Lg Excitation, Attenuation, and Source Spectral Scaling in Central and Eastern North America

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Abstract

Seismic moments and corner frequencies were obtained for many earthquakes in the central and eastern United States, and for a few events in the western United States, using the Lg phase and a recently developed inversion algorithm. Additionally, Q values for the Lg phase along paths to individual stations were obtained simultaneously with the source parameters. Both corner frequencies and magnitudes were found to vary systematically with moment. For moments between 0.15 and 400×10^{15} N-m corner frequencies vary between about 4 and 0.2 Hz while body-wave magnitude varies between about 3.5 and 5.8. A map of Lg Q values displays a systematic decrease from east to west. Maximum and minimum values are 989 and 160, respectively.

Lg coda Q values were obtained for the entire United States with excellent coverage in the eastern and western portions of the country and somewhat poorer coverage in the central portion. Lg coda Q is highest (700-750) in a region of the northeastern United States that includes portions of New York and Pennsylvania and lowest (>200) in California. Lg coda Q is lower (250-450) everywhere west of the Rocky Mountains than in the rest of the country (450-750). Q determinations for both the direct Lg phase and Lg coda indicate that, for an earthquake of a given magnitude, Lg and its coda will propagate much more efficiently, and cause damage over a wider area, in the eastern and central United States than it will in the western United States.

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1. Introduction

Over the period of this contract we have conducted research along three major lines. First, we have determined source properties of earthquakes (moment and corner frequency), primarily in the central and eastern United States. Second, we have determined Lg Q along paths from events, for which we have determined source properties, to numerous stations in North America. Most of these stations are in the central and eastern United States, but a few of them are in the western United States. The determinations of source properties and path-dependent Lg Q were performed simultaneously using a method developed for studies in Eurasia (*Xie et al.*, 1996; *Cong et al.*, 1996). Third, we developed a map of Lg coda Q variation for the entire United States. For the development of that map we measured Lg coda Q for numerous paths across the entire United States using a modern stacking technique (*Xie and Nuttli*, 1988) and inverted those values to obtain a tomographic image of the variations using a method developed by *Xie and Mitchell* (1990a).

The moment and corner frequency values that we have obtained enable us to infer how moment relates to corner frequency and to reported magnitudes of selected events. Our results show that regional variations of Lg Q and Lg coda Q can be related to past tectonics, with the lowest values occurring in regions that have undergone the most recent tectonic activity (*Mitchell*, 1995).

2. Lg and Lg Coda

Lg is often the most prominent and robust phase on short-period and broad-band seismograms recorded in continental regions. For that reason it has been used to determine magnitudes of small events at regional distances (*Baker*, 1970; *Nuttli*, 1973), yields of nuclear explosions (*Nuttli*, 1986), and regional variations of crustal attenuative properties (e.g. *Mitchell*, 1981; *Campillo and Plantee*, 1991). It can be treated as a superposition of higher-mode surface waves that propagate in the continental crust (*Knopoff et al.*, 1973; *Panza and Calcagnile*, 1975; *Kennett*, 1984). The onset of Lg arrives with a group velocity of 3.3 - 3.6 km/s, with young active regions being slower than stable shields.

A coda of up to several minutes duration follows Lg, the predominant frequency of which is lower than the direct phase, and decreases with time. The arrival of Lg coda energy is omnidirectional, indicating that it is scattered from heterogeneities in the crust (*Der et al.*, 1984). Being a scattered wave, it is sensitive to properties in a volume of the crust that surrounds the great circle path, including both the seismic source and the receiver, rather than to properties along a single ray path between them. Scattering had earlier been inferred as the cause for coda following body waves at short distances (*Aki*, 1969; *Aki and Chouet*, 1975).

The attenuation of both Lg and Lg coda is often expressed as the inverse of a quality factor, Q. In the present report, we use Q_{Lg} and Q_{Lg}^c to denote, respectively, the quality factors of the direct Lg phase and Lg coda. Q_{Lg} can be described by the equation

$$Q_{Lg} = Q_0 f^\eta$$

where Q_0 is Lg Q at a frequency (f) of 1 Hz and η is the frequency dependence of Lg coda Q in the frequency range near 1 Hz. The same form of equation can be used to describe Q_{Lg}^c but, of course, Q_0 and η may take on different values than those for Q_{Lg} in any region.

3. The Direct Lg Phase

Figure 1 shows examples of Lg and its coda for four paths in the United States. The uppermost trace is for a path in the eastern United States, the middle two traces are for paths in the central United States, and the lowest trace is for a path in the western United States. Note that the frequency content of the trace for the western United States covers a lower range of frequencies than that covered for the other traces. The high-frequency energy has been damped much more rapidly in the western portion of the United States than in the eastern portion.

3. The Direct Lg Phase

Method for obtaining Earthquake Source Parameters and Lg Q

Xie (1993) developed a method for simultaneous inversion of Lg spectral parameters (M_0 and f_c) and path-variable Q_0 and η (Lg Q and its frequency dependence) using Lg spectra from a single event. It was recently applied to nuclear explosions (Xie *et al.*, 1996) and earthquakes (Cong *et al.*, 1996) in Eurasia. The method is described in detail in Xie (1993), so will only be briefly summarized here.

The Lg spectrum is expressed as a product of (1) the Lg source spectrum (assumed to be a simple Brune source), (2) the source radiation spectrum for the higher-mode surface waves that comprise Lg, (3) an exponential factor that includes frequency raised to the $(1-\eta)$ power, (4) the mean Lg travel time, (5) Q_0 , and (6) a randomness factor. For each event studied, that expression can be solved by non-linear least-squares to obtain M_0 and η for the event as well as Q_0 and η for all paths between the event and the stations that recorded it.

Earthquake Source Parameters

The earthquakes for which moment (M_0) and corner frequency (f_c) were determined are listed in Table 1. Twenty-eight of these events were situated such that paths to recording stations lie entirely or predominantly in either the central or eastern United States. The other three earthquakes occurred in California and paths to recording stations lie in the western United States. Events, stations, and paths appear on the map in Figure 2. In addition to hypocentral information, Table 1 presents body-wave magnitudes (m_b) reported by the NEIC, M_0 and f_c values obtained in our research and the number of stations used for the analysis of each event.

Figure 3 plots corner frequency (f_c) versus seismic moment (M_0) for the events used in our work. The solid symbols denote results for which three or more stations were used in the analysis and the open symbols denote results for events in which one or two stations were used. A least-squares fit to the solid symbols (solid line) yields the M_0 - f_c relation

$$\log(M_0) = 15.36(\pm 0.48) - 2.32(\pm 0.36)\log(f_c) \quad (1)$$

while all symbols yield the relation

$$\log(M_0) = 15.29(\pm 0.50) - 1.97(\pm 0.25)\log(f_c). \quad (2)$$

The equations are the same, within calculated uncertainties. Taking into consideration the large uncertainties in these determinations, they are roughly consistent with values plotted in a compilation by Haar *et al.* (1986).

