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Earthquake Ground Motions in Eastern Canada

by

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A thesis submitted to the faculty of Graduate Studies and Research
in partial fulfilment of the requirements for the
degree of Doctor of Philosophy

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Ottawa, Ontario, Canada
May, 2004

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Abstract:

Seismic hazard assessment relies on accurate knowledge of path effects, where path effects describe the changes in earthquake ground motion amplitude with distance. If the variation of amplitude with distance is well known, then it is possible to determine the spectrum of earthquake ground motion near the source from earthquake ground motions observed at much greater distances. The reverse two-station method (RTSM) of Chun et al. (1987) is explored in this study as a means of determining the coefficient of total attenuation, modelled as R^{-b} , in northeastern North America.

The Brune spectral source model is compared to two methods of deriving the apparent source spectrum; the Direct method which removes the regional values of path effects and the Empirical Green's Function method, where an Empirical Green's Function event is used to calibrate the earth's response.

The modified RTSM gives values of the attenuation coefficient for the specific path between a pair of stations. These specific values may only be considered reliable within the path they describe, but average values give an approximation of the regional attenuation. Attenuation was found to be high within the Charlevoix Seismic Zone (CSZ), the most seismically active region within Eastern Canada. The average b value within the CSZ was found to be 1.36 ± 0.01 , much higher than the 1.0 found in Atkinson and Mereu (1992), but closer to the 1.3 found for all of Eastern North America in Atkinson (2004).

The Brune source model was found to be a very good approximation for the source spectrum of small magnitude earthquakes. The two methods of deriving source spectra agree within uncertainties.

Important parameters, such as seismic moment (M_0) and stress drop ($\Delta\sigma$) are derived from the source spectrum of an earthquake. From M_0 , moment magnitude (M after Hanks and Kanamori, 1979) can be calculated. Nuttli magnitude (after Nuttli, 1973) is derived from the time series of the earthquake and is the preferred magnitude scale used by the Geological Survey of Canada (GSC). Empirical relationships between these two magnitude scales are very useful. From the calculated values of this study combined with the values determined in Atkinson (1993), the relationship $M = 1.03 M_N - 0.61$ was determined.

Calculated stress drop values show a log-linear increase with increasing magnitude. This defies the concept of self-similarity, where one would expect constant stress drop for all magnitudes. Many (e.g. Sacks and Rydelek, 1995; Wu et al., 1996; etc.) have theorised that quantization of earthquakes, where earthquake size reaches an absolute minimum, leads to the breakdown of self-similarity. Calculated Brune source radii show a linear increase with increasing magnitude, even at small magnitudes ($M < 3.0$), leaving the cause of the apparent breakdown of self-similarity enigmatic.

Acknowledgements:

The completion of this thesis was possible due to the support and guidance of my supervisor, Dr. Gail Atkinson. Both Bill Shannon and Maurice Lamontagne (GSC Ottawa) gave many helpful hints regarding data acquisition and instrument response calculations. The thesis benefited greatly from discussions over the years with Dariush Motazedian, SanLinn Kaka and Stella Heenan.

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Frequently Used Acronyms

autodrm: Automatic Data Retrieval Manager (see www.seismo.nrcan.gc.ca).

CNSN: Canadian National Seismographic Network (see www.seismo.nrcan.gc.ca).

CSZ: Charlevoix Seismic Zone, approximately 100 km NE of Quebec City.

ECTN: Eastern Canada Telemetered Network. Precursor to CNSN (see www.seismo.nrcan.gc.ca).

IRIS: stands for Incorporated Research Institutions for Seismology (see www.iris.washington.edu). IRIS is a data storage and retrieval facility for most networks in the US.

LLSZ: Lower St. Lawrence Seismic Zone, at the mouth of the St. Lawrence River.

M: represents the moment magnitude, derived from seismic moment according to $\log M_0 = 1.5M + 16.05$ (Hanks and Kanamori, 1979)

MB: represents body-wave magnitude (see www.seismo.nrcan.gc.ca).

ML: represents local or Richter magnitude (see www.seismo.nrcan.gc.ca).

MN: represents Nuttli magnitude determined from the amplitude of the body wave after Nuttli (1973).

POLARIS: stands for Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity. There are roughly 90 stations in the network, in three regions (North West Territories, Southern Ontario and British Columbia). The array of interest in this study is the Southern Ontario array.

WQSZ: Western Quebec Seismic Zone, straddles the Quebec-Ontario border.

1. Introduction

1.1 Purpose

Seismic hazard assessment relies on accurate knowledge of path effects on ground motion. Path effects describe the changes in amplitude with distance, both by means of geometric spreading, the dissipation of energy, and anelastic attenuation, the absorption of energy by the Earth. The purpose of this study is to explore methods of quantifying earthquake path effects, and to determine attenuation within the Charlevoix Seismic Zone (CSZ) of eastern Canada. Data employed are seismograms of small earthquakes ($M_N > 1$, 1999 through 2002) from the Charlevoix Seismic Zone (CSZ), along with slightly larger events ($M_N > 2.5$, 1998 through 2002) from other regions of Eastern Canada.

If the attenuation of seismic waves with respect to distance is known, then the spectrum of earthquake motion near the source can be determined from regional ground motion observations. Both the spectral shape and the absolute level (related to seismic moment) give important information about ground motion processes, leading to better understanding of the seismic hazard. This study determines important source parameters for many small earthquakes, including seismic moment and stress drop.

1.2 Regional Seismicity, Tectonic and Geologic Setting

Although some 90% of seismic activity is related to activity at tectonic plate boundaries (Reiter, 1990), the remaining 10% causes moderate to significant hazard in 'stable' continental regions. Figure 1.1a shows that while the majority of earthquakes within Canada are concentrated on the west coast, eastern Canada (Figure 1.1b) experiences significant seismicity. Moderate-to-large intra-plate earthquakes are generally contained within ancient rift structures, representing breaks in the continuity of the North American plate caused by earlier active tectonic episodes; 71% of $M \geq 5$ events occur within such rift structures (Adams and Basham, 1989 and references therein). Historically, eastern Canada has experienced several such events, including the Grand Banks 1929 (7.2ML), Charlevoix 1925 (6.2MB) and Timiskaming 1935 (6.2ML) earthquakes (all magnitudes from GSC). These events resulted in significant property damage, which would be much greater if they occurred today, due to the increased population density. More recently, several moderate magnitude events (Charlevoix 2003 (4.1MN), Au Sable Forks, NY 2002 ($M5.0$), Cap-Rouge 1997 ($M5.2$), Cote-Nord 1999 (5.1MN), Cornwall-Massena 1944 (5.7ML), Saguenay 1988 ($M5.9$)) have yielded important information about earthquake hazard in eastern Canada. Outside Canada, there are numerous examples of large magnitude earthquakes in intra-continental regions, such as the 2001 Bhuj, India event of $M7.7$ (see CESS India) and the 1811-1812 New Madrid, USA earthquakes of $M \sim 7.5$ (Hough et al., 2000).

Seismic activity in Eastern Canada is clustered in several regions, as shown in Figures 1.1b and 1.2: the Western Quebec Seismic Zone (WQSZ), the Charlevoix Seismic Zone (CSZ) and the Lower St. Lawrence Seismic Zone (LLSZ). There is also an

Figure 1.1a: Seismicity in Canada [1997-2002]

Figure 1.1b: Seismicity in Eastern Canada [1997-2002]

Figure 1.2a: Western Quebec Seismic Zone (WQSZ)

Figure 1.2b: Charlevoix Seismic Zone (CSZ)

Figure 1.2c: Lower St. Lawrence Seismic Zone (LLSZ)

apparent clustering of low-level activity around and beneath Lake Ontario. Just south of the Canadian border, the Au Sable Forks, 2002, $M=5.0$ event occurred within a fault zone described by Daneshfar and Benn (2002) as the Adirondack Highlands (shown in Figure 1.3), viewed by Adams and Basham (1989) as an extension of the WQSZ.

