Lg Q in the North American Mid-Continent

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Abstract
The characteristics of seismic energy attenuation, mid-continent of the United States, are determined using high frequency *Lg* waves from 107 crustal earthquakes. *Lg* spectral amplitudes are measured in five pass-bands and inverted to determine a frequency-dependent quality factor, *Q(f),* model for three distinct regions that include: 1) the Wasatch mountain region of Utah; 2) the central Rocky mountains of Colorado and Wyoming; and 3) the western plains of eastern Colorado, Kansas, Nebraska and South Dakota. Inversions in this study yield frequency-dependent quality factors, in the form of a power law: $Q(f) = Q_0 f^\eta$. The Wasatch mountain region resulted in the lowest Q in this study with $Q(f)=160(\pm 10)\, f^{0.65(\pm 0.04)}$ ($0.5 \le f \le 16$Hz). The Central Rocky mountain region resulted in $Q(f)=181(\pm 16)\, f^{0.65(\pm 0.01)}$ ($0.5 \le f \le 16$Hz). The western plains region has the highest Q in this study with $Q(f)=380(\pm 40)\, f^{0.57(\pm 0.11)}$ ($0.5 \le f \le 16$Hz). The results for the Wasatch, Rocky mountains and western plains regions fall within Q values obtained for the western and eastern United States, respectively, from previous studies. In addition, the low Q values in the Rocky Mountain region are in agreement with the high heat flow observed in the region.

Introduction

In this study we focus on the attenuation characteristics of a large mid-continental region that ranges from the Wasatch Mountains in the west to the central plains to the east (Figure 1). It is well known that attenuation in the western United States is significantly higher than in the central and eastern United States [Chavez and Priestly*, 1986*; Mitchell, *1975, 1981*; Frankel *et al, 1990*; Frankel, *1991*; Benz *et al., 1997,* Erickson *et al., 2004,* Richter, *1958*, Nuttli *et al., 1979*] however very little is known about seismic attenuation in the Rocky Mountains region. In this study we determine a frequency-dependent quality factor, *Q(f),* model for three distinct regions that include: 1) the Wasatch mountain region of Utah; 2) the central Rocky mountains of Colorado and Wyoming; and 3) the western plains of eastern Colorado, Kansas, Nebraska and South Dakota.

For this study we examine the attenuation characteristics of the seismic phase *Lg*. *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 is sensitive to lateral heterogeneity in the crust due to varying tectonic environments. Global observations confirm that *Lg* attenuation is higher for regions with active tectonism than for stable continental interiors [Benz *et al., 1997*; McNamara *et al., 1996*, McNamara and Walter, *2000,* Xie *et al., 2003*; Atkinson *et al., 1992*; McNamara, *2002;* Erickson, et al*., 2004*]. 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,* Zhang and Lay, *1995,* Kennett, *1986*].

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*, Atkinson 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. This study presents the first estimate of *Lg* frequency dependent *Q* in the central Rocky mountains region using broadband instrumentation. Results from this study will be compared to previous *Lg* frequency dependent *Q* studies to obtain further understanding of the attenuation properties of the crust in our study region. Regionally-specific attenuation parameters are crucial for the improvement of probabilistic assessments of seismic hazard, such as the USGS national seismic hazard maps that are used for seismic provisions in building codes (Frankel et al., *2000*). Regionally-specific Q values are also important to estimate ground shaking for scenario large earthquakes and for use in Shakemaps that present in near real time the observed and inferred shaking from significant earthquakes as part of the Advanced National Seismic System (ANSS). Attenuation characteristics are also needed for magnitude detection threshold work being conducted to optimize future seismic stations locations and ANSS network design.

Data and Analysis, Instrumentation and Earthquakes.

