Frequency Dependence of *Lg* Attenuation in South-Central Alaska

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Abstract. The characteristics of seismic energy attenuation are determined using high frequency *Lg* waves from 27 crustal earthquakes, in south-central Alaska. *Lg* time-domain amplitudes are measured in five pass-bands and inverted to determine a frequency-dependent quality factor, *Q(f),* model for south-central Alaska. The inversion in this study yields the frequency-dependent quality factor, in the form of a power law: $Q(f) = Q_0 f^{\eta} = 220(\pm 30) f^{0.66(\pm 0.09)}$ $(0.75 \leq f \leq 12\text{Hz})$. Results from this study show that south-central Alaska has much lower values of Q_0 and a much higher frequency dependence than stable continental regions. This result is expected given the active tectonic setting of south-central Alaska. *Q(f)*, from this study, cannot distinguish between intrinsic and scattering attenuation but instead defines an apparent frequency-dependent attenuation for the whole crust. The results from this study are however, remarkably consistent with frequency dependent quality factor estimates, using local *S*-wave coda, in south-central Alaska. The consistency between *S*-coda *Q(f)* and *Lg Q(f)* enables constraints to be placed on the mechanism of crustal attenuation in south-central Alaska. For the range of frequencies considered in this study both mechanisms likely play an equal role.

1.Introduction

Regional differences in the attenuation of seismic waves were recognized prior to the advent of modern instrumented recordings. For example, shaking intensities of earthquakes in the western United States were observed to decrease at a faster rate, with epicentral distance, than those from comparable-sized earthquakes in the central and eastern United States [Richter, *1958*, Nuttli *et al., 1979*]. Direct phase and coda amplitude measurements, using modern digital seismic instruments, have confirmed that attenuation in the western United States is significantly higher than in the eastern United States [Mitchell, *1975, 1981*; Frankel *et al, 1990*; Benz *et al., 1997*]. In fact, global observations confirm that *S*-wave coda and *Lg* attenuation is higher for regions with active tectonism than for stable continental interiors [Aki, *1980a, 1980b*; Benz *et al., 1997*; McNamara *et al., 1996*]. Possible mechanisms to explain these observations are a highly fractured crust, occurring in tectonically active regions, that effectively absorbs high-frequency seismic energy [Aki, *1980*a], differences in crustal temperature [Frankel, *1991*], and variations in crustal structures that control elastic wave propagation [Gregersen, *1984*].

This study focuses on the frequency-dependence of the *Lg* wave quality-factor in south-central Alaska. *Lg* propagates with a group velocity of about 3.5 km/s, the average crustal shear wave velocity, and is commonly observed as the dominant phase on high-frequency, regional distance seismograms. *Lg* is generally thought to be generated by a superposition of higher mode surface waves [Oliver and Ewing, *1957*, Knopoff *et al*., *1973*] or as multiply reflected shear energy in a crustal waveguide [Press and Ewing, *1952*; Gutenberg, *1955*]. Consequently, *Lg* provides a good measure of path-averaged crustal properties, such as shear-wave velocity and attenuation.

Lg amplitude appears to be sensitive to lateral heterogeneity in the crust due to varying tectonic environments. In stable continental regions, such as northern Africa, *Lg* is observed at distances as great as 6000km [McNamara and Walter, *2000*]. In contrast, when propagating through active tectonic regions, such as the Himalaya and Tibetan Plateau [McNamara *et al., 1996*], or ocean basins [Zhang and Lay, *1995*], *Lg* is completely attenuated due to scattering along tectonic faults and variations in the thickness of the crustal waveguide [Kennett, *1986*].

The crustal properties of south-central Alaska, that affect the propagation quality of *Lg* are a direct result of the continuing north-south convergence of the Pacific and North American tectonic plates. Major crustal-seismotectonic characteristics of the region include: active volcanism of the Cook Inlet and the Wrangell-St. Elias Range [Nye, *1999*] (Figure 1), abundant intraplate seismicity [Ratchkovsky *et al., 1997, 1998*; Biswas and Tytgat, *1988*], active strike-slip motion along the Denali fault (~6mm/yr) [Fletcher and Freymueller, *1998*], and the high elevations of the Alaska Range (Figure 1).