The dominant tectonic structures in eastern North America are associated with the rifting of the Iapetus Ocean, viewed by some as a precursor to the current Atlantic Ocean. The initial rifting took place in the lower Palaeozoic (~540 m.y.a), throughout what is now the St. Lawrence and Ottawa valleys, with the present Atlantic beginning to open during the Cretaceous (Wilson, 1966). Faulting related to the Iapetan rifting episode is recognized by its NE trending strike, the normal faulting and the Proterozoic and Cambrian aged strata affected by the faulting (Wheeler, 1995). Throughout Eastern Canada and the North Eastern United States, Appalachian nappes (Silurian to Ordovician in age, ~490-420 Ma) overlie the Precambrian Grenvillian basement (shown in Figure 1.3), though little seismic activity is observed therein (Wheeler, 1995). The St. Lawrence Rift System (shown in Figure 1.3) is no longer actively rifting but rather is under a high horizontal stress regime, resulting in fault reactivation and hence seismic activity (Kumarapeli, 1976). The rift system took its current form due to a mid-Mesozoic (90-150 m.y.a) phase of rifting. This faulting phase overprints Hadrynian (600-700 m.y.a) faulting, likely related to the Appalachian orogen (Kumarapeli, 1976).

Faulting related to the opening and subsequent closing of the Iapetan Ocean (Lamontagne, 1999) is prevalent throughout the St. Lawrence Rift System, affecting Precambrian strata (Wilson, 1966). The faulted units are overlain by the Appalachian orogeny. The Logan Line, separating the outcropping of the Grenville province from the

Figure 1.3: Important tectonic and geologic features of eastern Canada.

Note that all boundaries are approximate and reflect the amalgamation of information found in Daneshfar and Benn (2002), Kumarapeli (1976), Forsyth (1981), Kumarapeli and Saull (1967) and Lamontagne (1999).

Appalachian nappes, loosely follows the St. Lawrence River. Earthquakes have predominantly thrust mechanisms aligned with the North American stress field (Lamontagne, 1999). Thrust faulting supports the hypothesis that the St. Lawrence rift is not undergoing active spreading, but rather is a pre-weakened zone undergoing a horizontal compressive stress field allowing fault reactivation. Ellsworth (2000) showed fault reactivation to be energetically favourable in the CSZ specifically, but also theoretically favourable in general, even considering zero pore fluid pressure, for faults near alignment with the stress field. Within the CSZ, Ellsworth (2000) found that faults within 10° of the preferred orientation of faults are reactivated. Thus, for many mapped faults within the CSZ, reactivation is possible even at zero pore fluid pressure. Regardless, by increasing pore fluid factor to 0.9, all orientations of faults could be reactivated (Ellsworth, 2000). Thus, for more mapped faults within the CSZ, reactivation is likely. The CSZ and LLSZ are the most seismically active sections of the St. Lawrence Rift System of Kumarapeli (1976).

It is important to note that whereas the St. Lawrence rift structure is the most important feature controlling the location of seismic activity, other structures may or may not influence seismic activity within specific areas. Such structures include the meteorite impact within the CSZ and the complicated geology of the WQSZ, as described below.

The depth determinations of earthquakes within the CSZ place the hypocentres within the Grenvillian aged rocks (depths 8 to 25 km, dipping to the SSE), with a void of earthquake hypocentres in the over-lying Appalachian units (Lamontagne, 1999). The northern riverbank is faulted within a Devonian meteorite impact structure (shown in Figure 1.3), where faults are oriented at a high angle to the faults prevalent in the rift

structure. The largest discrepancy between the dominant strike of focal mechanisms and the fault orientations preferred by the current stress field lie within the impact structure (Lamontagne, 1999). It appears possible the spatial coincidence of the meteorite impact within the rift structure may help localize events within the CSZ. However, the seismically active zone extends beyond the impact structure in both directions along the river. Furthermore, analogous impact structures elsewhere do not show such seismic activity. The CSZ has experienced many of the largest events in Eastern Canada. Six historical events of $M > 6$ have occurred within the CSZ (1663, 1791, 1860, 1870, 1925) as well as several slightly smaller magnitude events, 1939 (5.6MN), 1952 (5.2ML), 1979 (5.0MN), 1986 (4.2MN) (Adams and Basham, 1989 with magnitudes from GSC). Within the CSZ, the well-determined small magnitude earthquakes are concentrated beneath the river (see Figure 1.2b). In the northeastern section of the CSZ, a small region devoid of epicentres exists (Powell et al., 2003).

Earthquake depths within the LLSZ place the hypocentres within the Grenvillian aged basement rock beneath the St. Lawrence River, similar to the CSZ. Thrust focal mechanisms dominate within the region, supporting the theory of reactivation of Iapetan aged faults (Adams and Basham, 1989), as opposed to a gravitationally induced faulting mechanism proposed earlier by Goodacre and Hasegawa (1980). Magnitudes of historical events within the LLSZ are noticeably smaller than those in the CSZ; the largest measured event is the Cote-Nord M5.0 earthquake of 1999 (Lamontagne et al. 2003). Prior to 1999 no $M > 5$ earthquakes had been documented within the LLSZ, despite a similar recurrence rate of M3-4 with respect to the CSZ (Adams and Basham, 1989).

The seismic activity that defines the WQSZ lies within a wide belt, nearly perpendicular to the strike dominant of the geology, consisting of the Central Metasedimentary Belt and the Ontario and Quebec Gneiss belts (Forsyth, 1981). The Morin anorthosite body lies to the east of the Central Metasedimentary Belt and appears to be aseismic (Forsyth, 1981), forming the southeastern boundary of seismic activity (Lamontagne et al., 1994). It has been theorized that the outcropping anorthosite bodies act as stress barriers, instigating the seismic activity in the WQSZ by disturbing the tectonic stress pattern, thus concentrating stress in the surroundings (Lamontagne et al., 1994). Approximate locations of the above mentioned geological boundaries are shown in Figure 1.3. The largest historical earthquake to occur within this zone is the 1990 Mont-Laurier earthquake (m_{bLg} 5.0). Earthquake depths within this region are generally constrained to the 7 to 25 km range, with the Mont-Laurier event occurring at 12 km depth (Lamontagne et al., 1994).

The WQSZ is an offshoot of the St. Lawrence Rift System, perhaps related to a buttressing effect in the Morin anorthosite (Martignole, 1969, Forsyth, 1981). The earthquake locations seem to correlate well with geological and geophysical features, including the marble line described by Forsyth (1981). The WQSZ lies entirely within the Grenville province, striking at an acute angle to the Ottawa River, from where it meets the St. Lawrence River. In direct contrast to the other discrete zones of seismic activity within Eastern Canada, the eastern portion of the WQSZ is not associated with the failed Iapetan-aged rift.

Focal mechanisms of events within the WQSZ differ from those in the remainder of eastern Canada. While the majority of earthquakes in eastern Canada occur on fault

planes striking NE-SW, many in the WQSZ (including the M4.5 Mont-Laurier event of 1990) occurred on an E-W striking plane. The tectonic origin of the WQSZ seismicity remains enigmatic, with the proposal of a hotspot traverse as a mechanism (Adams and Basham, 1989) refuted by Lamontagne et al. (1994). Adams and Basham (1989) cite the presence of two subparallel mountain chains, the Montereian and the New England Seamount, as evidence of the passage of a hotspot between 140 and 120 million years before present. However, Lamontagne et al. (1994) report a seismic void within the Montereian chain and the absence of such a chain within the Metasedimentary belt, where seismicity is focused.

The Ottawa-Bonnechere Graben may represent a western splay of the St. Lawrence Rift System (Kumarapeli and Saull, 1966). Regional seismicity is generally associated with faulting at depth within the graben, with typical focal depths being in the range from 1 to 7 km (Forsyth, 1981). The 5.8 ML Cornwall-Massena event of 1944 may be associated with the graben. The recurrence rates of recent moderate seismic activity are lower within the Ottawa Valley than that of the nearby WQSZ, despite the presence of rift structures within the Ottawa Valley which are generally associated with non plate-boundary seismicity.

The seismicity within the Adirondack Highlands is dominated by reactivated Iapetan aged faulting within a dome of Grenville-aged rock (Seeber et al., 2002). The epicentre of the April 20, 2002 Au Sable Forks (M 5.0) event falls within the Lake Champlain boundary zone, within the exposed Grenvillian aged rock (Seeber et al., 2002). A similar event within the Highlands, although significantly south of the 2002 event, occurred near

the town of Goodnow, October 7, 1983 (M_{bLg} 5.1). Similarity of tectonic environment has been suggested by Seeber et al. (2002) for further study.

1.3 Organisation of Thesis

This study focuses on quantifying the effect of source, path and site on earthquake ground motions in eastern Canada, with emphasis on path effects in the Charlevoix Seismic Zone (CSZ). Chapter 2 will overview the importance and role of source parameters, path effects (including geometric spreading and anelastic attenuation) and site amplification due to the near-surface soil column on observed ground motion. Chapter 3 describes different methods that have been developed in past studies for quantifying source and path effects. Chapter 4 presents data sources used in this research and describes the processing of the seismic data. Chapter 5 presents the source parameters obtained for earthquakes in the CSZ, including comparisons of moment magnitude to Nuttli (1973) magnitude and stress drop observations. Chapter 6 develops a new approach to determining attenuation, with emphasis on the accurate determination of geometric spreading in the CSZ. Chapter 7 presents conclusions.