The *Lg* waveforms used in this study were obtained from the vertical component of seismograms from local and regional crustal earthquakes that occurred in the central and western United States from 1995 to 2004, and were digitally recorded at backbone stations within the Advanced National Seismic System (ANSS) (Figure 1). The seismometer at each site was either a broadband, active-feedback, three-component, Guralp CMG-3ESP that is flat to velocity from 0.30 to 50 Hz or a Streckheisen STS-2 that is flat to velocity from 0.05 to 50 Hz. Data were continuously recorded at a rate of 40 samples per second. Earthquake locations and magnitudes used in this study were obtained from USGS Preliminary Determination of Epicenters (PDE) (Figure 1). For this analysis *Lg* waveforms were restricted to well recorded ($M_L \geq 2.0$), crustal events (depth≤40 km), with paths confined to each specific region. 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.

Waveform selection criteria and amplitude measurement. Signal to noise was analyzed to obtain high quality *Lg* amplitude measurements. We required an *Lg/P-coda* RMS amplitude ratio greater than two. The RMS amplitude for *Lg* was windowed from 3.6-3.0 km/s and the *P*-coda was windowed from 5.8-4.8 km/s The window for the *P*-coda was chosen to select 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*]. The goal was to eliminate paths crossing *Lg* blocking structures that would bias the regional *Q* estimate. Regional waveforms that passed the signal-to-noise criteria were further processed to obtain *Lg* spectral amplitude measurements. This included deconvolving the instrument response from the bandpass-filtered vertical component seismogram. 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. After applying the earthquake and waveform selection criteria to over 20000 regional seismograms, nearly 400 high-quality *Lg* waveforms, from 107 events, recorded at 15 stations, with a distance range of 100-1000 km, remained (Figure 1).

Inversion Methods and Results

Single frequency *Lg Q* inversion. The inversion method used in this study to estimate the frequency dependence of *Lg* is well known [McNamara et al., *1996*, McNamara *2002*; Erickson et al., *2004*] and described in detail by Benz *et al.,* [*1997*]. The observed *Lg* amplitude, *A,* at frequency *f* for the *j*th earthquake recorded at the *i*th station can be modeled as:

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

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:

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

When *Lg* amplitude corrected for geometric spreading (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 and receiver terms (G_i) as well as a regionally averaged *Lg Q* for a single frequency passband, with center frequency, f.

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 estimates for each passband. Figure 2 shows the *Lg* amplitudes corrected for the source (S_j) and receiver (G_i) terms plotted versus distance for all regions in this study. The straight lines represent the best fitting Q for the particular frequency band. Figure 3 is an example of the source terms (S_j) determined for the 3Hz inversion using the Wasatch data set. As expected a strong relationship exists between the amplitude of the source term and the magnitude of the earthquake.

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:

$$lnQ = lnQ_0 + \eta ln(f) \qquad (4)$$

where lnQ_0 and η are the unknowns to be determined.

Results

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;* Erickson *et al., 2004*].

Results from this study suggest that the attenuation characteristics of both the Wasatch and the central Rocky mountain region are closer to those of the Basin and Range Province while the *Q* obtained for the western plains is more similar to those of the central U.S [Erickson *et al., 2004*]. The lowest *Q* values, in this study, are observed in the Wasatch Region, and the highest *Q* to the east in the western plains region. We will discuss the results in detail below.

Wasatch region. Figure 1 shows the distribution of broadband stations (white triangles), earthquakes (black circles), and source-receiver Lg paths (red lines) for the Wasatch region. The region, ranging from 36°N to 43°N and 110°W to 114°W, runs from southern Utah, up the Wasatch to the north into southern Wyoming and Idaho. 190 raypaths from 53 earthquakes and recorded at 10 stations were used in the inversion for *Q(f)* (Figure 1).