Numerous researchers have estimated frequency dependent *Lg* attenuation for continental crust throughout the world [Benz *et al., 1997*; McNamara *et al, 1996*; Chavez and Priestly, *1986*, Atinson and Mereu, *1992*]. The frequency-dependent quality factor, *Q(f),* is commonly modeled using a power law of the form:

$$Q(f) = Q_0(f/f_0)^{\eta} \qquad (1)$$

where f_0 is a reference frequency (generally 1 Hz), Q_0 is Q at the reference frequency, and η is assumed constant over the frequencies of interest. The $Q(f)$ function can vary significantly depending on the tectonic activity of the region. For example, several studies in the tectonically active Basin and Range province have documented low Q_0 and strong frequency dependent attenuation (e.g. $Q(f)=214f^{0.54}$, Chavez and Priestly [*1986*]). In contrast, numerous studies in the tectonically stable areas of the central and northeastern United States and eastern Canada found higher values of Q_0 and a much weaker frequency dependent attenuation (e.g. $Q(f)=670f^{0.33}$, [Atkinson and Mereu, *1992*]; $Q(f)=1052f^{0.22}$, [Benz *et al., 1997*]). In south-central Alaska, Steensma and Biswas [*1988*] noted a strong frequency dependent attenuation, from *S*-wave coda decay, measured on short period seismograms. Theoretical studies indicate that coda *Q* may not be directly comparable to *Lg Q* in strongly scattering media [Frankel and Wennerberg, *1987*]; however, good correlation between coda *Q* and *Lg Q* estimates have been observed in regions such as the Tibetan Plateau [Xie and Mitchell, *1991*; McNamara *et al, 1996*]. This study presents the first estimate of *Lg* frequency dependent *Q* in south-central Alaska using broadband instrumentation. Results from this study will be compared to previous *Lg* and *S*-wave coda frequency dependent *Q* studies to obtain further understanding of the attenuation properties of the crust in south-central Alaska.

2. Data and Analysis

2.1 Instrumentation and earthquakes.

The *Lg* waveforms used in this study were obtained from local and regional crustal earthquakes that occurred in central Alaska, and were digitally recorded as a part of the Broadband Experiment Across the Alaska Range (BEAAR) [Meyers *et al., 1999*] (Figure 1) (Table 1). The sensor at each site was a broadband, active-feedback, three-component, Guralp CMG-3ESP that is flat to velocity from 0.30 to 50 Hz. Data were continuously recorded at a rate of 50 samples per second. Earthquake locations and magnitudes used in this study were obtained from the Alaska Earthquake Information Center (AEIC), June

1999, catalog of hypocenters [McNamara *et al., 1999*] (Figure 1) (Table 2). All phase picks were reviewed and hypocenters recalculated to minimize travel time residuals. For this analysis *Lg* waveforms were restricted to well recorded (Ml≥2.0), crustal events (depth≤40 km, [Biswas and Tytgat, *1988*]), with paths confined to south-central Alaska. For inclusion in the inversion, we also required that each station recorded at least two events and that each event be recorded by at least two stations.

2.2 Waveform selection criteria and amplitude measurement.

A two step signal to noise analysis was performed to obtain high quality *Lg* amplitude measurements. First, the root-mean-square (RMS) amplitude of the first arriving body wave (*Pn*, windowed from 7.8-8.2km/s, or *Pg*, windowed from 5.8-6.5km/s), on the vertical component, velocity seismogram was required to be ten times greater than the RMS amplitude of the pre-event noise. The pre-event noise window (13.0-11.0km/s) was a similar length, and well ahead of the *P*-wave window. This step eliminated small and poorly recorded events. Second, we required an *Lg/P-coda* RMS amplitude ratio greater than two. *Lg* was windowed from 3.6-3.0 km/s and the *P-coda* (windowed from 5.8-4.8 km/s) was chosen as the scattered energy between faster crustal *P*-waves (*Pg*) and slower upper mantle *S*-waves (*Sn*). This step eliminated very few paths, since *Lg* is generally the dominant arrival on regional seismograms, and ensured that only amplitude measurements are included in the inversion where *Lg* is present at all distances [McNamara *et al., 1996*; McNamara and Walter, *2000*]. The goal was to eliminate paths crossing *Lg* blocking structures, such as ocean basins, that would bias the regional *Q* estimate.