2. Source, Path and Site Effects

2.1 Spectral Source models

A key objective of engineering seismological research is to compute ground motion at the site of an engineered structure, given the rupture of a fault in the vicinity (Papageorgiou, 2003, after Aki). This appears simple; a fault at distance X from the site may cause a magnitude Y event, producing waves of Z amplitude at the site. However, the controlling elements, involving the effects of source, path and site, are complex processes. A practical approach for many ground motion applications is to characterize the earthquake source by its Fourier amplitude spectrum. Source spectral models describe an idealized (empirical or theoretical) version of the generation of ground motion, as a function of frequency. Several models have been developed to describe the 'engine of an earthquake' in the frequency domain.

To understand the source of an earthquake, understanding of both the rupture process and the beginning of wave propagation is necessary. Two general models for the rupture process are generally accepted as the basis for source spectral models (Papageorgiou, 2003 and references therein). One is a point source model, where rupture begins at a single point and radiates in all directions until the (arbitrary) fault plane limit is met. The other is the Haskell model, where a fault has length and width, with the rupture beginning at one end and propagating to the other over the rise time.

The ω^2 model of Brune (1970, 1971) is the most commonly cited point-source spectral model, due mainly to its simplicity. Brune (1970, 1971) models earthquake dislocation as a tangential stress pulse applied at the fault surface instantaneously at a single point (therefore termed point source). The result is a pure shear stress wave

propagating perpendicular to the fault surface. For points near the fault, displacement increases linearly with time. This function will have a frequency domain spectrum that decays with ω^2 . The functional form of the Brune model (Boore, 1983) is as follows:

$$D(f)=CM_0/[1+(f/f_0)^2] \quad (2.1)$$

where M_0 is the seismic moment in dyne-cm, f_0 is the corner frequency in Hz, and $C=\mathbb{R}_p FV/4\pi\rho\beta^3R$, where $\mathbb{R}_p$ is the radiation pattern (0.55), F is the free surface amplification (2.0), V is the partition onto the horizontal components (0.71), ρ is the crustal density (2.8 g/cm^3 , after Atkinson, 1993), β is the shear wave velocity (3.8 km/s after Atkinson, 1993) and R is the hypocentral distance. The corner frequency f_0 is related to the stress drop by:

$$f_0=4.9*10^6\beta(\Delta\sigma/M_0)^{1/2} \quad (2.2)$$

where f_0 is in Hz, β is in km/s, $\Delta\sigma$ is in bars and M_0 is in dyne-cm (Boore, 1983).

Figure 2.1 illustrates the shape of the Brune source spectral model for earthquakes of M_6 and M_4 (or $M_0= 1.1*10^{25}$ dyne-cm and $1.1*10^{22}$ dyne-cm) respectively, for a stress drop of 150 bars.

The Brune source spectral model is generally accepted for small to moderate magnitude earthquakes, with $M \leq 5$. Since the fault dimensions required to generate earthquakes of this size are of the order of 1 km^2 or less, the point source assumption is reasonable. For larger earthquakes, a source spectral model having two corner frequencies was proposed (Atkinson, 1993). The impetus for this development was the misfit of the Brune source model shape to the computed source spectrum of the Saguenay earthquake of 1988 as well as other moderate magnitude earthquakes in ENA (Atkinson, 1993). In the two-corner model the lower corner frequency relates to the overall fault

Figure 2.1a: Comparison of Brune (1970) Source Model and Two-Corner model (Atkinson, 1993) for Moment Magnitude 6, $\Delta\sigma=150$ bars.

Figure 2.1b: Comparison of Brune (1970) Source Model and the two-corner model (Atkinson, 1993) for Moment Magnitude 4, $\Delta\sigma=150$ bars. The models are practically equal at this magnitude.

rupture duration, similar to the corner frequency of the Brune model. The higher of the two corner frequencies relates to localized source complexity (barriers, asperities, etc.) (Atkinson, 1993). Atkinson (1993) made use of a database of $4 \leq M \leq 7$ events in eastern North America (ENA), to empirically determine a relationship for the corners:

$$\log f_A = 2.41 - 0.522M \quad (2.3)$$

$$\log f_B = 1.42 - 0.188M \quad (2.4)$$

and the functional form of the source spectrum is then:

$$A(f) = C(2\pi f^2)M_0 \left\{ (1-\epsilon)/[1+(f/f_A)^2] + \epsilon/[1+(f/f_B)^2] \right\} \quad (2.5)$$

where $\log \epsilon = 2.52 - 0.637M$, again determined empirically (Atkinson, 1993).

Figure 2.1a shows the differences between the two models for the arbitrary $M6$ event and similarly Figure 2.1b shows the $M4$ event. It is obvious from Figure 2.1b why this model is generally considered only for $M > 4$, as the two models are nearly identical at $M4$. Furthermore, $\log f_A = \log f_B$ for $M = 3$, and the two-corner model reduces to the Brune model.

The two-corner model has also been shown to provide a better fit to Californian earthquakes of $M \geq 6$ than the Brune point source model (Atkinson and Silva, 1997). Furthermore, work in determining the basis for the two corner shape suggests that the source spectra may be similar for both ENA and western North America (Beresnev and Atkinson, 2002); the presence of two corners in both tectonic settings can be explained by finite fault effects. By dividing the ruptured fault into many subfaults, spectral amplitudes are large at high frequencies due to the high corner frequencies of ground motion on the subfaults, while at low frequencies spectral amplitudes are constrained by the seismic moment (Beresnev and Atkinson, 2002); at intermediate frequencies there is

an apparent sag. The subfault size determines the location of the 'sag' within the earthquake spectrum. An empirical method of specifying appropriate subfault size has been explored in Beresnev and Atkinson (1999, 2002).

The main difference between the Brune source model and the Haskell model is the assumed means of applying initial stress. The Haskell model assumes a trapezoid-shaped stress input applied over the rise time (τ) on a fault with both length and width. Because it has both length and width, the Haskell model results in two corner frequencies, with an intermediate spectral slope proportional to frequency.

The events considered within this study are of sufficiently small magnitude to adopt the Brune model exclusively, with the exception of the 2002 Au Sable Forks event. In that specific instance, the two-corner model will also be considered.

2.2 Path effects

The second element required to predict ground motion is the attenuation of seismic waves with distance. In a homogeneous elastic half-space, the decay of wave amplitude with distance is a trivial calculation. However the earth is highly heterogeneous, with a complex internal structure, leading to complex and stochastic wave propagation, especially at high frequencies. Thus, empirical models of attenuation are often required.

The dissipation of wave energy with distance (volume effect) is termed geometric spreading. In the simplest of earth models (perfect elasticity), this is the only amplitude reduction. Geometric spreading is generally modeled according to R^{-B} where B is typically ~ 1 for direct waves ($R < 70$ km) and 0.5 for surface waves in an elastic half-space. Geometric spreading is generally considered to be frequency independent.

The reduction in amplitude due to the loss of energy during travel through the Earth is termed anelastic attenuation. Since the earth is not perfectly elastic at seismic frequencies, some wave energy is lost. Anelastic attenuation is frequently modeled according to $\exp(-\gamma R)$ where γ is the coefficient of anelastic attenuation, of the form $\gamma = \pi f / Q\beta$ with a typical range of $0 < \gamma < 0.004$. Q is the quality factor, a term borrowed from electric circuit theory (O'Connell and Budiansky, 1978), β is the shear wave velocity, and f denotes frequency.

The quality factor is generally determined empirically, typically modeled as:

$$Q(f) = Q_0 (f/f_0)^\eta \quad (2.6)$$

where f_0 is the reference frequency, Q_0 is the quality factor at the reference frequency and η is assumed constant within the bandwidth of interest (Benz et al., 1997).

For eastern North America, noticeable effects of anelastic attenuation are generally observed at distances greater than 150 km (Hanks and Johnston, 1992). This is in direct contrast to the observations made in more active regions, such as the western US, where anelastic attenuation greatly reduces amplitudes, even at short distances. The strong motion that results from moderate to large events ($M > 5$) is therefore felt over a much wider area in eastern North America than in the west.