3. The Direct Lg Phase

Example showing Lg phases recorded at four stations in the United States.

Figure 1

3. The Direct Lg Phase

Table 1. Earthquakes used for determination of source parameters for the United States

Event No	Date (m d y)	Origin time (h:m:s)	Latitude	Longitude	Depth (km)	m_b (mb)	M_0 ($\times 10^{15}$ N-m)	f_c (Hz)	No. of stations
1	01 29 90	13:16:10.60	34.463	-106.879	12.0	4.5	0.9	1.12	1
2	04 18 90	13:53:51.40	36.910	-121.652	05.0	5.4	11.0	0.30	2
3	09 26 90	13:18:51.30	37.165	-089.577	12.0	4.7	2.2	1.36	2
4	10 19 90	07:01:57.40	46.470	-075.590	13.0	4.6	5.8	1.40	2
5	10 24 90	06:15:20.70	38.047	-119.157	12.0	5.4	15.0	0.30	4
6	12 31 90	03:53:58.30	47.579	-072.556	18.0	4.2	0.9	1.18	1
7	01 02 92	11:45:35.60	32.336	-103.101	05.0	4.6	1.5	1.30	2
8	08 21 92	16:31:55.10	33.050	-080.116	10.0	4.1	5.0	0.25	1
9	08 22 92	12:20:32.60	39.106	-070.319	10.0	4.8	53.5	0.20	3
10	11 17 92	03:58:00.90	45.764	-074.862	18.0	4.0	1.5	0.50	1
11	04 09 93	12:29:19.10	28.811	-098.124	05.0	4.1	7.0	0.45	4
12	06 02 93	02:08:32.70	25.946	-109.989	10.0	4.7	16.5	0.70	3
13	12 05 93	00:58:20.20	27.831	-102.737	05.0	4.7	15.0	0.60	4
14	01 16 94	00:42:43.24	40.327	-076.007	05.0	4.2	0.25	3.60	2
15	01 16 94	01:49:16.20	40.330	-076.037	05.0	4.6	3.2	1.30	4
16	05 12 94	00:22:21.80	24.953	-109.284	10.0	4.7	88.0	0.40	1
17	05 12 94	01:14:02.20	24.678	-109.188	10.0	4.2	14.0	0.20	1
18	09 13 94	06:01:23.00	38.156	-107.982	10.0	4.4	5.0	0.40	3
19	09 25 94	00:53:28.00	47.770	-069.950	18.0	4.1	0.3	2.20	3
20	02 03 95	15:26:10.07	41.527	-109.639	01.0	5.2	10.0	0.80	4
21	03 11 95	08:15:52.00	36.983	-083.150	01.0	3.8	1.5	0.90	4
22	04 14 95	00:32:54.20	30.244	-103.325	05.0	5.7	280	0.30	5
23	05 27 95	19:51:10.40	36.170	-089.430	06.0	3.8	0.6	1.80	5
24	01 07 96	14:32:53.10	35.766	-117.649	06.0	4.6	26.0	0.33	3
25	02 06 96	15:10:27.60	42.500	-097.500	shallow	3.6	0.19	1.97	2
26	02 20 96	14:40:41.90	27.552	-111.678	10.0	4.3	9.10	0.39	2
27	03 01 96	11:49:14.70	29.499	-113.627	10.0	4.1	12.4	0.31	1
28	03 19 96	15:31:36.40	25.006	-109.320	10.0	5.0	53.0	0.24	3
29	03 25 96	14:15:50.40	32.100	-088.700	shallow	3.5	0.15	2.20	2
30	05 16 96	15:14:01.90	42.587	-111.202	05.0	3.9	0.80	0.80	2
31	08 16 96	04:56:46.00	49.210	-082.920	18.0	3.5	0.16	1.80	3

The origin times and locations are from the U.S. Geological Survey's Preliminary Determination of Epicenters.

3. The Direct Lg Phase

Earthquakes and great-circle paths used for the determination of source parameters and Lg Q in the United States.

Figure 2

3. The Direct Lg Phase

Corner frequency versus seismic moment for events studied. The solid circles are for events recorded at more than two stations.

Figure 3

Using reported m_b values, we can also determine moment-magnitude relations for events in the United States (Figure 4). As with Figure 3, solid symbols denote events for which three or more stations were used in the analysis and open symbols denote events for which one or two stations were used. A linear least-squares fit to the solid symbols (solid line) yields the M_0 - m_b relation

$$\log(M_0) = 10.20(\pm 1.08) + 1.24(\pm 0.21)m_b \quad (3)$$

while all symbols yield the relation

$$\log(M_0) = 10.41(\pm 1.00) + 1.18(\pm 0.19)m_b \quad (4)$$

As with the moment - corner frequency relation, these equations are the same, within the calculated uncertainties.

Lg Q Values

During the inversion for source parameters for each event, we simultaneously determined Q_0 and η along all individual paths to stations. The Q_0 values appear in the map in Figure 5 and are listed in Table 2. The highest values occur in regions of the northeastern and the central United States while the lowest values are in the westernmost United States. Our pattern of Lg Q in the northeastern region is roughly consistent with the values of *Shi et al.* (1996) there. Their values, at 1 Hz, vary between about 550 and 850, while for paths for that region, in our study, Lg Q varies between 600 and 720. Most of our paths crossing that region, however, are much longer than those of *Shi et al.* (1996) and are likely to traverse crust with laterally varying attenuative properties. Some values in Figure 5 seem unrealistic and are not consistent with other values in the region. For instance, values of 222 and 252 along paths from an earthquake in southern Texas to stations in Missouri and Arkansas seem unrealistically low. Such values may occur because the Lg radiation is not really radially symmetric as assumed in the inversion process. For that reason, we think that Lg coda will provide more reliable values of Q. Lg coda Q results are discussed in a later section.

Figures 6a-o show the fits between observed and theoretical spectra for 15 recent events in our study. For each event we have plotted the spectra for each recording station used in the study, and for events recorded by two or more stations we have also plotted the station average. These plots indicate that we can obtain excellent agreement between observed and theoretical spectra in nearly all cases. In addition to the spectral fits, the plots indicate the Lg Q value for each path and the distance of travel.

4. Lg Coda Q

Data Processing

Xie and Nuttli (1988) developed a stochastic model for the interpretation of single-trace Lg coda waves and an inversion method, based on that model, to determine Lg coda Q and its frequency dependence at 1 Hz (Q_0 and η , respectively). Advantages of their inversion method are that, with data of sufficient quality, tradeoffs between Q_0 and η are avoided (often a problem with earlier methods) and that variances in those quantities are reduced compared to other inversion methods. Application of their stochastic model to examples of recorded ground motion showed that the randomness that occurs in Lg coda waves can be approximated by simple band-limited white Gaussian noise, a result that allows us to make quantitative estimates of variances when estimating Lg coda attenuation.

3. The Direct Lg Phase

Magnitude versus seismic moment for events studied. The solid circles are for events recorded at more than two stations.