Regional waveforms, that passed the signal-to-noise criteria were further processed to obtain *Lg* time-domain amplitude measurements. This included deconvolving the instrument response from the bandpass-filtered vertical component seismogram. The vertical component was selected for comparison with previous studies, that used only short-period vertical sensors, [Hansen *et al., 1998*; Steensma and Biswas, *1988*] and is supported by previous studies showing that energy in the *Lg* window is evenly scattered across all three-components of motion [McNamara *et al., 1996*]. Finally, the RMS amplitude of *Lg* (3.6-3.0 km/s) was measured in five, one-octave, passbands, with center frequencies of 0.75, 1.5, 3, 6 and 12 Hz. Figure 2 shows an example of the filtered time domain *Lg* arrivals, from a single event (origin time 6/25/1999, 11:34:30.16, Ml=4.0, depth=9.35km, lat=63.447°, lon=-151.297°) recorded at station TLKY (dist=157km).

After applying the earthquake and waveform selection criteria to over 2000 regional seismograms, 105 high-quality *Lg* waveforms, from 27 events, recorded at six stations, with a distance range of 75-500 km, remained. Due to the restricted raypath coverage, the *Q(f)* determined in this study is only representative of the south-central portion of Alaska (Figure 1b).

3. Inversion Methods and Results

3.1 Single frequency *Lg Q* inversion.

The inversion method used in this study to estimate the frequency dependence of *Lg* is described in detail by Benz *et al.,* [*1997*] and further implemented by McNamara *et al*., [*1996*]. The observed *Lg* amplitude, *A,* at frequency *f* for the *j*th earthquake recorded at the *i*th station can be modeled as:

$$A_{ij}(f) = R_{ij}^{\;-\gamma}\, S_j(f) G_i(f)\, e^{-\pi f R_{ij}/Q\beta} \tag{2}$$

Where $S_j(f)$ is the source spectra, $G_i(f)$ is the site amplification, R_{ij} is the epicentral distance between the earthquake, j, and station, i, γ is the exponent for geometrical spreading, 0.5 in this study [Benz *et al., 1997*; McNamara *et al., 1996*], Q is the *Lg* quality factor at frequency f, and β is the average shear-wave velocity for the crust, 3.5 km/s for this study. Taking the logarithm of (2) yields the following equation:

$$\ln A_{ij}(f) + \gamma \ln R_{ij} = \ln G_i(f) + \ln S_j(f) - \pi f R_{ij}/Q\beta \tag{3}$$

When the left hand side of (3) is plotted with respect to distance, the right side of (3) describes a line where the receiver (G_i) and source (S_j) terms control the intercept and the Q term controls the slope. Using a data set with many source-receiver pairs, a system of linear equations can be set up based on equation (3). The system of equations is then solved using a singular-value decomposition inversion [e.g. Menke, *1990*]. The inversion solves for both the source (S_j) and receiver terms (G_i) as well as a regionally averaged *Lg Q* for a single frequency passband, with center frequency, *f*.

3.2 Frequency dependent *Lg Q(f)*

By repeating the inversion, over five octaves, with center frequencies of 0.75, 1.5, 3, 6 and 12 Hz, we obtain a *Q* estimate for each passband. Figure 3 shows the south-central Alaska *Lg* amplitudes corrected for the source (S_j) and receiver (G_i) terms plotted versus distance. The straight lines represent the best fitting *Q* for the particular frequency band. *Q* in south-central Alaska ranges from 198 at 0.75 Hz to 1190 at 12 Hz.

A weighted least-squares regression analysis is then used to fit the frequency-dependent *Q* function, *Q(f)* (1), to the *Q* estimates. Taking the logarithm of both sides of (1) yields:

$$lnQ = lnQ_0 + \eta ln(f) \tag{4}$$

where lnQ_0 and η are the unknowns to be determined. The least-squares fit to the south-central Alaska *Lg Q* estimates, shown in Figure 4 (AKLg), is given in the form of a power law by:

$$Q(f) = 220(\pm 30)\, f^{\,0.66(\pm 0.09)} \quad (0.75 \le f \le 12 \text{ Hz}). \tag{5}$$

4. Discussion

4.1 Previous results.

Figure 4 shows apparent *Q(f)* functions, from several previous studies, obtained for a variety of tectonic regions. Tectonically stable continental regions, such as the northeastern United States, generally have the highest values of Q_0, and the weakest frequency dependence, (low η) (Figure 4; NEUS), while low Q_0 and high η values are observed in tectonically active regions (Figure 4; BRP, TP) [Benz *et al., 1997*]. Direct comparison of the results from this study to other areas in North America show that south-central Alaska has much lower values of Q_0 and a much higher frequency dependence than stable continental regions. As expected for south-central Alaska, the Q_0 and η determined from this study are more indicative of a tectonically active region.