In addition to the effects of geometric spreading and anelastic attenuation, the propagation of ground motion within the real Earth is complicated by Earth structure. The most important complicating factor of propagation at regional distances is the Mohorovicic discontinuity (Moho), separating the crust from the upper mantle. The change in velocity and density at the Moho generates a strong reflection (“the Moho bounce”) as well as refraction of the seismic waves. Figure 2.2 (from Ou and Hermann, 1990) shows how waves reflected at the Moho add at the receiver. In Eastern Canada, the effect of the Moho bounce is generally observed in the form of higher than expected amplitudes measured at stations in the distance range from 70-130 km (Atkinson and Mereu, 1992). Similar effects have been observed in the US, both east and west, although at somewhat differing distance ranges (see Somerville and Yoshimura, 1990).

Burger et al. (1987) show that the most likely reason for the large amplitudes at certain distance ranges is the postcritical reflection of S waves at the Moho. Postcritical reflection implies complete reflection, with zero energy dispersed to the mantle. This reflected energy is then added to the direct wave, causing an overall increase in observed amplitude. The critical distance at which the Moho bounce produces a strong amplitude effect depends on focal depth, crustal thickness and the shear wave velocity gradient

Figure 2.2: Figure A1 from Ou and Hermann (1990). Ray diagram illustrating the reflection of waves adding at the receiver for a typical eastern North America crustal structure.

(Burger et al., 1987).

The effects of the Moho bounce are obvious in the tri-linear attenuation curves of Atkinson and Mereu (1992), proposed as an empirical model of amplitude decay in ENA, as shown in Figure 2.3. At distances between 70 km and 130 km, the Moho reflections cause the flattening of the attenuation curve. In addition to creating a reflected phase, the Moho can create a waveguide within the crust, further complicating the travel path of earthquake waves. A waveguide is generally considered to consist of two impenetrable surfaces through which any type of wave travels by means of multiple reflections. Depending on the properties of the waveguide, wave velocity and amplitude may or may not be conserved. Specifically, multiple reflections of the L_g phase of earthquake waves within a crustal waveguide have the effect of postponing the peak arrival, amplifying the peak and increasing the group velocity (Bowman and Kennett, 1991). In the North Australian Craton study of Bowman and Kennett (1991), a velocity gradient is deemed a more likely cause of the observed multiple reflections than the more traditional view of two reflecting discontinuities. However, the net results are not affected by this initial condition, as the same effect on amplitudes is still observed. Typically, geometric spreading of L_g in the crustal waveguide is described by $R^{-0.5}$ attenuation in the frequency domain, although in practice it is difficult to distinguish between geometric spreading and anelastic attenuation (Atkinson and Mereu, 1992).

Figure 2.3: Figure 5 from Atkinson and Mereu (1992). The tri-linear empirical model describing observed decay of spectral amplitudes. Note the effect of the Moho bounce at ~ 100 km. Symbols show mean normalized amplitudes and their stand errors.

2.3 Site effects

Soil deposits at a recording site may amplify incoming wave amplitudes relative to those of underlying bedrock due to changes in seismic impedance, which is the product of density and shear wave velocity. The amplification is strongest at frequencies for which resonance is established; the conditions for resonance depend on soil depth. Both impedance and resonance effects have been well documented for simple models, such as a layered earth model (e.g. Shearer and Orcutt, 1987). Further complicating factors may include interface topography and basin effects (Shearer and Orcutt, 1987; Frankel and Vidale, 1992). Although rock sites are generally sought for seismographic instrument installations, site amplification must still be considered as siting on soil is sometimes necessary. Furthermore, even rock sites are subject to amplification due to near-surface weathering (Boore and Joyner, 1997).

The quarter wavelength approximation (Joyner et al., 1981) may be used to estimate site amplification where the shear wave velocity profile is known (either from borehole data or other techniques). The velocity and density differences with depth may be related to either the presence of soil or the presence of fractures within the rock (Boore and Joyner, 1997). The amplification factor is given by:

$$A[f(z)] = [\rho_s \beta_s / \rho(z) \beta(z)]^{1/2} \quad (2.7)$$

where the subscript s represents the values near the earthquake source. The values in the denominator are averages over the column that comprises the quarter wavelength down from the surface (Boore and Joyner, 1997). The quarter wavelength depth was chosen to best fit observations in the Joyner et al. (1981) study, but appears to

be transportable to other regions (e.g. Boore and Joyner, 1997), with theoretical basis explored by Day (1996).

Boore and Joyner (1997) used the quarter wavelength approach to calculate amplification for typical sites in both eastern and western North America, where the site profiles were based on borehole data. Typical hard rock ENA sites, scoured by glaciation, produce low amplification (about a factor of 1.15). In contrast, typical Californian sites amplify motions by a factor of >2 .

The quarter wavelength approach has also been modified to encompass two-wave travel time profile (Day, 1996) instead of a complete density and shear wave profile. The crustal structure beneath the site is assumed to be a perfectly elastic (infinite Q) layered model with excitation incident from an underlying uniform half-space. Although the assumed structure appears unrealistic for the real earth, this method has none-the-less reproduced surface spectral amplification observations (Day, 1996).

As seen in the previous discussion, most methods of determining the site response require knowledge of the crustal density and wave velocity structure beneath the site in question. However, it is generally accepted that the vertical component experiences much less amplification than the horizontal components. Thus the ratio of the horizontal component to the vertical component (H/V) is often adopted as a crude estimate of the site response. This does not have sound theoretical justification, but appears to be justified empirically in many instances (e.g. Nakamura, 1989; Lermo and Chavez-Garcia, 1993; Beresnev and Atkinson, 1998; Atkinson and Cassidy, 2000). Where no site profile data exist, the H/V ratio provides a crude estimation of site effect, which may be reasonable for simple site conditions. Siddiqi and Atkinson (2002) use H/V ratios to

suggest near zero amplification for most eastern CNSN stations, as expected for hard rock sites. It is important to note that A61 (Sainte Mathilde, Quebec, in the Charlevoix array) experiences a maximum amplification factor of nearly 4, much higher than expected for hard rock sites. Siddiqi and Atkinson (2002) theorize that the local geology in the surrounding area, a pocket of marine sediments, may influence the site.

3. Empirical Methods of Determining Source, Path and Site Effects

3.1 Empirical Methods of Determining Attenuation

There are several means of determining the overall effect of attenuation of ground motion amplitudes with distance from empirical data, although distinguishing between geometric attenuation and anelastic attenuation is not trivial. Many methods yield only a general overall description of the net effect of attenuation on amplitude. Most methods cannot provide a unique solution to the available data. Empirical methods may make use of a large dataset, through regression with distance or simultaneous inversion of source and path effects. Alternatively, studies may be based on smaller datasets using spectral division to isolate attenuation for specific paths. Ideally, attenuation results obtained from these varied approaches should be broadly similar.

Atkinson and Mereu (1992) use regression of amplitudes versus distance for a large eastern North American dataset to detail the change in amplitude with distance. The dataset comprised approximately 100 events recorded on the Eastern Canada Telemetered Network (ECTN). The dataset was mostly vertical component records and the few horizontal recordings were normalized to the vertical component after Boore and Atkinson (1987). Each event was recorded at several distances and azimuths. Atkinson and Mereu (1992) normalized all spectral observations to a common source level. Regression was then used to determine the best fit to a tri-linear curve, including the best transition distances. Atkinson and Mereu (1992) find that attenuation of Fourier spectral amplitudes with distance can be described by the tri-linear form shown in Figure 2.3. The tri-linear form is described by $1/R$ geometric spreading for $R < 70$ km, R^0 for $70 < R < 150$ km, resulting from the Moho bounce and $R^{-0.5}$ for $R > 150$ km, which is a

widely accepted geometric spreading coefficient for observations at large distances where surface wave spreading predominates (e.g. Chun et al., 1987). The associated anelastic attenuation is given by $Q=670f^{0.33}$, where Q is inversely proportional to the anelastic attenuation coefficient. Note that there is a trade-off between geometric spreading and anelastic attenuation. Therefore, the data could also be fit with a somewhat different model for geometric spreading with a different associated Q .