Figure 2a shows a comparison of Lg spectral amplitude versus epicentral distance at center frequencies of 0.75, 1.5, 3.0, 6.0, and 12 Hz, corrected for source and receiver terms determined from the inversion. Source terms are plotted versus event magnitude in figure 3 for the Wasatch region 3 Hz inversion. As expected, source terms determined from the inversion procedure increase with magnitude. We used HWUT as the reference station for the Wasatch region, which is located in Northeastern Utah near the town of Logan (Figure 1). An arbitrary reference station was selected to normalize the remaining stations. The reference station was chosen based on low background noise and well known response characteristics, but in the end, the choice of reference station had no effect on *Q* [Erickson *et al., 2004*]. Selection of a reference station is critical to determine relative receiver terms, however this topic is not discussed here. The individual frequency *Q* fits in Figure 2a show an increase in *Lg Q* from 140 at 0.75 Hz to 854 at 12.0 Hz. A least-squares fit to the Wasatch region *Lg Q* estimates versus frequency, shown in Figure 4, is given in the form of a power law by: $Q(f)=160(\pm 10) f^{0.65(\pm 0.04)}$ ($0.5 \le f \le 16$Hz). This is the lowest *Q* value in the study and fits the general west to east trend of increasing *Q* within the study region. It is somewhat surprising that the Q value obtained for the Wasatch region is lower than *Q* values previously obtained for the Basin and Range Province [$Q(f) = 235(\pm 11)\ (f/1)^{0.56(\pm 0.04)}$: Benz *et al., 1997*; $Q(f) = 200(\pm 40)\ (f/1)^{0.68\ (\pm 0.12)}$: Erickson *et al., 2004*] (Figure 4). The difference in the BRP values determined from these previous studies may be in the number of Wasatch crossing paths included in their solution. Erickson et al. [2004] include numerous Wasatch paths, which resulted in a lower overall BRP *Q* than Benz et al, [1997], which is closer to our Wasatch result.

Central Rocky Mountain region. The Central Rockies region, from 36°N to 43°N and 104°W to 110°W, ranges from eastern Utah to central Colorado and runs from southern Colorado, north up the Rockies into central Wyoming. 62 raypaths from 47 earthquakes and recorded at 4 stations were used in the inversion for *Q(f)* (Figure 1). Figure 2b shows a comparison of Lg spectral amplitude versus epicentral distance at center frequencies of 0.75, 1.5, 3.0, 6.0, and 12 Hz, corrected for source and receiver terms determined from the inversion. We used ISCO as the reference station for the region, which is located 100 km west of Denver, CO (Figure 1). The individual frequency *Q* fits in Figure 2b show an increase in *Lg Q* from 150 at 0.75 Hz to 906 at 12.0 Hz. A least-squares fit to the Central Rockies region *Lg Q* estimates versus frequency, shown in Figure 4, is given in the form of a power law by: $Q(f)=181(\pm 16) f^{0.65(\pm 0.01)}$ ($0.5 \le f \le 16$Hz). Results for this region show a mid-continent transitional *Q* value that fits the general west to east trend of increasing *Q* that is commonly observed for the United States (Figure 4). However, it is again surprising that that the *Q* value obtained for the

Rocky mountain region is lower than *Q* values previously obtained for the Basin and Range Province.

Western Plains region. As expected, the tectonically stable western Plains region has the highest *Q* in this study. The region, from 32°N to 45°N and 95°W to 107°W, ranges from the front range of central Colorado to central Kansas and Nebraska and runs from northern New Mexico, north into central South Dakota. 60 raypaths from 28 earthquakes and recorded at 4 stations were used in the inversion for *Q(f)* (Figure 1). Figure 2c shows a comparison of Lg spectral amplitude versus epicentral distance at center frequencies of 0.75, 1.5, 3.0, 6.0, and 12 Hz, corrected for source and receiver terms determined from the inversion. We used ISCO as the reference station for the region, which is located 100 km west of Denver, CO (Figure 1). The individual frequency *Q* fits in Figure 2c show an increase in *Lg Q* from 324 at 0.75 Hz to 1738 at 12.0 Hz. A least-squares fit to the western plains region *Lg Q* estimates versus frequency, shown in Figure 4, is given in the form of a power law by: $Q(f)=380(\pm 40)\, f^{\,0.57(\pm 0.11)}$ ($0.5 \leq f \leq 16$Hz). *Q* results for this region are the highest in the study and are similar to the higher Q vaules obtained in previous studies for the central and eastern United States [Benz *et al., 1997*; Erickson *et al., 2004*]. From these results we find that the sharpest transition of *Q* values occurs near the eastern edge of the Rocky Mountain region, rather than at the eastern edge of the Basin and Range Province.