Figure 4

Lg Q values for paths between events studies and selected stations.

Figure 5

3. The Direct Lg Phase

Table 2. Earthquakes used for determination of Lg Q values for the United States

Event	Station	Lg Q	Station	Lg Q	Station	Lg Q	Station	Lg Q	Station	Lg Q
1	CCM	545								
2	PAS	166	COR	166						
3	HRV	434	SCP	989						
4	HRV	141	SCP	718						
5	COR	221	ANMO	225	GSC	232	PAS	328		
6	SCP	718								
7	CCM	817	HRV	885						
8	JFWS	822								
9	HRV	489	CEH	302	JFWS	629				
10	HRV	325								
11	CCM	221	GOL	600	MIAR	252	WMOK	356		
12	CCM	259	LTX	342	MAIR	308				
13	CCM	278	GOL	325	MAIR	381	WMOK	529		
14	CEH	483	LSCT	676						
15	CEH	718	GOGA	464	LBNH	895	MYNC	524		
16	LTX	407								
17	LTX	407								
18	LTX	472	MAIR	728	WMOK	641				
19	BINY	718	LBNH	738	HRV	587				
20	CBKS	658	CCM	652	WMOK	356				
21	CCM	406	JFWS	850	MIAR	602	OXF	736		
22	CCM	743	CBKS	1068	JFWS	868	MIAR	384	EYMN	964
23	CEH	289	GOGA	289	JFWS	327	MIAR	261	WMOK	356
24	GOL	240	NEW	173	WMOK	565				
25	GOL	479	CBKS	353						
26	CBKS	375	WMOK	371						
27	LTX	186								
28	CBKS	531	MIAR	457	MYNC	452				
29	BLA	405	MYNC	623						
30	CBKS	789	NEW	328						
31	EYMN	297	JFWS	597	YSNY	677				

The event numbers are the same as those in Table 1.

3. The Direct Lg Phase

Jan. 29, 1990 $M_b = 4.5$

Comparison of observed and predicted source spectra for the
earthquake of January 29, 1990.

Figure 6a

3. The Direct Lg Phase

Apr. 18, 1990 Mb = 5.4

PAS Qo=166 D=441.9km

ANMO Qo=201 D=1387.2km

COR Qo=164 D=862.8km

STATION AVERAGE

Comparison of observed and predicted source spectra for the earthquake of April 18, 1990.

Figure 6b

3. The Direct Lg Phase

Sept. 26, 1990 $M_b = 4.7$

Comparison of observed and predicted source spectra for the
earthquake of September 09, 1990.

Figure 6c

3. The Direct Lg Phase

Oct. 19, 1990 $M_b = 4.6$

Comparison of observed and predicted source spectra for the
earthquake of Oct. 19, 1990.

Figure 6d

Oct. 24, 1990 Mb = 5.4

Comparison of observed and predicted source spectra for the earthquake of Oct. 24, 1990.

Figure 6e

3. The Direct Lg Phase

Dec. 31, 1990 Mb = 4.2

Comparison of observed and predicted source spectra for the
earthquake of December 31, 1990.

Figure 6f

Jan. 2, 1992 Mb = 4.6

Comparison of observed and predicted source spectra for the
earthquake of January 2, 1992.

Figure 6g

3. The Direct Lg Phase

Jan. 07, 1996 Mb = 4.6

Comparison of observed and predicted source spectra
for the earthquake of January 07, 1996.

Figure 6h

February 06, 1996 Mb = 3.6

Comparison of observed and predicted source spectra
for the earthquake of February 06, 1996.

Figure 6i

3. The Direct Lg Phase

February 20, 1996 Mb = 4.3

Comparison of observed and predicted source spectra
for the earthquake of February 20, 1996.

Figure 6j

March 01, 1996 Mb = 4.1

Comparison of observed and predicted source spectra
for the earthquake of March 01, 1996.

Figure 6k

3. The Direct Lg Phase

March 19, 1996 Mb = 5.0

Comparison of observed and predicted source spectra
for the earthquake of March 19, 1996.

Figure 61

March 25, 1996 Mb = 3.5

Comparison of observed and predicted source spectra
for the earthquake of March 25, 1996.

Figure 6m

3. The Direct Lg Phase

May 16, 1996 Mb = 3.9

Comparison of observed and predicted source spectra
for the earthquake of May 16, 1996.

Figure 6n

Aug. 16, 1996 Mb = 3.5

Comparison of observed and predicted source spectra
for the earthquake of August 16, 1996.

Figure 60

4. Lg Coda Q

The method for determining Lg coda Q, termed the stacked spectral ratio (SSR) method, has been discussed elsewhere (*Xie and Nuttli, 1988; Xie and Mitchell, 1990a*); for that reason it is only summarized here. It begins by dividing the Lg coda time series into a number, N_w , of non-overlapping time windows of constant length and applying the discrete Fourier transform to each window to obtain the geometrical mean of the amplitude spectrum at each frequency. The length of each group velocity window for Lg is given by

$$U_m = v\tau_m(1/v_{\min} - 1/v_{\max}) \quad (5)$$

where τ_m is the mean lag time for the m th window, and v , $v_{\max}$, and $v_{\min}$ are, respectively, the average, maximum, and minimum group velocities of the coda wave train. Geometrical spreading is obtained using

$$G_m = (2\pi R)^{-1/2} (v^2 \tau_m^2 / R^2 - 1)^{-1/4} \quad (6)$$

where R is the event-station distance. The SSR is defined as

$$F_k = \frac{1}{M} \sum_{m=1}^M \frac{1}{\pi(\tau_{M+m} - \tau_m)} \log \left[\frac{G_{M+m} \sqrt{U_m} \langle A_{k,m} \rangle}{G_m \sqrt{U_{M+m}} \langle A_{k,m+M} \rangle} \right] \quad (7)$$

where M is $N_w/2$ when N_w is even and $(N_w + 1)/2$ when N_w is odd. All of the quantities on the right-hand side of (7) are calculable from a coda time series.

Assuming that the frequency dependence of Lg coda Q can be expressed by a power law, $Q(f) = Q_0 f^\eta$, where Q_0 and η are, respectively, Q and its frequency dependence at 1 Hz, then

$$\log F_k = (1 - \eta) \log f_k - \log Q_0 + \varepsilon \quad (8)$$

where ε represents a random error. Theoretical and observational calculations have shown that the SSR method provides a statistically stable Q estimator, with the standard error in Q_0 often being an order of magnitude smaller than Q_0 itself.

The SSR method was applied to all traces beginning at a group velocity of 3.15 km/s and continuing on in time to cover a window length of 300 seconds or more, with the average length being about 450 seconds and the maximum duration being 600 seconds. We tried to minimize variations in coda length from path to path in order to avoid possible systematic biases that might be proportional to coda duration. An example of a seismic trace with its associated SSR appears in Figure 7. The best fit straight line for the spectral values in that example show that, at 1 Hz, Q_{Lg}^c is 621 and η (given by the slope of the line) is 0.47. Table 3 gives Lg coda Q values determined for individual traces in the central and eastern United States and Table 4 presents those values for the western United States.