An inversion scheme results in the best-fit model for two of the three functions describing observed ground motion; source effects, propagation effects and site effects. By assuming a functional form for each of these functions, changes in absolute value are iteratively made to achieve the least variation from observed data. Specifically, Andrews (1986) proposed the decomposition of body wave spectra to:

$$U(f)=(1/R) m'(f) s(f) \quad (3.1)$$

where $1/R$ represents geometric spreading (assumed $R<70$ km, may be changed to match Atkinson and Mereu (1992) decay scheme), $m'(f)$ is the moment rate spectrum and $s(f)$ is the site response function. The Andrews (1986) model does not constrain the source spectra. Boatwright et al. (1991) refined the method by using the Brune model as a constraint on the source spectrum. Following the iterative scheme, the seismic moment and stress drop for each event in the study were determined such that the least variation from observed data was obtained. The result of the Boatwright et al. (1991) study is a method that allows discrimination of the site, source and path effects by assuming the general shape of the source spectrum and inverting observed spectra to determine seismic moment and corner frequency. Many significantly different solutions will result in equal variations. Poorly recorded events result in a non-uniqueness of the solution. It is also

important that the observations be radially varied, as data skewed towards a particular azimuth will not reflect the net attenuation observations.

Another approach to determining attenuation involves simultaneously resolving a combination of source, site and path effects. Various schemes exist; in all cases one of the three terms must be assumed as a constraint. A general scheme, such as the genetic algorithm given by Moya et al. (2000), is to choose an introductory model for one of the two target terms, use the assumed model of the third to calculate the second term and refine the introductory model to minimize the variation of target term. For instance, Moya et al. (2000) choose the source mechanism (Brune source spectral model) to compute the site effects given a Q value for Kobe, Japan. By iteratively changing the source model to achieve the most stable site response function (e.g. smallest variation between sites), the site response and source model are simultaneously achieved. The simplest methods require drastic assumptions: for instance, site response must be invariant over all recording stations in the Xie (1998) study.

All of the methods discussed above have the shortcoming of neglecting radiation pattern and directivity effects; it is implicitly assumed that these effects average out over many stations and events, and therefore only contribute to the overall scatter. A method that resolves this shortcoming involves spectral division to eliminate source and site effects (e.g. Chun et al., 1987). The frequency domain function of observed spectra can be expressed as:

$$\Omega_{\text{obs}}(f, R) = \Omega_{R=1} P(f, R) S(f) I(f) \quad (3.2)$$

where Ω represents the displacement spectrum, P represents the path effects, S represents site effects and I represents the instrument response function. Instrument

response is assumed to be well defined and therefore easily removed. Hence it is not difficult to isolate different portions of the observed ground motion by appropriate spectral division. Specifically, Chun et al. (1987) isolated attenuation by assuming that the path effects have the form $R^{-b}\exp[-\gamma R]$. Then, they formulated the following Reverse-Two Station Method (RTSM) to isolate anelastic attenuation (γ), assuming $b=0.5$ for distances > 150 km. The idea behind this formulation is that specific paths can be isolated from the region (i.e. between two recording stations). By taking the spectral ratio, the source spectrum of the two events is removed from the calculation and the site effects are similarly removed. Thus, we can write for the i^{th} event and the j^{th} station:

$$\begin{aligned} \frac{\Omega_{11}\Omega_{22}}{\Omega_{12}\Omega_{21}} &= \frac{\Omega_{1(R=1)}(f)P(f, d_{11})S_1(f) \cdot \Omega_{2(R=1)}(f)P(f, d_{22})S_2(f)}{\Omega_{1(R=1)}(f)P(f, d_{12})S_2(f) \cdot \Omega_{2(R=1)}(f)P(f, d_{21})S_1(f)} \\ &= \frac{P(f, d_{11}) \cdot P(f, d_{22})}{P(f, d_{12}) \cdot P(f, d_{21})} \\ &= \left(\frac{d_{11}d_{22}}{d_{12}d_{21}} \right)^{-B} \exp[-2\gamma\Delta] \end{aligned} \quad (3.3)$$

where Ω_{ij} represents the displacement spectrum, $\Omega_{i(R=1)}$ represents the source spectrum, d_{ij} is the hypocentral distance, P represents the path effects, S_j is the site effects function, B is the geometric spreading coefficient, γ is the anelastic attenuation coefficient and Δ is the station separation. Figure 3.1 illustrates the geometry.

Given knowledge of the geometric spreading (e.g. Atkinson and Mereu, 1992), this method can be extended to observations at distances less than 150 km. A modified version of this method is used for this study, as described in Chapter 6.

Figure 3.1: Figure 4 of Chun et al. (1987). Schematic drawing of station pair and the relationship to event pairs, where PR is the product of two spectral ratios.

3.2 Methods of determining source spectra

3.2.1 Direct Method

If we can determine the average regional values of attenuation, both geometric spreading and anelastic attenuation, observed spectra can be ‘corrected’ back to the source, by applying the appropriate values to:

$$\Omega_{\text{source}}(f) = \Omega_{\text{OBS}}(f) R^B \exp(\gamma R)/S(f) \quad (3.4)$$

where Ω_{OBS} is the observed spectrum, Ω_{source} is the source spectrum, B is the coefficient of geometric spreading, γ is the coefficient of anelastic attenuation and $S(f)$ is the site effects.

This correction results in an approximation of the source spectrum of the particular earthquake (Boore and Atkinson, 1987). It is important to have earthquakes located inside the network of recording stations, as the regional values of attenuation assume that directivity and radiation pattern effects will average out over a number of azimuths.

For the purposes of this study direct estimates of the source spectrum for selected events within the dataset are made assuming geometrical attenuation is given by the tri-linear amplitude decay scheme of Atkinson and Mereu (1992) as described in section 3.1, with generally accepted ENA values for $\gamma = \pi f / \beta Q$ (coefficient of anelastic attenuation), where Q is the quality factor given by $Q = 680f^{0.36}$, with $\beta = 3.8$ km/s (shear wave velocity), f is the frequency in Hz and $S(f)$ is given by the H/V ratios of Siddiqi and Atkinson (2002). The method used to select specific events will be discussed in Chapter 4.

Results from the direct method were then compared to the Brune source model, to determine seismic moment, and hence moment magnitude, as well as the stress drop. Findings from this method will be discussed in Chapter 5.

3.2.2 Empirical Green's Function Method

A Green's function is the response of a system to an impulsive change to the system (Butkov, 1968 section 12.1). In seismological studies, the system is the Earth and the impulsive change to the system is an earthquake. The Green's function is the Earth's impulse response, where a small earthquake is typically assumed to represent an impulse. Many authors (beginning with Hartzell, 1978) have made use of smaller magnitude events to represent the Earth's response to a larger magnitude earthquake.

The technique has been applied to Californian events (see Hough et al., 1991; Hough, 1997) and to ENA events (see Mueller, 1985; Haddon, 1996; Sonley and Atkinson, 2001; Atkinson and Sonley, 2003). The underlying idea is that the Fourier spectrum of an 'EGF' event differs from the 'target' or 'mainshock' event spectrum only due to differences in source parameters. Both mainshock and EGF ground motion observations have the form of Equation 3.2. The path effects will be identical for co-located events and the site effects are identical when observations are made at the same site. Hence, taking the ratio of the observed spectra of the target event to the EGF event will eliminate the path and site effects:

$$\frac{\Omega_{\text{MAIN}}(f,d)}{\Omega_{\text{EGF}}(f,d)} = \frac{\Omega_{\text{MAIN}}(d=1) P(f,d) S(f)}{\Omega_{\text{EGF}}(d=1) P(f,d) S(f)}$$

$$= \Omega_{\text{MAIN}, R=1/\text{EGFLEVEL}} \quad (3.5)$$

where EGFLEVEL is the long period displacement Brune model level of the EGF event, Ω_{MAIN} is the mainshock spectrum, $P(f,d)$ represents the path effects and $S(f)$ represents the site effects.

The spectral ratio provides the source spectrum of the mainshock, when normalized with the long-period level of the EGF event, since the EGF event is

sufficiently small such that its corner frequency lies above the bandwidth of interest (and hence $\Omega_{\text{EGF}(d=1)}$ is constant).

The application of the EGF method requires co-located events as well as identical focal mechanisms. Co-located events ensure that the earthquake waves have traveled the same path. Identical focal mechanisms ensure an identical radiation pattern. Similarity of waveform can be used as a secondary check in conjunction with co-location where focal mechanisms are not available (Lamontagne, 1999). Furthermore, where significant directivity or reflected energy is observed in the mainshock, the method may pose difficulties (Mueller, 1985).

Aftershocks are frequently targeted for use as EGF events, although they are not always suitable. Aftershocks are frequently located all along the fault plane of the mainshock meaning significant location differences may be present. As well, the focal mechanism may have changed. It is not necessary to only consider aftershocks for EGF events, as small co-located events with similarity of waveform (and hence similarity of focal mechanism) are suitable, though they may be vastly separated in time, before or after the mainshock.