Discussion and Conclusions

Our objective in this work is to document differences in *Lg* attenuation in the transitional mid-continent between the low attenuation of the western US and the higher attenuation of the eastern US. Standardized instrumentation and consistent processing provide attenuation functions that can be used in a variety of applications including seismic network detection assessment, local magnitude estimates, earthquake hazard assessment in populated areas, and structural engineering applications.

The low *Q* values for theRocky Mountain region, that we find in this initial study are somewhat surprising since it is lower than BRP values obtained from previous studies. In general, areas of relatively moderate seismic activity, such as much of the Rocky Mountain region, are commonly found to have higher *Q* values. The southern part of the

Rocky Mountain region is associated with crustal extension related to the northern extension of the Rio Grande rift. Furthermore the high mountains of the Rockies region are characterized by high heat flow (>100 mWatts/m^2), as much as 60 mWatts/m^2 higher than the low elevation regions of eastern Utah and eastern Colorado [Roy et al., *1972*]. The high crustal temperatures will likely increase intrinsic attenuation in the crust causing very low values of *Q* determined from *Lg* amplitudes. The structural complexity of the Rocky Mountain region and its lateral variability of crustal thickness may also contribute to lowering the apparent *Q* of the region. Similar high levels of heat flow are also observed for the Wasatch region (80-100 mWatts/m^2) [Roy et al., *1972*] while the BRP has a large region with a relatively lower level of heat flow (40-60 mWatts/m^2) [Roy et al., *1972*], similar to eastern Utah and eastern Colorado. This provides the most likely explanation for why the BRP has slightly higher values of *Lg Q* than the Wasatch and Rocky mountains regions in this study.

As more data become available for the Wasatch and Rocky Mountain region,s these issues can be further studies. Specifically, a detailed analysis of eastern Utah should allow us to determine if we can directly correlate *Lg Q* with the regional variability in crustal heat flow levels. Further work will also include obtaining more data to determine *Lg Q* for the remaining tectonic areas of the U.S., and expanding the technique to a 2 D tomographic inversion of the entire continental United States.

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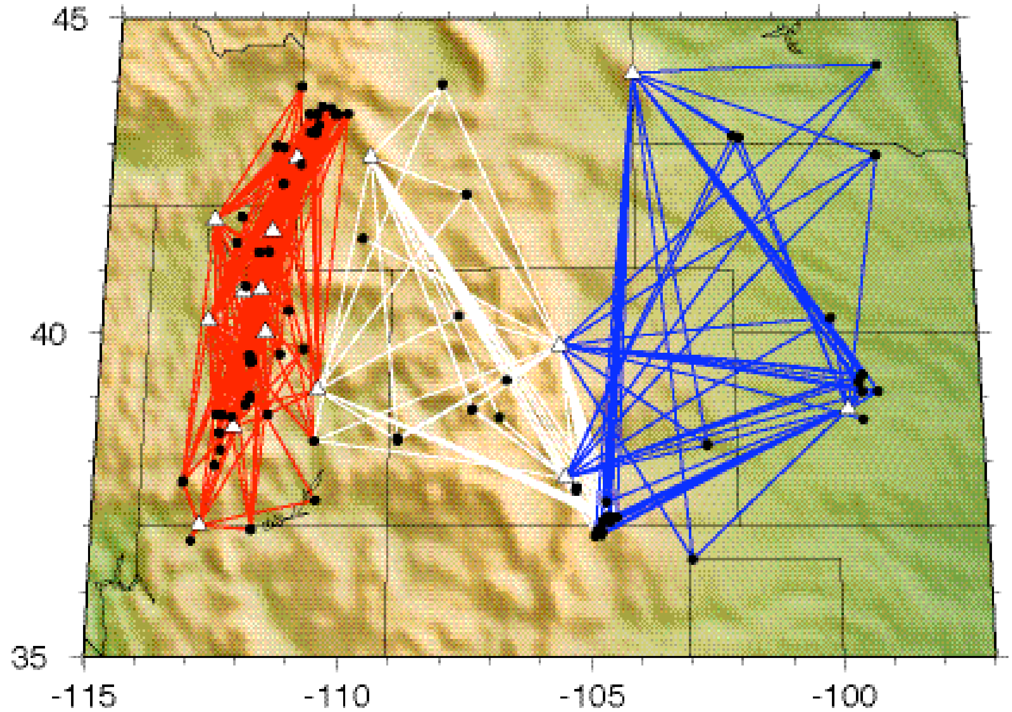
Figure Captions