Another possible source of bias in our determinations can arise if a large portion of the scattering ellipse overlaps oceanic regions (*Xie and Mitchell, 1990b*). For that reason we avoided events that occurred in oceanic regions as well as continental events for which a large fraction of the scattering ellipse overlaps an oceanic region.

The linear regression determination of Lg coda Q at 1 Hz and its frequency dependence.

Figure 7

4. Lg Coda Q

Table 3. Earthquakes and results of single-trace analysis for Lg coda Q in the central and eastern United States

Date	Origin (h:m:s)	Lat (° N)	Lon (° E)	Recording station	Distance (km)	Q ₀	η
920821	16:31:35.1	33.00	-079.10	BLA	462.0	561 ± 124	0.43 ± 0.07
921117	03:58:00.9	45.80	-074.90	BLA	1057.0	451 ± 84	0.61 ± 0.10
940116	01:49:16.0	40.30	-076.00	BLA	514.8	604 ± 86	0.74 ± 0.06
940116	00:42:43.2	40.33	-076.05	BLA	516.5	455 ± 88	0.70 ± 0.11
940925	00:53:28.0	47.78	-069.95	BLA	780.4	677 ± 232	0.57 ± 0.09
950311	08:15:52.0	37.00	-083.20	BLA	243.9	523 ± 52	0.70 ± 0.09
950417	13:45:57.8	32.90	-080.10	BLA	474.2	510 ± 170	0.59 ± 0.10
950527	19:51:10.3	36.20	-089.40	BLA	813.2	619 ± 150	0.57 ± 0.20
960325	14:15:50.4	32.10	-088.70	BLA	946.7	442 ± 78	0.52 ± 0.10
940913	06:01:23.0	38.16	-107.98	CBKS	722.5	427 ± 109	0.96 ± 0.06
950203	15:26:10.7	41.50	-109.60	CBKS	895.2	432 ± 98	0.50 ± 0.09
950414	00:32:54.2	30.20	-103.30	CBKS	1005.8	425 ± 97	0.69 ± 0.06
960206	15:10:27.6	42.50	-097.50	CBKS	451.0	413 ± 51	0.76 ± 0.20
960220	14:40:41.9	27.55	-111.68	CBKS	1670.0	553 ± 72	0.85 ± 0.10
960516	15:41:01.9	44.12	-104.06	CBKS	1054.8	438 ± 46	0.67 ± 0.10
921117	03:58:00.9	45.80	-074.90	CBM	535.1	1102 ± 147	0.25 ± 0.04
900129	13:16:10.6	34.46	-106.88	CCM	1458.6	603 ± 60	0.58 ± 0.01
930409	00:59:49.5	28.81	-098.12	CCM	1207.5	749 ± 89	0.17 ± 0.01
931205	00:58:20.2	27.83	-102.74	CCM	1559.5	512 ± 34	0.24 ± 0.09
940512	00:22:23.0	24.95	-109.28	CCM	2230.4	582 ± 168	1.00 ± 0.20
940925	00:53:28.0	47.78	-069.95	CCM	2036.4	713 ± 162	0.74 ± 0.10
950203	15:26:10.7	41.50	-109.60	CCM	1619.0	511 ± 104	0.42 ± 0.07
950311	08:15:52.0	37.00	-083.20	CCM	725.3	697 ± 127	0.74 ± 0.10
950414	00:32:54.2	30.20	-103.30	CCM	1409.2	432 ± 91	0.78 ± 0.06
950417	13:45:57.8	32.90	-080.10	CCM	1160.5	876 ± 128	0.51 ± 0.10
950527	19:51:10.3	36.20	-089.40	CCM	264.2	765 ± 311	0.60 ± 0.10
920102	11:45:35.8	32.30	-103.10	CCM	1250.9	631 ± 28	0.34 ± 0.05
920821	16:31:55.1	33.00	-080.10	CEH	328.8	557 ± 78	0.58 ± 0.04
920822	12:20:32.6	39.10	-070.30	CEH	853.6	636 ± 128	0.54 ± 0.10
940116	01:49:16.0	40.30	-076.00	CEH	560.9	745 ± 71	0.47 ± 0.05
950417	13:45:57.8	32.90	-080.10	CEH	338.6	643 ± 174	0.43 ± 0.07
950527	19:51:10.3	36.20	-089.40	CEH	931.8	384 ± 91	0.49 ± 0.10
950417	13:45:57.8	32.90	-080.10	CVL	577.3	711 ± 153	0.10 ± 0.09
950414	00:32:54.2	30.20	-103.30	EYMN	2210.3	426 ± 71	0.74 ± 0.07
960816	04:56:49.2	49.20	-082.90	EYMN	648.3	490 ± 43	0.59 ± 0.09
950527	19:51:10.3	36.20	-089.40	FVM	220.0	725 ± 180	0.81 ± 0.10
960325	14:15:50.4	32.10	-088.70	FVM	671.4	455 ± 47	0.54 ± 0.10
940116	01:49:16.0	40.30	-076.00	GOGA	1013.4	412 ± 121	0.80 ± 0.07
950527	19:51:10.3	36.20	-089.40	GOGA	625.5	683 ± 190	0.44 ± 0.10
960325	14:15:50.4	32.10	-088.70	GOGA	511.4	469 ± 48	0.43 ± 0.10
950414	00:32:54.2	30.20	-103.30	GLD	1068.7	462 ± 112	0.70 ± 0.08
960516	15:41:01.9	44.10	-104.04	GLD	592.5	316 ± 41	0.60 ± 0.10
931205	00:58:20.2	27.80	-102.70	GOL	1338.6	744 ± 96	0.58 ± 0.30
940913	06:01:23.0	38.20	-107.98	GOL	283.9	427 ± 111	0.64 ± 0.06
950203	15:26:10.7	41.50	-109.60	GOL	414.3	640 ± 117	0.86 ± 0.10
960107	14:32:52.1	35.80	-117.65	GOL	1166.0	528 ± 39	0.52 ± 0.10
950527	19:51:10.3	36.20	-089.40	HBV	904.6	458 ± 184	0.62 ± 0.10
900926	13:18:51.3	37.20	-089.58	HRV	1648.9	534 ± 111	0.54 ± 0.20
901019	07:01:57.4	46.47	-075.59	HRV	545.0	711 ± 50	0.31 ± 0.07
920102	11:45:35.8	32.33	-103.10	HRV	2990.4	443 ± 33	0.80 ± 0.10
940116	01:49:16.0	40.30	-076.00	HRV	445.7	655 ± 130	0.56 ± 0.07
950527	19:51:10.4	36.20	-089.40	JFWS	752.3	788 ± 190	0.67 ± 0.10
940925	00:53:28.0	47.78	-069.95	LBNI	421.1	723 ± 192	0.54 ± 0.05
940116	01:49:16.0	40.35	-076.05	LBNI	551.1	1305 ± 170	0.20 ± 0.06
950417	13:45:57.8	32.9	-80.100	LBNI	1444.9	539 ± 100	0.95 ± 0.09
940116	01:49:16.0	40.30	-076.00	LSCT	280.1	642 ± 84	0.52 ± 0.04
940116	00:42:43.2	40.35	-076.04	MCWV	278.2	682 ± 192	0.80 ± 0.10
940116	01:49:16.0	40.30	-076.00	MCWV	333.8	729 ± 60	0.40 ± 0.03
931205	00:58:20.2	27.83	-102.74	MIAR	1146.2	466 ± 28	0.51 ± 0.09
940913	06:01:23.0	38.16	-107.98	MIAR	1351.8	600 ± 96	0.60 ± 0.06
950311	08:15:52.0	37.00	-083.20	MIAR	980.0	519 ± 187	0.60 ± 0.10
950414	00:32:54.2	30.20	-103.30	MIAR	1033.3	412 ± 49	0.20 ± 0.10
950527	19:51:10.3	36.20	-089.40	MIAR	417.4	618 ± 181	0.79 ± 0.10
960325	14:15:50.4	32.10	-088.70	MYNK	537.4	460 ± 26	0.53 ± 0.06