The bandwidth of the EGF method is limited. Noise contamination and suspect instrument response (to be discussed in Chapter 4) at long periods produces unreliable data at long periods as shown in Figure 3.2. At frequencies above the corner frequency, the displacement spectrum of the smaller event is no longer flat, as shown in Figure 3.2, and cannot be used to normalize the ratio. Only where the EGF spectrum is flat can the normalization of the spectral ratio be considered. Fortunately, EGF events are of small magnitude, with typically large corner frequencies.

Figure 3.2: Typical EGF source spectrum. For normalization in EGF method, bandwidth is limited by noise contamination and EGF corner frequency. (Data from event 00/08/01 04:27, 1.9 MN). In this case the available bandwidth for the EGF method is 2 to 12 Hz.

Within the dataset, to be discussed later (Chapter 4), several groupings (multiplets after Lamontagne, 1999) have been identified through location proximity. Visual determination of waveform similarity assured that these multiplets meet the conditions required to term the smaller magnitude events EGF events. Spectral ratios were then calculated for each grouping, determining the source spectrum of the largest magnitude event within the group for comparison with the Direct method results. Results are presented and discussed in chapter 5.

4. Data for this Study

4.1 Available Data

The Geological Survey of Canada (GSC) produces a web listing of all earthquakes occurring within Canada, which includes most of the large events in the northeastern United States (www.seismo.nrcan.gc.ca). Based on this list, ~350 earthquakes of magnitude greater than 1 (either ML or MN) occurred in the CSZ between June 1999 and April 2002, as shown in Figure 4.1. Seismographic waveform data for these events were collected for the three component, seven-station array in the CSZ. In addition, for all events greater than MN3.0 between May 1998 and November 2002 (~250 events) as shown in Figure 4.2, data were collected for all stations of the Canadian National Seismographic Network (CNSN) within a reasonable distance (1000 km for $MN < 3.5$, 2000 km for $MN > 3.5$). Date, time, magnitude and GSC locations for events used in this study are listed in Appendices 1A and B for the extended CSZ set and the larger magnitude dataset respectively. Stations from which waveform data were obtained are listed in Table 4.1.

Seismograms collected at a recording site are amplified and digitized on site. The seismometer and digitizer convolve the incoming seismic wave with their own transfer functions, termed instrument response. For all instruments in this study, the instrument response curves are well determined. The instruments measure velocity, and the velocity response curve is flat with respect to frequency over some bandwidth. Short-period instruments have flat instrument response over the high frequency (or short periods) band (1-40 Hz). Broadband instruments have flat response over a greater bandwidth, extending to lower frequencies (typically a flat response from 0.05 – 30 Hz).

Figure 4.1: Charlevoix Seismic Zone; inset Eastern North America. Open circles are study event locations as given in Appendix 3. Triangles are Charlevoix Array stations.

Figure 4.2: Event locations in Eastern North America. Circles represent event locations. Triangles represent CNSN stations.

Station Name	Type	Lat	Long	Location	Notes
A11	CMG-3R	47.242	-70.198	St. Roch De Aulnaies, QUE	Broad Band, effective 09/2000
A11	S-13	47.242	-70.198	St. Roch De Aulnaies, QUE	Short Period, until 09/2000
A16	CMG-3R	47.471	-70.006	Riviere Ouelle, QUE	Broad Band, effective 09/2000
A16	S-13	47.471	-70.006	Riviere Ouelle, QUE	Short Period, until 09/2000
A21	CMG-3R	47.704	-69.69	St. Andre, QUE	Broad Band, effective 09/2000
A21	S-13	47.704	-69.69	St. Andre, QUE	Short Period, until 09/2000
A54	CMG-3R	47.457	-70.412	Misere, QUE	Broad Band, effective 09/2000
A54	S-13	47.457	-70.412	Misere, QUE	Short Period, until 09/2000
A61	CMG-3R	47.693	-70.09	Sainte Mathilde, QUE	Broad Band, effective 09/2000
A61	S-13	47.693	-70.09	Sainte Mathilde, QUE	Short Period, until 09/2000
A64	CMG-3R	47.826	-69.892	Saint-Simeon, QUE	Broad Band, effective 09/2000
A64	S-13	47.826	-69.892	Saint-Simeon, QUE	Short Period, until 09/2000
CNQ	S-13	49.302	-68.074	Cote-Nord, QUE	Short Period
CRLO	S-13	46.038	-77.38	Chalk River, ONT	Short Period
DAQ	S-13	47.964	-71.243	Lac Daran, QUE	Short Period
DPQ	S-13	46.68	-72.77	St-Jean_Des-Piles, QUE	Short Period
EEO	S-13	46.641	-79.073	Eldee, ONT	Short Period
GAC	S-13	45.703	-75.478	Glen Almond, QUE	Short Period
GAC	STS-1	45.703	-75.478	Glen Almond, QUE	Broadband
GRQ	S-13	46.607	-75.86	GrandRemous, QUE	Short Period
GSQ	S-13	48.914	-67.111	Grosses-Roches, QUE	Short Period
ICQ	S-13	49.522	-67.272	Islets-Caribou, QUE	Short Period
LMN	CMG-3E	45.852	-64.806	Caledonia Mtn, NB	Broad Band
LMQ	CMG-3E	47.548	-70.327	La Malbaie, QUE	Broad Band
MNQ	S-13	50.533	-68.774	Manicouagan, QUE	Short Period
MNT	S-13	45.502	-73.623	Montreal, QUE	Short Period
MOQ	S-13	45.312	-72.254	Mont-Orfor, QUE	Short Period
OTT	S-13	45.394	-75.717	Ottawa, ONT	Short Period
SADO	CMG-3E	44.769	-79.142	Sadowa, ONT	Broad Band
SMQ	S-13	50.222	-66.703	Ste-Marguerite, QUE	Short Period
TRQ	S-13	46.22	-74.556	Mont-Tremblant, QUE	Short Period
WBO	S-13	45	-75.275	Williamsburg, ONT	Short Period

Table 4.1: Station seismometer names, locations and instrument types

The sampling rate influences the upper frequency limit of the data. Signal cannot be recovered above the Nyquist frequency (half the sampling rate). Short period instruments generally have a high sampling rate (100 samples/s), while the broadband instruments typically have a sampling rate in the range from 40 to 100 samples/s. The newer installations in the Charlevoix array have a sampling rate of 100 samples/s, as do the POLARIS stations. For simplicity the lowest Nyquist frequency, 20 Hz, was used as the upper frequency bound for this study. Most short-period stations measure only the vertical component of motion, while most broadband stations were installed as three component stations; north-south, east-west and vertical. Figure 4.3 shows examples of the instrument response for various instruments used in this study.

The CNSN is comprised of both short-period stations with S-13 seismometers (e.g. A11EHE in Figure 4.3) and broadband stations with CMG-3E/R seismometers (e.g. GACBHE in Figure 4.3). Other seismometer types are also sometimes used, as indicated in Table 4.1. It is important to note that the 6 short period instruments located in the CSZ (A11, A16, A21, A54, A61, A64) were short period instruments prior to October 2000, but were replaced with broadband instruments in 2000 (see A11BHE in Figure 4.3). Since the instrument change spans the dataset for this study, both response curves must be considered for these stations, depending on the data of the event. The data from the Incorporated Research Institutions for Seismology (IRIS) archive, which stores data from various networks including United States National Seismographic Network (USNSN), the Lamont-Doherty Cooperative Seismographic Network (LCSN), etc., as well as the POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity) Southern Ontario array, were added to the CNSN data for the April 20, 2002

Figure 4.3: Instrument Response Curves for some representative stations.

A11EHE is pre-October 2000, A11HHE is post-October 2000 (see text for explanation).

A11, CRLO and LMQ are CNSN (Canadian National Seismographic Network) stations, ACTO is a POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity) station, ACCN is a LCSN (Lamont-Doherty Cooperative Seismographic Network) station and AAM is a USNSN (United States National Seismographic Network) station.

M5.0 event in Au Sable Forks, New York and its aftershock sequence. The locations of relevant stations for this event are shown in Figure 4.4, after Atkinson and Sonley (2003). Data used for this event were broadband, three component instruments, with examples of the instrument response curves for each network shown in Figure 4.3.