An earlier attempt at characterizing the *Lg* quality factor in south-central Alaska was presented by Hansen *et al*., [*1998*] (Figure 4 AEIC). The Q_0 from this study is comparable to the results of Hansen *et al.,* [*1998*] however, the frequency dependence is weaker (Figure 4). This difference is likely due to the limited data available to Hansen *et al*., [*1998*]. Specifically, their study was only able to measure *Lg* amplitudes on short period (1Hz), vertical component seismograms within a limited epicentral distance range (100-300km). The limited distance range was a function of noise on the short-period seismograms and resulted in unreliable fits to the individual passbands *Q* estimates. Also, the amplitude spectra were generally too noisy, at higher and lower frequencies, to allow for reliable *Q* estimates at frequencies outside the range of 1.5-8Hz. These differences likely account for the discrepancies between the results of Hansen *et al*., [1*998*] and this study.

A remarkably similar estimate of *Q(f)* in south-central Alaska was obtained by Steensma and Biswas [*1988*]. They measured the decay of *S*-wave coda and determined a frequency-dependent *Q* (Q_0=215, η=0.62) that falls well within the uncertainty of results obtained in this study (Q_0=220±30, η=0.66±0.09) (Figure 4, AKS). Steensma and Biswas [*1988*] measured *S*-wave coda decay from local events with focal depths ranging from 6-129km and event-station distances ranging from 2-435km. While shallower events (≤40km) with greater epicentral distances (75-500km) are used in this study, the data sets are very similar. Also, since the *Lg* window chosen for this study contains a large component of *S*-wave coda scattered energy, it is not surprising that these results are comparable.

4.2 Scattering and intrinsic attenuation mechanisms.

Seismic attenuation is generally caused by a combination of both scattering and intrinsic mechanisms. Scattering redistributes wave energy within the medium but does not remove energy from the overall wavefield. In contrast, intrinsic attenuation mechanisms convert wave energy to heat through friction, viscosity, and thermal relaxation processes. It is not yet clear which attenuation mechanism is dominant and the results from this study cannot independently distinguish between the two. The *Lg Q(f)* estimate, obtained from this study, is also a combination of both intrinsic and scattering mechanisms and defines an apparent frequency-dependent attenuation for the whole crust.

The consistency of these results, *Lg Q(f*) with the *S*-coda *Q(f)* results of Steensma and Biswas [*1988*], can allow some constraints to be placed on attenuation mechanisms. For example, several studies demonstrate that seismic coda is relatively insensitive to scattering suggesting that intrinsic rock properties likely dominate attenuation [Mayeda and Walter, *1996*; Frankel and Clayton, *1986*; Frankel and Wennerberg, *1987*]. Mayeda *et al., 1992* more precisely define the contribution of the individual attenuation mechanisms in a broad study of coda *Q* in Hawaii, Long Valley and central California. They conclude that, in all three regions, for frequencies less than or equal to 6.0 Hz, scattering dominates attenuation, whereas above 6.0 Hz, intrinsic rock properties are the dominant mechanism. Given this observation and the consistency between *S*-coda *Q(f)* and *Lg Q(f),* for the range of frequencies considered in this study (0.75-12 Hz), both scattering and intrinsic mechanisms likely play and equal role in attenuating *Lg* energy.

4.3 Tectonic implications.

Several geologic factors may contribute to the apparent *Lg Q* within the crust of south-central Alaska. First, *Lg* amplitudes (≤6 Hz) likely decrease due to scattering along fractures, faults and sutures. The crust of south-central Alaska is highly fractured and faulted, consisting of numerous suture zones, bounding tectonic terranes, and large strike-slip faults, along which the crust is actively deforming [Fletcher and Freymueller, *1998;* McNamara *et al., 1999*]. Second, in regions with active crustal deformation and tectonic activity, the intrinsic rock properties of the crust may cause attenuation of *Lg* energy at frequencies >6 Hz. For example, interstitial fluids may be present in crustal fractures, from melt and metamorphism due to elevated temperatures from internal deformation and/or heating from the upward migration of volcanic material.