Table 3. (continued)

Date	Origin (h:m:s)	Lat (° N)	Lon (° E)	Recording station	Distance (km)	Q_0	η
940116	01:49:16.0	40.35	-076.04	MYNC	921.0	773 ± 150	0.30 ± 0.09
950311	08:15:52.0	37.00	-083.20	OXF	629.9	541 ± 104	0.45 ± 0.10
931205	00:58:20.0	27.83	-102.70	OXF	1468.5	594 ± 65	0.66 ± 0.10
950417	13:45:57.8	32.90	-080.10	PRM	247.7	650 ± 131	0.39 ± 0.07
940116	01:49:16.0	40.35	-076.04	RSNY	484.6	765 ± 103	0.43 ± 0.05
940925	06:01:23.0	47.78	-069.95	RSNY	503.0	730 ± 162	0.69 ± 0.09
950311	08:15:52.0	37.00	-083.20	RSNY	1110.6	637 ± 150	0.25 ± 0.10
950527	19:15:52.0	36.20	-089.40	RSNY	1563.0	566 ± 100	0.49 ± 0.09
950527	19:51:10.3	36.20	-089.40	SGS	881.0	402 ± 195	0.88 ± 0.10
930409	00:59:49.5	28.81	-098.12	WMOK	660.0	505 ± 33	0.15 ± 0.01
931205	00:58:20.2	27.83	-102.74	WMOK	853.0	282 ± 07	0.79 ± 0.03
940913	06:01:23.0	38.16	-107.98	WMOK	906.7	554 ± 138	0.69 ± 0.10
950414	00:32:54.2	30.20	-103.30	WMOK	656.0	422 ± 54	0.59 ± 0.03
950527	19:51:10.3	36.20	-089.40	WMOK	863.3	727 ± 175	0.50 ± 0.10
960319	15:31:36.4	25.00	-109.30	WMOK	1481.6	463 ± 18	0.78 ± 0.04
960220	14:40:41.9	27.55	-111.68	WMOK	1463.0	349 ± 40	0.68 ± 0.10
960107	14:32:53.1	35.77	-117.65	WMOK	1718.3	897 ± 50	0.80 ± 0.06
940116	01:49:16.0	40.30	-076.00	YSNY	317.1	947 ± 223	0.30 ± 0.10
960325	14:15:50.4	32.10	-088.70	JSC	734.5	313 ± 14	0.80 ± 0.05
960325	14:15:50.4	32.10	-088.70	LHS	780.7	310 ± 31	0.76 ± 0.10
920102	11:45:35.8	32.34	-103.10	SCP	2435.4	470 ± 36	0.40 ± 0.10
900926	13:18:51.3	37.20	-089.58	SCP	1091.1	647 ± 25	0.63 ± 0.06
901019	07:01:57.4	47.58	-072.56	SCP	656.9	831 ± 16	0.30 ± 0.03
901231	03:53:58.3	47.58	-072.56	SCP	865.0	620 ± 39	0.47 ± 0.09
931205	00:58:20.2	27.83	-102.74	RSSD	1811.2	425 ± 24	0.79 ± 0.09
940913	06:01:23.0	38.16	-107.98	RSSD	740.9	430 ± 84	0.73 ± 0.06
960107	14:32:53.1	35.77	-117.65	RSSD	1485.0	436 ± 85	0.90 ± 0.10
960516	15:41:01.9	44.12	-104.04	RSSD	605.5	412 ± 27	0.70 ± 0.10
960516	15:41:01.9	44.12	-104.04	NEW	782.6	439 ± 44	0.64 ± 0.10
930602	02:08:32.7	25.95	-109.99	LTX	727.7	288 ± 16	0.49 ± 0.07
940512	00:22:23.0	24.90	-109.28	LTX	730.4	317 ± 75	0.74 ± 0.07
940512	01:14:07.7	24.68	-109.10	LTX	730.0	305 ± 65	0.50 ± 0.07
940925	00:53:28.0	47.78	-069.95	BINY	781.7	677 ± 100	0.57 ± 0.09

The origin times and locations are from the U.S. Geological Survey's Preliminary Determination of Epicenters; The Q_0 and η values with standard errors for each path are obtained in this study.