Several groups of events that are co-located and have similar waveforms, termed multiplets (after Lamontagne, 1999), were identified within the CSZ dataset. The EGF method was applied to determine source spectra for such events (section 5.2), where the largest event within the multiplet exceeded magnitude 2.0MN. The direct method was also applied to these data for two reasons: 1) to determine the long-period displacement level of the Brune model for the EGF events and 2) to enable comparison of the source spectra determined by the two methods. In addition to the events that are part of the multiplets, the direct method was used to compute source spectra for all events of magnitude $>2.0\text{MN}$.

Figure 4.4: Figure 1 of Atkinson and Sonley (2003). Location of Au Sable Forks earthquake of April 20, 2002, M5.0 and stations from both Canadian and US networks.

4.2 Data Processing

Waveform data were collected from the GSC autodrm, from which the S (secondary, shear) wave and P (primary, compressional) wave windows were selected. The selections were made such that the S wave window begins with the onset of an S-phase, and includes the largest ground motion amplitudes, as shown in Figure 4.5. For the selected time window, the Fortran program AGRAM was used to calculate and remove instrument response, perform the Fourier transform and perform the transformation from velocity to displacement. AGRAM is a program originally written by Atkinson (1993), that has been modified as required over the years by various collaborators. The AGRAM program performs the following steps:

- 1) Read data;
- 2) Windows the signal and noise. The signal window is user selected (see Figure 4.5 in which B and C mark the beginning and end of the S window respectively), the noise window is selected as 10 seconds prior to the P window start time;
- 3) Removes glitches and DC trend if any. Glitches are spikes in the waveform that are most likely due to electronic instrument noise. The program removes points that are more than 10 times larger than the log average of the past 20 data points. A DC trend shifts the zero amplitude level above or below the instrumental zero;
- 4) Pads the time series. To compute the fast Fourier transform, the number of data points must be a power of 2 (e.g. 2^N). The padding is accomplished by adding extra zeros to the end of the time series file;
- 5) Converts real data to a complex number array;
- 6) Computes the fast Fourier transform;

Figure 4.5: Waveform for event 990812a

Figure 4.5: Waveform for event 990812a

Figure 4.5: Waveform for event 990812a

- 7) Removes instrument response by dividing the complex transfer function in the frequency domain. The velocity spectrum is also transformed to the acceleration spectrum in the frequency domain by multiplication by ω ;
- 8) Lightly smoothes the Fourier spectrum using 3 point smoothing;
- 9) Calculates the epicentral distance;
- 10) Assigns a flag value (9.99) to frequency bins where no data are available;
- 11) Outputs Fourier acceleration spectral amplitudes averaged over selected frequency bins. In this study frequency bins of 0.1 log units in width were used.

Table 4.2 gives the output of AGRAM for Figure 4.5 for the S wave window only. For all events in this study, the S wave window is used exclusively.

The earthquake signal must be larger than the background noise (instrumental, cultural and natural) to be considered a reliable signal. A signal to noise ratio of 2 or greater was chosen as the acceptable threshold. The signal to noise ratio is calculated using the pre-event noise window, normalized to the same length as the signal window. All spectral data in this study where the signal to noise ratio less than 2 were eliminated from all calculations.

There is an additional instrument response problem, related to the sensitivity for signals near the lowest levels that the instrument can record (Atkinson, 2004). As shown on Figure 4.6a-d, the attenuation of amplitudes appears to be magnitude dependent, with small events showing almost no attenuation at lower frequencies (i.e. Figure 4.6a, at 1 Hz). This occurs because the instruments are not capable of distinguishing amplitude over the entire frequency band at these low ground motion levels. The threshold distances within which the data are reliable are inferred from inspection of figures such as

Freq	A21EHZ	A21EHN	A21EHE	A54EHZ	A54EHN	A54EHE	A61EHZ	A61EHN	A61EHE
0.1	-3.096	-3.375	-3.077	-3.881	-3.764	-3.535	-3.176	-3.277	-3.354
0.126	-3.143	-3.458	-3.131	-3.602	-3.799	-3.765	-3.192	-3.29	-3.347
0.158	-3.382	-3.587	-3.365	-3.408	-3.414	-3.784	-3.457	-3.6	-3.486
0.2	-3.089	-3.211	-3.395	-3.615	-3.547	-3.583	-3.493	-3.248	-3.379
0.251	-3.332	-3.35	-3.453	-3.321	-3.77	-3.523	-3.485	-3.393	-3.569
0.316	-3.51	-3.752	-3.54	-3.856	-3.99	-3.655	-3.758	-3.741	-3.564
0.398	-3.867	-3.91	-3.913	-4.164	-3.908	-4.087	-4.339	-3.98	-3.991
0.501	-4.299	-3.952	-4.028	-4.139	-4.27	-4.451	-4.568	-4.209	-4.246
0.631	-4.201	-4.408	-4.358	-4.56	-4.213	-4.278	-4.721	-4.444	-4.352
0.794	-4.273	-4.568	-4.422	-4.605	-4.274	-4.608	-4.654	-4.371	-4.157
1	-4.063	-4.2	-4.496	-4.51	-4.262	-4.547	-4.46	-4.43	-4.099
1.259	-3.872	-3.885	-4.404	-4.388	-4.049	-4.594	-4.6	-4.463	-4.106
1.585	-3.858	-3.982	-3.997	-4.062	-3.984	-4.157	-4.377	-4.199	-3.911
1.995	-3.657	-3.521	-3.714	-4.046	-4.256	-4.078	-4.27	-3.754	-3.756
2.512	-3.34	-3.393	-3.294	-3.874	-3.577	-3.891	-4.034	-3.584	-3.502
3.162	-3.025	-3.058	-3.11	-3.646	-3.341	-3.516	-4.136	-3.419	-3.431
3.981	-2.849	-2.794	-2.925	-3.241	-3.39	-3.253	-3.853	-3.465	-3.4
5.012	-2.804	-2.634	-3.033	-3.183	-3.134	-3.25	-3.641	-3.295	-3.18
6.31	-2.667	-2.578	-2.94	-2.78	-2.772	-3.018	-3.511	-3.105	-2.84
7.943	-2.592	-2.564	-2.527	-2.665	-2.756	-2.927	-3.431	-2.66	-2.431
10	-2.501	-2.357	-2.523	-2.392	-2.575	-2.469	-3.116	-2.467	-2.474
12.589	-2.6	-2.225	-2.509	-2.498	-2.548	-2.382	-3.067	-2.288	-2.264
15.849	-2.66	-2.408	-2.261	-2.386	-2.345	-2.337	-2.769	-2.165	-2.134
19.953	-2.558	-2.414	-2.321	-2.047	-2.179	-2.155	-2.684	-2.019	-2.007

Table 4.2 Agram S window signal, accompanies Figure 4.5

Output is log Fourier acceleration in cm/s.

Event: 1999/08/12 03:09:00.000 47.57 -70.00 2.3 15.4 MN

Figure 4.6a: Fourier Amplitudes at 1.0Hz. Note the constant level of amplitude evident at progressively higher hypocentral distances and at progressively higher frequencies (in subsequent figures).

Figure 4.6b: Fourier Amplitudes at 2.0Hz. Note the constant level of amplitude evident at progressively higher hypocentral distances and at progressively higher frequencies (in subsequent and previous figures).

Figure 4.6c: Fourier Amplitudes at 5.0Hz. Note the constant level of amplitude evident at progressively higher hypocentral distances and at progressively higher frequencies (in subsequent and previous figures).

Figure 4.6c: Fourier Amplitudes at 10 Hz. Note the constant level of amplitude evident at progressively higher hypocentral distances and at progressively higher frequencies (in subsequent and previous figures).

those shown in Figure 4.6. Table 4.3 gives the threshold distances used for this study for magnitude bins of 0.5MN. The columns for $MN > 3.5$ are taken from Atkinson (2004).

Freq.	1.0<MN<1.5	1.5<MN<2.0	2.0<MN<2.5	2.5<MN<3.0	3.0<MN<3.5	3.5<MN<4.0	4.0<MN<4.5	MN>4.5
0.1	0	0	0	0	0	0	0	0
0.126	0	0	0	0	0	0	0	0
0.158	0	0	0	0	0	0	0	0
0.2	0	0	0	0	0	0	0	0
0.251	0	0	0	0	0	0	0	0
0.316	0	0	0	0	0	0	0	0
0.398	0	0	0	0	0	0	0	0
0.501	0	0	0	0	0	30	0	0
0.631	0	0	0	0	0	70	100	0
0.794	0	0	0	30	0	100	400	0
1	0	0	0	30	40	200	1000	*
1.259	0	0	0	35	60	*	*	*
1.585	0	0	0	35	100	*	*	*
1.995	0	10	15	40	500	*	*	*
2.512	0	15	20	40	500	*	*	*
3.162	20	20	30	40	500	*	*	*
3.981	20	25	30	40	500	*	*	*
5.012	20	25	30	40	500	*	*	*
6.31	20	25	30	40	500	*	*	*
7.943	20	25	30	50	500	*	*	*
10	20	25	30	50	500	*	*	*
12.589	25	30	30	50	500	*	*	*
15.849	25	30	30	50	500	*	*	*
19.953	25	30	30	100	500	*	*	*

Table 4.3: Distance threshold values for reliable recovery of ground motion amplitudes. Data with hypocentral distance (km) less than the value given are retained.