The thermal properties of south-central Alaska are not well known, however, there are several seismic and geologic observations that can be interpreted as evidence for high temperatures in the upper mantle and crust. For example, low upper mantle and crustal *P*-wave velocities [Zhao *et al*., *1995*] are consistent with high heat production. There is also an abundance of recent volcanism, extending from the Cook Inlet, into the Alaska range and eastward to the St. Elias range (Figure 1) [Nye, *1999*]. These flows are due to melt from the subducting Pacific plate and would significantly heat the overlying crust of the North American plate. Crustal heating is likely to significantly increase crustal attenuation (Frankel *et al., 1990*).

5. Conclusions

The goal of this paper is to document the frequency-dependent *Lg Q* of south-central Alaska and compare it with *Q(f)* observed in different tectonic regions throughout the world. The results from this work are consistent with previous *Q(f)* estimates in south-central Alaska, showing much lower values of Q_0 and a much higher frequency dependence than stable continental regions. This result is expected given the active tectonic setting of south-central Alaska. The close agreement between *Lg Q(f),* obtained in this study and previous *S*-coda *Q(f)* estimates, argue for an equal contribution from both scattering and intrinsic attenuation mechanisms in south-central Alaska. Scattering structures and intrinsic properties of crustal rocks, responsible for attenuation of *Lg*, include tectonic terrane sutures, faults, high heat flow and the presence of interstitial fluids. Each is directly related to the fact that the south-central Alaskan crust is over-riding the active subduction of the Pacific plate. The results from this work, provide an attenuation function that can be used in a variety of scientific and engineering applications including local magnitude estimates, earthquake hazard assessment in populated areas and understanding the shaking intensity expected at structures, such as the Alaska Pipeline.

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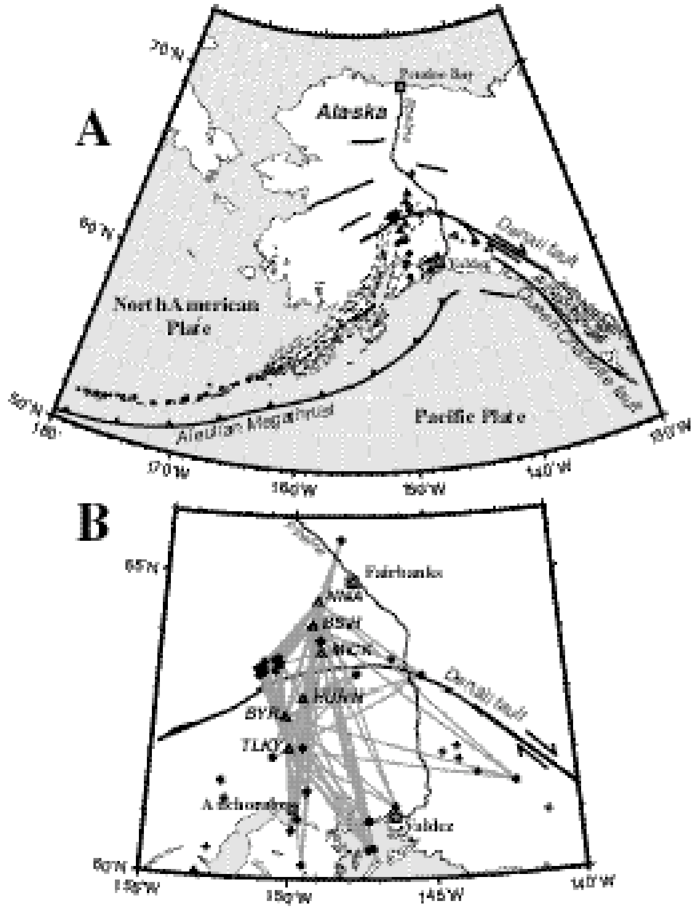
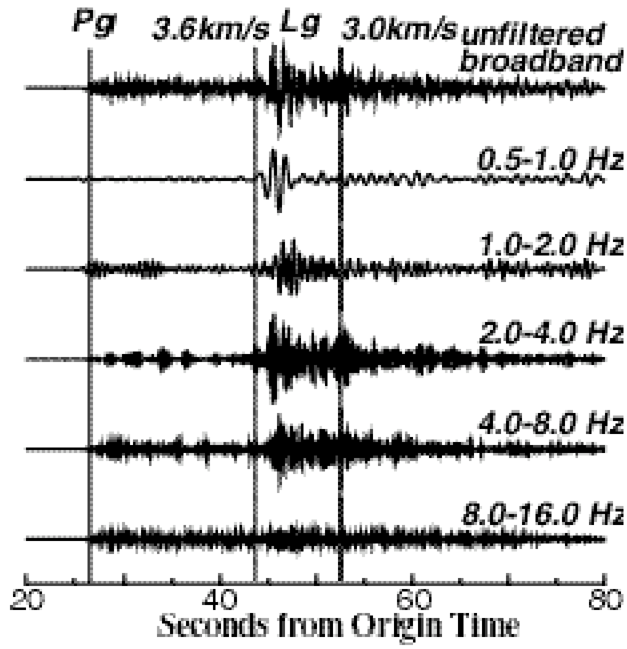
Figure Captions