4. Lg Coda Q

**Table 4. Earthquakes and results of single-trace analysis
for Lg coda Q in the western United States**

Date	Origin (h:m:s)	Lat (° N)	Lon (° E)	Recording station	Distance (km)	Q ₀	η
890627	15:30:00.1	37.28	-116.35	ELK	397.0	225 ± 31	0.46 ± 0.03
890622	21:15:00.0	37.28	-116.41	ELK	397.5	234 ± 62	0.30 ± 0.08
891031	59:30:00.0	37.26	-116.49	ELK	401.4	221 ± 23	0.44 ± 0.03
890309	14:05:00.1	37.14	-116.07	ELK	401.7	235 ± 34	0.51 ± 0.05
890210	20:06:00.0	37.08	-116.00	ELK	412.9	246 ± 29	0.45 ± 0.04
900725	15:00:00.0	37.21	-116.21	ELK	401.7	224 ± 42	0.31 ± 0.06
900613	16:00:00.0	37.26	-116.42	ELK	400.0	239 ± 20	0.38 ± 0.03
890627	15:30:00.1	37.28	-116.35	KNB	314.7	280 ± 38	0.58 ± 0.07
890622	21:15:00.0	37.28	-116.41	KNB	320.1	297 ± 58	0.51 ± 0.06
891031	15:30:00.0	37.26	-116.49	KNB	327.0	254 ± 29	0.60 ± 0.06
890309	14:05:00.1	37.14	-116.07	KNB	288.4	242 ± 35	0.26 ± 0.08
890210	20:06:00.0	37.08	-116.00	KNB	282.4	283 ± 56	0.42 ± 0.06
900613	16:00:00.0	37.26	-116.42	KNB	320.8	287 ± 48	0.45 ± 0.05
900310	16:00:00.0	37.11	-116.06	KNB	288.1	259 ± 45	0.46 ± 0.05
900725	15:00:00.0	37.21	-116.21	KNB	301.8	275 ± 33	0.41 ± 0.03
910404	18:59:59.9	37.29	-116.31	KNB	311.3	276 ± 38	0.51 ± 0.04
920326	16:30:00.0	37.27	-116.36	KNB	315.5	266 ± 24	0.38 ± 0.03
890627	15:30:00.1	37.28	-116.35	MNV	204.2	200 ± 18	0.30 ± 0.04
890622	21:15:00.0	37.28	-116.41	MNV	199.6	268 ± 48	0.46 ± 0.05
891031	59:30:00.0	37.26	-116.49	MNV	195.7	230 ± 23	0.40 ± 0.04
890309	14:05:00.1	37.14	-116.07	MNV	226.9	243 ± 39	0.56 ± 0.05
900725	15:00:00.0	37.21	-116.21	MNV	208.6	233 ± 42	0.35 ± 0.05
900613	16:00:00.0	37.26	-116.42	MNV	200.5	236 ± 26	0.40 ± 0.03
900310	16:00:00.0	37.11	-116.06	MNV	235.0	228 ± 32	0.40 ± 0.04
910404	19:00:00.0	37.29	-116.31	MNV	205.5	224 ± 27	0.35 ± 0.04
891031	59:29:59.9	37.26	-116.49	LAC	318.9	241 ± 34	0.50 ± 0.05
900613	16:00:00.0	37.26	-116.42	LAC	318.7	257 ± 31	0.59 ± 0.04
900310	16:00:00.0	37.11	-116.06	LAC	303.8	265 ± 30	0.38 ± 0.03
900725	15:00:00.0	37.21	-116.21	LAC	313.1	245 ± 45	0.53 ± 0.06
910404	18:59:59.9	37.29	-116.31	LAC	322.6	231 ± 30	0.58 ± 0.04
920326	16:30:00.0	37.27	-116.36	LAC	319.8	235 ± 31	0.59 ± 0.04
831030	01:24:51.1	44.08	-113.97	LON	679.0	370 ± 30	0.30 ± 0.02
830317	07:25:56.6	47.53	-112.70	LON	696.0	444 ± 70	0.60 ± 0.09
831212	04:55:36.3	44.43	-114.10	LON	654.6	456 ± 15	0.50 ± 0.10
831030	01:59:01.4	44.22	-114.19	LON	658.1	370 ± 30	0.76 ± 0.04
831028	19:51:24.3	44.07	-113.91	LON	686.4	370 ± 30	0.67 ± 0.04
840822	09:46:30.2	44.47	-114.01	LON	659.1	377 ± 55	0.51 ± 0.04
840216	11:14:57.5	39.93	-117.76	LON	825.9	383 ± 12	0.41 ± 0.10
840324	00:07:47.8	44.74	-114.43	LON	616.3	384 ± 71	0.47 ± 0.00
840908	13:56:37.6	44.42	-114.15	LON	651.5	265 ± 67	0.36 ± 0.09
840908	06:16:40.2	44.42	-114.15	LON	650.5	382 ± 47	0.65 ± 0.04
850821	18:05:38.2	43.17	-110.78	LON	956.3	450 ± 10	0.60 ± 0.10
850206	19:34:19.5	44.55	-114.18	LON	641.5	314 ± 87	0.60 ± 0.07
850401	09:13:14.2	47.28	-113.23	LON	655.2	390 ± 42	0.70 ± 0.04
850317	06:56:17.0	44.55	-114.18	LON	643.1	372 ± 71	0.52 ± 0.06
821014	04:10:24.3	42.59	-111.43	JAS	922.9	431 ± 124	0.80 ± 0.10
821110	11:21:25.6	34.05	-116.67	JAS	550.0	521 ± 16	0.31 ± 0.10
831008	11:57:54.2	40.75	-111.99	JAS	791.7	444 ± 63	0.36 ± 0.10
830713	21:16:48.2	33.20	-115.53	JAS	689.2	281 ± 86	0.60 ± 0.07
831030	01:59:01.6	44.08	-113.97	RSSD	812.9	346 ± 71	0.75 ± 0.08
830317	07:25:56.7	47.53	-112.70	RSSD	696.6	480 ± 84	0.80 ± 0.07
831212	04:55:36.4	44.43	-114.10	RSSD	804.1	546 ± 66	0.70 ± 0.03
831028	19:51:24.4	44.07	-113.91	RSSD	790.7	297 ± 54	1.08 ± 0.09
840822	09:46:30.1	44.47	-114.01	RSSD	796.9	667 ± 46	0.50 ± 0.04
841103	09:30:30.5	42.49	-108.85	RSSD	430.6	485 ± 30	0.52 ± 0.03
850401	09:13:14.2	47.28	-113.23	RSSD	797.3	677 ± 45	0.50 ± 0.03
850317	06:57:45.5	44.55	-114.18	RSSD	810.3	403 ± 95	0.78 ± 0.07
811001	19:00:00.0	37.08	-116.01	ALQ	892.7	524 ± 15	0.40 ± 0.10
810425	07:03:13.5	33.12	-115.65	ALQ	872.4	494 ± 14	0.40 ± 0.10
810606	18:00:00.0	37.30	-116.33	ALQ	925.8	422 ± 66	0.70 ± 0.05
820415	21:52:08.7	38.04	-118.50	ALQ	1064.0	604 ± 14	0.80 ± 0.10
820212	41:55:00.1	37.22	-116.46	ALQ	935.6	465 ± 10	0.80 ± 0.07
811112	15:00:00.2	37.11	-116.05	ANMO	869.8	386 ± 62	0.20 ± 0.09
811001	19:00:00.0	37.08	-116.01	ANMO	892.7	360 ± 93	0.10 ± 0.04
810606	18:00:00.0	37.30	-116.33	ANMO	925.7	397 ± 67	0.50 ± 0.08

Table 4. (continued)