Figure 1: Map of the three regions studied in this work. *Lg* raypaths, passing the data selection criteria and used in the inversion for frequency-dependent quality factor, *Q(f)* are mapped as solid lines. Red lines show the *Lg* paths used in the Wasatch region, white lines show *Lg* paths used in the central Rockies region and blue lines show the distribution of paths used in the western plains region. The distribution of ANSS backbone and regional stations used in the study are shown as white triangles and the distribution of regional events are mapped as black circles. The study area crosses major tectonic features including the front range fault, the Rocky Mountains and the Wasatch Range.

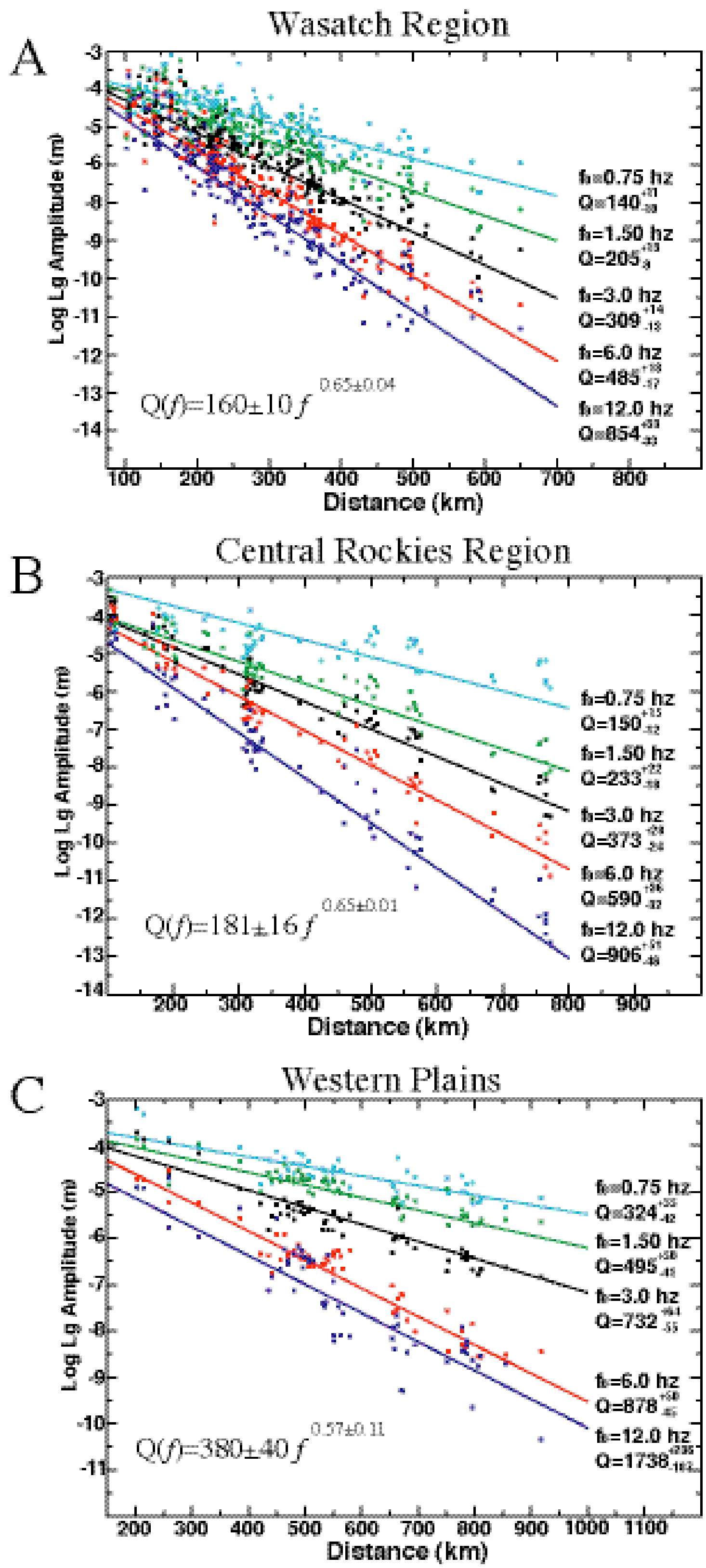
Figure 2: Best fit *Q*, determined from the inversion in each region, over 5 different passbands. a) Wasatch region. b) central Rockies region. c) western plains region.