(Figure 1: McNamara, 2000)

Figure 1: (a) Map of Alaska showing the BEAAR broadband stations (white triangles) (Table 1) and the distribution of regional events (solid circles) (Table 2) used in this study. The BEAAR array crosses major tectonic features including the Denali fault and

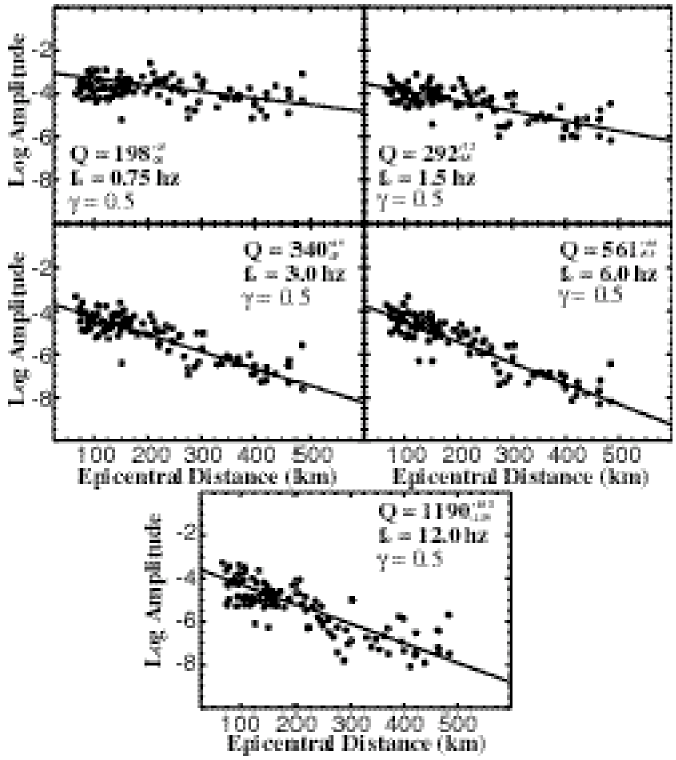
the Alaska Range. (b) *Lg* raypaths, passing the data selection criteria and used in the inversion for frequency-dependent quality factor, *Q(f)*.



(Figure 2: McNamara, 2000)

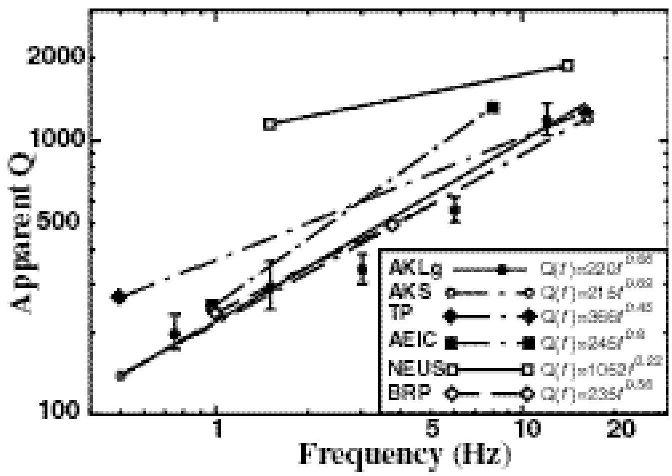
Figure 2: *Lg* from one earthquake (origin time 6/25/1999, 11:34:30.16, Ml=4.0, depth=9.35km, lat=63.447°, lon=-151.297°) recorded at station TLKY (dist=157km). Shown is the vertical component of the instrument corrected displacement seismogram. The seismogram is filtered in five passbands for amplitude measurement. Filtered traces

are plotted on the same scale to show amplitude decay with increasing frequency. *Lg* amplitude was taken as the RMS within a window from 3.6-3.0km/s.