Date	Origin (h:m:s)	Lat (° N)	Lon (° E)	Recording station	Distance (km)	Q ₀	η
810425	07:03:13.7	33.12	-115.65	ANMO	872.5	414 ± 13	0.60 ± 0.10
820524	12:13:26.9	38.71	-112.04	ANMO	646.7	324 ± 78	0.40 ± 0.07
821014	04:10:00.3	42.59	-111.43	ANMO	952.0	257 ± 97	0.50 ± 0.10
820212	14:55:00.2	37.22	-116.46	ANMO	935.5	564 ± 10	0.70 ± 0.10
820425	18:04:59.9	37.26	-116.44	ANMO	935.2	399 ± 65	0.40 ± 0.10
820706	02:10:43.4	34.95	-106.46	ANMO	829.4	218 ± 41	0.30 ± 0.09
830703	18:40:08.3	37.54	-118.86	ANMO	1110.5	300 ± 92	0.90 ± 0.09
831209	08:58:41.4	38.58	-112.58	ANMO	549.8	275 ± 66	0.41 ± 0.08
910817	19:29:39.9	40.26	-124.30	ANMO	1712.9	466 ± 12	1.00 ± 0.10
920629	10:14:22.2	36.71	-116.29	ANMO	937.7	386 ± 74	0.61 ± 0.09
921204	02:08:57.4	34.37	-116.90	ANMO	976.2	359 ± 64	0.50 ± 0.06
940204	02:42:11.9	42.71	-111.03	ANMO	994.1	504 ± 18	0.90 ± 0.10
910817	19:29:39.9	40.26	-124.30	COR	487.6	231 ± 52	0.40 ± 0.10
920308	03:43:04.6	40.24	-123.99	COR	486.6	208 ± 52	0.21 ± 0.10
930325	13:34:00.0	45.04	-122.61	COR	073.3	186 ± 19	0.30 ± 0.03
940119	22:27:31.2	42.30	-121.96	COR	276.3	303 ± 88	0.60 ± 0.10
920624	07:31:20.8	38.89	-111.46	TUC	763.3	359 ± 97	0.72 ± 0.11
921204	02:08:57.4	34.37	-116.90	TUC	613.2	325 ± 57	0.39 ± 0.06
930429	08:21:00.9	35.58	-112.12	TUC	402.3	330 ± 56	0.52 ± 0.06
930528	04:47:40.5	35.09	-119.15	TUC	834.4	293 ± 69	0.54 ± 0.09
930517	23:20:49.1	37.10	-117.80	TUC	833.5	385 ± 80	0.70 ± 0.09
930528	04:47:38.9	35.09	-119.15	TUC	833.2	207 ± 73	0.28 ± 0.18
930520	20:14:14.0	36.02	-117.64	TUC	753.7	253 ± 40	0.30 ± 0.08
930518	01:03:06.4	37.10	-117.75	TUC	830.0	302 ± 80	0.46 ± 0.10
940211	14:59:49.5	42.76	-110.99	TUC	1160.5	363 ± 16	0.86 ± 0.15
940117	12:30:55.3	34.21	-118.54	TUC	752.3	304 ± 47	0.54 ± 0.05
940204	02:42:11.9	42.71	-111.03	TUC	1154.5	330 ± 88	0.51 ± 0.10
910817	19:29:39.9	40.26	-124.30	GSC	890.0	304 ± 57	0.51 ± 0.09
930528	04:47:40.5	35.09	-119.15	GSC	243.6	234 ± 23	0.30 ± 0.04
930517	23:20:49.0	37.10	-117.80	GSC	243.9	379 ± 10	0.65 ± 0.10
930210	21:48:34.9	40.43	-119.60	GSC	644.5	238 ± 42	0.32 ± 0.08
930116	06:29:34.8	36.90	-121.60	GSC	461.9	235 ± 56	0.40 ± 0.09
940117	12:30:55.3	34.21	-118.54	GSC	216.0	320 ± 62	0.69 ± 0.09
940204	14:59:50.5	42.71	-111.03	GSC	966.6	395 ± 17	0.70 ± 0.20
921204	02:08:57.4	34.37	-116.90	ISA	202.4	238 ± 66	0.49 ± 0.01
920629	10:14:22.2	36.71	-116.29	ISA	227.4	279 ± 49	0.41 ± 0.09
930116	06:29:35.8	36.90	-121.60	ISA	307.1	225 ± 38	0.30 ± 0.07
930210	21:48:35.1	40.43	-119.60	ISA	538.8	207 ± 41	0.30 ± 0.07
921204	02:09:03.1	34.37	-116.90	MLA	402.3	217 ± 56	0.37 ± 0.10
930528	04:47:40.6	35.09	-119.15	MLA	283.1	207 ± 32	0.30 ± 0.07
910817	19:29:39.9	40.26	-124.30	PAS	869.2	299 ± 66	0.54 ± 0.09
920629	10:14:22.1	36.71	-116.29	PAS	733.3	290 ± 14	0.63 ± 0.33
930517	23:20:49.2	37.10	-117.80	PAS	329.2	279 ± 48	0.60 ± 0.06
930517	23:20:49.1	37.10	-117.80	CMB	251.3	286 ± 74	0.31 ± 0.08
930528	04:47:40.5	35.09	-119.15	CMB	344.6	218 ± 35	0.23 ± 0.05
930116	06:29:34.9	36.90	-121.60	CMB	173.3	218 ± 39	0.25 ± 0.05
910817	19:29:39.9	40.26	-124.30	SBC	762.9	291 ± 74	0.45 ± 0.12
921204	02:08:57.5	34.37	-116.90	SBC	258.0	245 ± 48	0.30 ± 0.08
920629	10:14:22.1	36.71	-116.29	MHC	481.0	287 ± 46	0.31 ± 0.08
930528	04:47:40.6	35.09	-119.15	PFO	297.3	237 ± 45	0.20 ± 0.07
930116	06:29:34.9	36.90	-121.60	ARC	500.3	265 ± 70	0.50 ± 0.17
920629	10:14:22.9	36.71	-116.29	STAN	528.7	348 ± 48	0.49 ± 0.06
920629	10:14:22.2	36.71	-116.29	SAO	459.8	335 ± 68	0.51 ± 0.08
910817	19:29:40.1	40.26	-124.30	WCK	576.4	404 ± 45	0.71 ± 0.05
920629	10:14:22.2	36.71	-116.29	BKS	543.1	304 ± 49	0.66 ± 0.07

The origin times and locations are from the U.S. Geological Survey's Preliminary Determination of Epicenters; The Q₀ and η values with standard error for each path are obtained in this study.

4. Lg Coda Q

Mapping Lg Coda Q Variations - Method

Although seismic tomography has been very successful in mapping velocities in the Earth, it has not been used extensively to map variations of attenuative properties. The first such study for regional phases was done for the African continent where a set of Lg coda records that covered much of the continent was assembled and the SSR method was applied to them (Xie and Mitchell, 1990a). As discussed earlier, the resulting tomographic image revealed striking regional variations of Q_{Lg}^c that coincide with some of the major tectonic features of Africa.

In the present study we apply the same method to United States. It is a back-projection algorithm that produces a tomographic image of Q_{Lg}^c over any broad region using a number, (N_d) of individual determinations of Q_{Lg}^c from Lg coda recordings within that region. Since Lg coda consists of scattered waves the energy arriving at a recording station does not follow a straight path between from the seismic event, but is contained within a volume of the crust that includes the source and recording station.