Figure 3: Source terms plotted versus magnitude. Source terms were determined by the inversion procedure for the Wasatch region at 3 hz.

Figure 4: Weighted least-squares *Q(f)* fits to the *Q* estimates from this study (western Plains, Central Rockies, Wasatch). Also shown are several different regions for comparison, including the northeastern United States (NEUS) the Basin and Range (BRP) [Benz et al., *1997*], northern California (N. California) [Erickson, et al., *2004*].



(Figure 1: McNamara et al., 2004)



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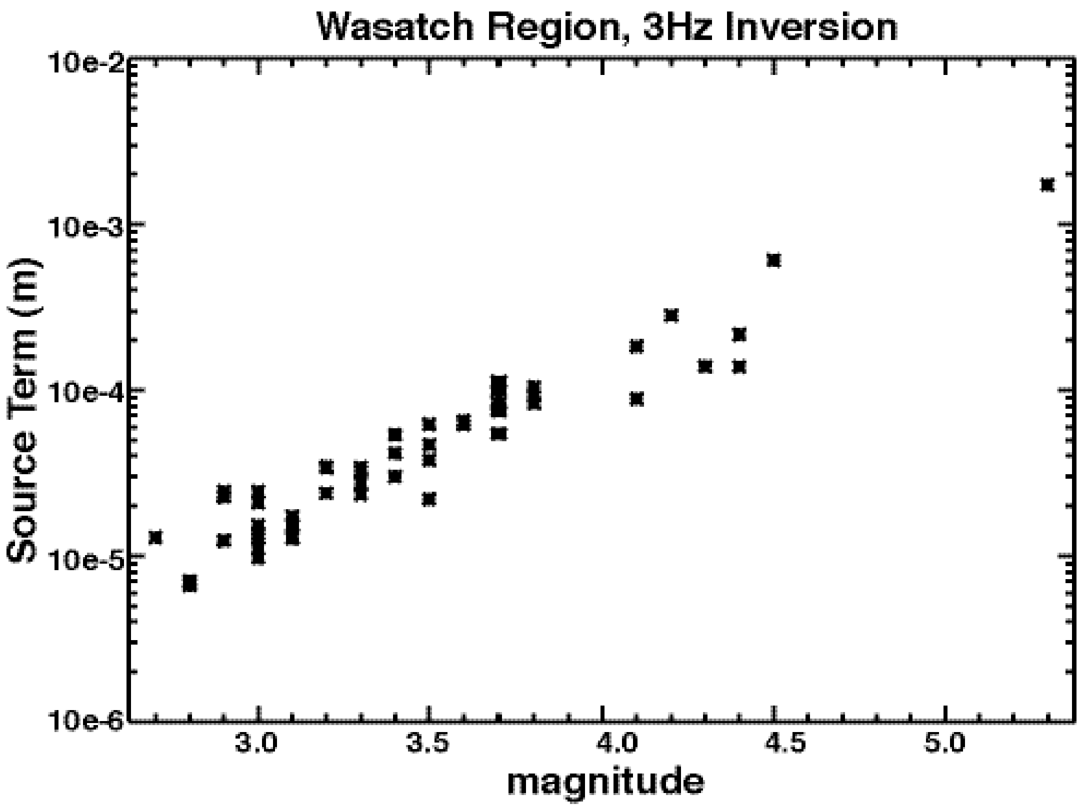

