves: Source, attenuation, and scattering effects, *J. Geophys. Res.*, **80**, 3322–3342. ANSS catalog, http://quake.geo.berkely.edu/anss, 1975.

Chouet, B., Temporal variation in the attenuation of earthquake coda near Stone Canyon, California, *Geophys. Res. Lett.*, **6**, 143–146, 1979.

Hiramatsu, Y., N. Hayashi, M. Furumoto, and H. Katao, Temporal change in coda Q^{-1} and b-value due to the static stress change associated with the 1995 Hyoko-ken Nanbu earthquake, *J. Geophys. Res.*, **105**, 1641–1651, 2000.

Jin, A. and K. Aki, Temporal change in coda Q before the Tangshan earthquake of 1976 and the Haicheng earthquake of 1975, *J. Geophys. Res.*, **91**, 665–673, 1986.

Jin, A. and K. Aki, Spatial and temporal correlation between coda Q^{-1} and seismicity and its physical mechanism, *J, Geophys. Res.*, **94**, 14041–14059, 1989.

Jin, A. and K. Aki, Temporal correlation between coda Q^{-1} and seismicity—Evidence for a structure unit in the brittle-ductile transition zone, *J. Geodynamics*, **17**, 95–119, 1993.

Li, Q. and B. Chen, Spatial and temporal change of b-value before the Tangshan Earthquake of 1976, *J. Geophys.*, **21**, 89–96 (in Chinese with English abstract). SCEC catalog, http://scec.gps.caltech.edu/catalog-search.html, 1981.

Tsukuda, T., Coda Q before and after the 1983 Misasa earthquake of M6.2, Tottori Pref. Japan, *PAGEOPH*, **128**, 261–280, 1988.

Zaliapin, I., A. Gabrielov, and V. Keilis-Borok, Multiscale trend analysis, submitted to Fractals, 2003.

Zaliapin, I., A. Jin, Z. Liu, and K. Aki, Temporal (un)correlations between coda Q and seismicity—a multiscale trend analysis, *PAGEOPH,* 2004 (in press).

Zoback, M. D. and M. L. Zoback, State of stress in the Earth's lithosphere, *International Handbook of Earthquake and Engineering Seismology*, Academic press, Amsterdam, 559–568, 2002.

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