For single scattering the surface projection of the scattered energy takes the form of an ellipse with the source at one focus and the recording station at the other. The ellipse covers a larger and larger area as the lag time of the coda increases. The elliptical areas for the event-station pairs used in this study are shown in Figure 8 at the maximum lapse time used for the SSR analysis described earlier. If coda waves are scattered through a volume as approximated by the elliptical surface projections in Figure 8, and if many events and recording stations are available, then much overlap occurs among some of the ellipses. This overlap provides data redundancy that is ideal for applying modern inversion techniques to map regional variations of attenuation.

To apply the tomographic method we divided the United States into a number, N_c , of cells that are small enough to allow us to resolve tectonic features of interest. Q_m , Lg coda Q within the mth cell, is assumed to be constant throughout the cell. We take the cell dimensions to be $2^\circ \times 2^\circ$. Q_n , the Lg coda Q value calculated for the nth time series, gives the areal average of Lg coda Q over the elliptical area sampled by the coda waves received at the maximum lapse time of the Lg coda waves of interest. If we denote the area that the nth ellipse overlaps the mth cell by s_{mn} , then

$$\frac{1}{Q_n} = \frac{1}{S_n} \sum_{m=1}^{N_c} \frac{s_{mn}}{Q_m} + \epsilon_n, \quad n=1, 2, \dots, N_d \quad (9)$$

where

$$S_n = \sum_{j=1}^{N_c} s_{jn} \quad (10)$$

and ϵ_n is the residual due to the errors in the measurement and modeling of Lg coda. We solve (5) by a back-projection, or ART technique (Gordon, 1974), that has been used successfully in seismic velocity tomography. The numerical procedure used to obtain that solution is described by Xie and Mitchell (1990a) and will not be repeated here.

A disadvantage of the back-projection technique is that it does not provide formal estimates of resolution or standard error. Humphreys and Clayton (1988) have, however, suggested using a "point spreading function" as an approximation for the resolution kernel. The point spreading function (hereafter abbreviated *psf*) is obtained by constructing a

The theoretical elliptical pattern sampled by Lg coda. The size of the area depends on the maximum lapse time and the location of both the seismic source and the recording site.

Figure 8

4. Lg Coda Q

model in which Q^{-1} has the value of unity in a single cell at the geographical point of interest and is zero everywhere else. We then compute synthetic data using this model and perform an inversion using the same event-station pair locations that are available to us. The resulting image gives the *psf* at the point of interest, a quantity whose area and falloff with distance from the central cell gives a measure of resolution.

The effect that random noise on Lg coda has on our tomographic images can be empirically tested using the sample standard error in Q_n caused by randomness of the SSR's. If the standard error for each determination of Q_n is denoted by δQ_n , $n=1,2, \dots, N_d$, we can construct a noise series for each Lg coda time series that has an absolute value equal to δQ_n and a sign that is chosen randomly. The n th term of the noise series is added to Q_n and the sums of the two series are then inverted to obtain a new Q_m image. The difference between this image and the original one gives us an error estimate for the Q_m values. Since the sign of δQ_n is chosen by a random binary generator, the process should be repeated several times to obtain an average error estimate.

Mapping Lg Coda Q Variations - Results

We used the back projection method described above to image lateral variations of Lg coda Q across most of the United States. The map depicting Lg coda scattering ellipses (Figure 8) indicates the extent of our data coverage. We inverted the Q_{Lg}^c data using equation 9 and a starting model in which $Q_m^o = 600$, $m = 1, 2, \dots, N_c$ for the entire region of study. The equation was inverted using our measured Q_o values and the areas of each ellipse at a time late in the coda. Residuals were calculated for each iteration and the stopping criterion was either that the number of iterations reached 20 or the relative change in the sum of squares of residuals became less than 10^{-5} . Figure 9 displays a tomographic image of Q_o for the United States using symbols to denote Q_o values and Figure 10 is the same map using color coding. Q_o ranges between about 250 and about 750, in a pattern that exhibits a predominant east-to-west trend of decreasing Q.

The process for determining the frequency dependence of Lg coda Q begins by using the Q_o and η values obtained for each trace to estimate Lg coda Q at another frequency; that being 3 Hz in this study. These new values were used as Q_n in equation 5 and yielded a map of Lg coda Q at 3 Hz. Using the maps of Lg coda Q at 1 Hz and 3 Hz we calculated the frequency dependence of Lg coda Q using the relationship

$$\eta = \frac{1}{\ln 3} \ln \left[\frac{Q(f)_{3Hz}}{Q_o} \right]. \quad (11)$$

Figure 11 shows the distribution of η across the United States resulting from this process.

Resolution and Error

Figure 12 presents *psf* plots for three selected regions of the United States. As discussed earlier the areas covered by these plots and the rapidity of their falloff with distance from the center cell can be used to estimate our ability to resolve features of the mapped Q_o and η distributions. The resolution in the western and eastern regions are similar to one another and somewhat better than that for the central region.

The method described in the previous section permits estimates of the effect of random errors in Lg coda Q measurements on our images of Q_o and η . Five tests were run to estimate the error in the images of the two quantities. In each of the tests we constructed

Distribution of Lg coda Q at 1 Hz for the United States.

Figure 9

Lg Coda Q at 1 Hz

Figure 10

Frequency Dependence of Lg Coda Q

Figure 11

4. Lg Coda Q

Relative Value of psf

Figure 12

Standard Error for Q_0

Figure 13

Standard Error for Frequency Dependence

Figure 14

two noise series, in both of which the absolute values of the n th terms equal the standard errors found for Q_0 and η from the n th coda seismogram. The signs of the n th terms were generated by a random binary generator. The n th terms of the two noise series were then added to the n th measurements of Q_0 and η measurements to construct new synthetic maps of Q_0 and η . The differences between these new maps and the original ones were calculated and stored after each test. The average values of the differences for the five tests give empirical estimates of absolute error in Q_0 and η as shown in Figures 13 and 14.

5. Conclusions

Source parameters for events selected for this study indicate that both corner frequency and magnitude vary systematically with moment for earthquakes in the central and eastern United States. The moments of events used in this study vary between about 0.15 and 400×10^{15} N-m. Over that range, corner frequency varies between about 4 Hz and 0.2 Hz and body-wave magnitude varies between about 3.5 and 5.8 .

Lg Q and Lg coda Q both vary systematically from east to west with the lowest values occurring in the westernmost United States. The excellent coverage for Lg coda Q has permitted us to obtain a tomographic image of those values. Lg coda Q values are highest in a region of the northeastern United States that includes portions of New York and Pennsylvania (700 - 750) and lowest throughout much of California. Another region of relatively high Q lies in the central United States in portions of Missouri, Illinois, and Iowa (650 - 700). The entire western portion of the United States west of the Rocky Mountains is characterized by much lower Lg coda Q values (250 - 400) than the rest of the country (450 - 750). These results indicate that for an earthquake of a given magnitude Lg and its coda will propagate much more efficiently (and cause damage or be felt over a larger area) in the eastern United States than it will in the western United States.

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