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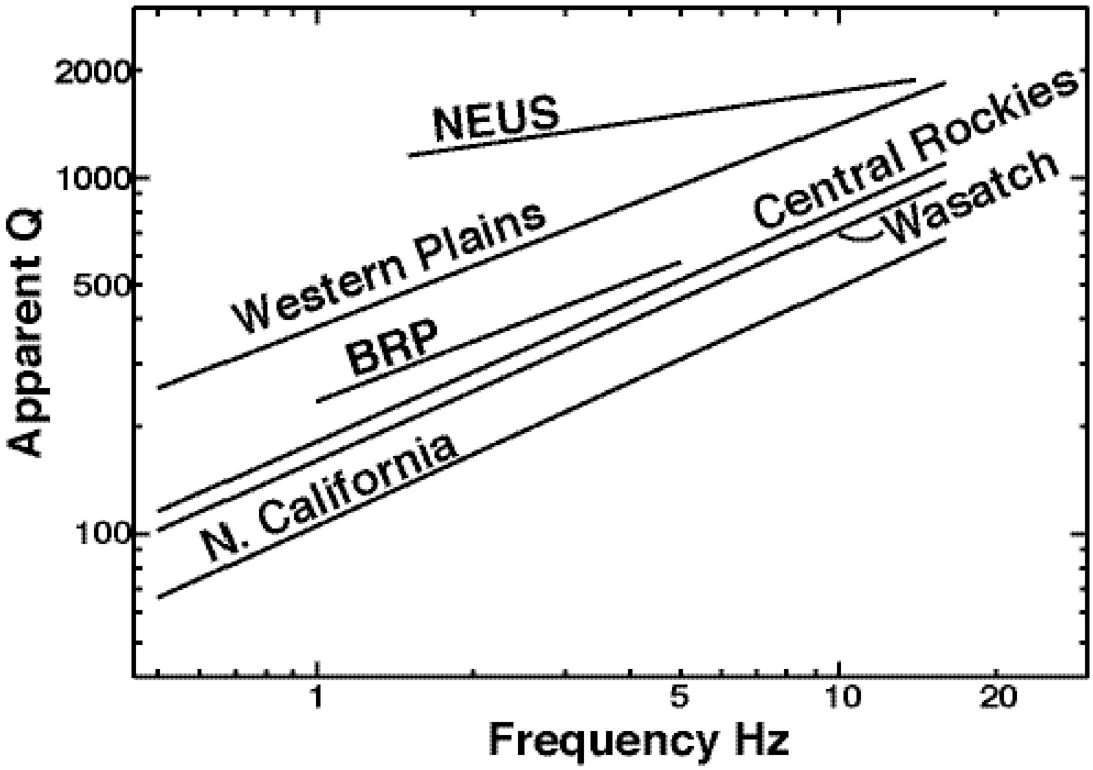

(Figure 4: McNamara et al., 2004)