(Figure 3: McNamara, 2000)

Figure 3: Best fit *Q*, determined from the inversion, over 5 different passbands.



(Figure 4: McNamara, 2000)

Figure 4: The weighted least-squares *Q(f)* fit (AKLg, solid line) to the *Q* estimates from this study (solid circles). Also shown are *Q(f)* estimates from Alaska, using different techniques (AKS) [Steensma and Biswas, *1988*] (AEIC) [Hansen *et al., 1998*], and several different regions for comparison, including the northeastern United States (NEUS) the Basin and Range (BRP) [Benz *et al., 1997*] and the Tibetan Plateau (TP) [McNamara *et al., 1996*]. Apparent *Q* is a combination of both intrinsic and scattering *Q*.

Table 1

Locations of the Broadband Stations used in this Study

Station	Lat. (°N)	Lon. (°W)	Elevation (m)
BSH	64.1713	-149.2951	284.0
BYR	62.6892	-150.2319	388.0
HURN	62.9991	-149.6064	612.0
MCK	63.7323	-148.9368	646.0
NNA	64.5797	-149.0786	384.0
TLKY	62.1499	-150.0610	132.0

Table 2

Locations of Earthquakes used in this Study

Date M/DD/Year	(jday)	Origin Time HH:MM:SS.msec	Lat. (°N)	Lon. (°W)	Depth (km)	Mag. (Ml)
6/07/1999	(158)	13:12:48.080	63.3768	-147.7143	12.3100	3.00
6/08/1999	(159)	18:34:23.690	63.5478	-150.5377	17.0100	2.80
6/09/1999	(160)	23:14:47.240	62.0165	-150.6397	37.5000	2.80
6/10/1999	(161)	11:31:45.300	63.4092	-151.0855	17.4900	3.00
6/13/1999	(164)	9:06:39.770	61.4587	-149.3897	29.3600	2.80
6/14/1999	(165)	20:26:35.560	63.6345	-150.5315	12.5800	3.10
6/14/1999	(165)	20:26:35.110	63.5838	-150.6767	16.7300	3.10
6/16/1999	(167)	23:08:20.100	60.5000	-147.1760	6.4800	2.70
6/17/1999	(168)	21:41:33.960	61.1988	-146.3863	15.0000	2.50
6/18/1999	(169)	10:00:53.400	62.1798	-149.5755	6.4600	2.50
6/18/1999	(169)	14:14:15.580	63.3387	-145.3063	7.2300	2.50
6/18/1999	(169)	23:40:32.320	63.9158	-148.9858	2.7700	2.70
6/19/1999	(170)	5:19:05.740	63.3890	-151.0538	15.8600	3.00
6/19/1999	(170)	18:34:29.530	61.5512	-142.1288	0.4800	2.70
6/20/1999	(171)	20:21:44.630	60.9898	-149.7285	35.6300	3.00
6/21/1999	(172)	6:02:04.380	63.3307	-151.2355	9.8400	2.70
6/23/1999	(174)	1:17:04.730	65.6117	-148.2018	14.0300	2.70
6/24/1999	(175)	2:33:02.990	63.5582	-151.0682	12.7600	2.60
6/24/1999	(175)	9:45:00.070	63.4808	-151.0917	11.6100	3.30
6/25/1999	(176)	6:29:52.000	63.4200	-150.6545	16.1000	2.90

6/25/1999	(176)	11:34:30.160	63.4470	-151.2970	9.3500	4.00
6/25/1999	(176)	22:06:07.590	60.9622	-147.3092	21.7000	3.00
6/04/1999	(155)	17:29:05.810	60.4832	-147.3632	12.7100	2.50
6/04/1999	(155)	22:12:59.660	63.9238	-148.9538	3.9200	2.70
6/05/1999	(156)	15:08:01.200	60.2278	-149.5388	24.7900	2.80
6/06/1999	(157)	3:37:35.210	60.7983	-149.9245	24.7700	2.80
6/06/1999	(157)	7:22:22.550	63.5422	-150.4500	12.0100	3.00