NOTE: * represents no distance limitation. Zero denotes insufficient data to estimate limiting distance. Data not used in these cases.

5. Results: Source Spectra

5.1 From Direct Method

The Direct method was applied to the CSZ dataset and the Au Sable Forks (M5.0, 2002) sequence to obtain apparent source spectra. The observed spectrum for each recording of all target events were used to obtain source spectra according to (for $R \leq 70$ km):

$$\Omega_{\text{source},i}(f) = \Omega_i(f) R \exp[\pi R f / (\beta Q)] / S(f) \quad (5.1)$$

where $\Omega_{\text{source},i}(f)$ is the inferred source displacement given the i^{th} station recording, $\Omega_i(f)$ is the observed displacement at the i^{th} site, R is the hypocentral distance in km, f is the frequency, β is the shear wave velocity in km/s, $Q = 680f^{0.36}$ (after Atkinson and Boore, 1995) and $S(f)$ is the site response. $S(f)$ is assumed to be given by the H/V ratios determined by Siddiqi & Atkinson (2002) for horizontal components and $S(f) = 1$ for the vertical component [after Boore and Atkinson, 1987]. For each event, an apparent source spectrum was obtained by taking a log average over all N records of that event:

$$\log(\Omega_{\text{source}}) = (\sum_i \log(\Omega_{\text{source},i})) / N \quad (5.2)$$

The resulting source spectrum allows the determination of important source parameters of the earthquake: seismic moment (M_0) and corner frequency (f_0). From these parameters, moment magnitude (M) and stress drop ($\Delta\sigma$) can also be determined. These parameters are determined by comparison of the computed source spectrum (Equation 5.2) to the Brune Source Model (Brune, 1970) as follows:

$$\Omega_{\text{longperiod}} = CM_0 \quad (5.3)$$

$$A_{\text{highfrequency}} = 4CM_0\pi^2 f_0^2$$

$$\Delta\sigma = M_0 \left(\frac{f_0}{4.9 \times 10^6 \beta} \right)^3 \quad (5.4)$$

$$M = (2/3)(\log M_0 - 16.05) \quad (5.5)$$

where $\Omega_{\text{longperiod}}$ is the constant level of the source displacement spectrum at long periods and $A_{\text{highfrequency}}$ is the constant level of the source acceleration spectrum at high frequencies. In Equation 5.4, $\Delta\sigma$ is in bars, M_0 is in dyne-cm, f_0 is in Hz and β is in km/s. The long period source displacement level is determined from the log average of at least three data points that are judged (by eye) to represent the flat level. Similarly, at least three points are required for the high-frequency level of the acceleration spectrum; the frequency range over which the acceleration spectrum is flat is also judged subjectively. The levels (long-period level for displacement spectrum and high frequency level for acceleration spectrum) are then obtained as the average log spectral value over the frequencies that make up the 'flat part' of the spectrum. The approach of Shi et al. (1996), where a least-square fit was applied to determine the optimum moment and corner frequency was not used, as it forces the existence of a corner frequency on the basis of data well below that corner frequency. A small deviation from a flat displacement level at frequencies nearing the high frequency limit would then be interpreted as the beginning of the ω^2 decay, which may or may not be the case. Without sufficient data beyond the corner frequency, this method may produce erroneously low corner frequencies.

For eastern North America at mid-crustal depths, accepted values of the physical constants in Equation 5.3 are $\rho=2.8 \text{ g/cm}^3$ (crustal density) and $\beta=3.8 \text{ km/s}$ (shear wave velocity). The other constants are taken as $R_p=0.55$ (average radiation pattern), $F=2$ (free surface amplification) and $V=0.71$ (partition onto the 2 horizontal components), after

Boore and Atkinson (1987). The source spectrum is defined at $R=1$ km (hypocentral distance).

Results of the calculated spectra are shown in Appendix 2 as compared to a Brune source model. All calculated source spectra agree reasonably well with a Brune model source spectrum, as illustrated for one event in Figure 5.1. A composite of all the results is presented in Figures 5.2 and 5.3. The top panel of Figure 5.2 shows all displacement spectra normalized to $\log CM_0=1$. By subdividing the normalized spectra by magnitude bins of $0.5M$, as shown in Figure 5.2, the degree of inter-event variability of the source spectra at moderate to high frequencies becomes readily apparent. This reflects inter-event variability of the corner frequency (or equivalently the stress-drop). Figure 5.3 shows the same results in terms of the acceleration spectra, obtained by multiplying the amplitudes of Figure 5.2 by $(2\pi f)^2$. Table 5.1 provides the parameters of Brune models spectra, including M , f_0 and $\Delta\sigma$.

Figure 5.4 (after Atkinson and Sonley, 2003) illustrates the apparent source spectra for the Au Sable Forks, $M5.0$ event of April 20, 2002, the largest event in this study. Figure 5.4 is divided into two parts to show the source spectra of the vertical components (top panel) and the horizontal components (bottom panel) separately. This event was recorded over a much wider area than the remainder of the dataset, including stations of POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity), many of which are sited on soil. The Siddiqqi and Atkinson (2003) study, which calculated H/V ratios for Canadian stations, predated the POLARIS network installation, so the site corrections were unavailable for the POLARIS stations. Thus no site corrections were made in this figure, resulting in the substantial difference

Figure 5.1: Typical example of Direct method derived source spectra fit to Brune model. Upper panel shows the source displacement spectrum, where M_0 is determined from the constant long period level, according to Equation 5.3. The Upper panel shows the acceleration spectrum, where f_0 is determined from the high frequency constant level, according to Equation 5.3 given M_0 determined from the displacement spectrum. $\Delta\sigma$ is determined from the corner frequency according to Equation 5.4.

Figure 5.2: Normalised source displacement curves for events, binned by moment magnitude. Although there is some scatter, the long period levels of each spectrum are similar. The larger scatter at higher frequencies for the higher magnitude bins is expected, as the corner frequency decreases.

Figure 5.3: Normalised source acceleration curves for events, binned by moment magnitude. The bracketing normalized Brune models are for stress drop of 10 and 100 bars respectively, typical values for small to moderate magnitude earthquakes. At low magnitudes ($M < 2$), the corner frequency is usually beyond the bandwidth of the data. Accurately determining stress drop is not possible in these cases.

Table 5.1: Parameters determined from Direct method.

* 'min' indicates that a minimum corner frequency was assigned.

Filename	MN	M	fo [Hz]	Stress Drop [bars]	Brune Radius [m]
990609a	2.8	2.0	12.6 min	3.89 min	112
990812a	2.3	1.7	12.6 min	1.21 min	112
990813a	2.1	1.5	12.33	0.67	115
991002a	3.0	2.5	5 min	1.41 min	282
991013b	1.6	1.1	12.6 min	0.13 min	114
991028a	2.8	2.0	12.4	3.3	114
991120a	1.5	1.0	9.58 min	0.048 min	147
991210a	2.1	1.3	12.6 min	0.35 min	113
000106a	2.0	1.7	10 min	0.63 min	141
000110a	2.6	2.1	12.6 min	4.2 min	112
000111b	1.6	1.1	12.6 min	0.17 min	112
000115a	2.8	2.3	10 min	4.35 min	141
000123a	2.5	2.1	5 min	0.31 min	281
000131a	2.0	1.7	10 min	0.6 min	141
000203a	2.1	1.8	10 min	0.9 min	141
000209a	2.5	1.8	12.6 min	1.75 min	112
000210a	1.7	1.2	12.6 min	0.24 min	113
000224b	2.0	1.4	12.6 min	0.47 min	112
000308c	2.0	1.1	12.6 min	0.14 min	111
000314a	2.3	1.4	12.6 min	0.48 min	112
000417b	2.4	2.1	10 min	2.13 min	141
000429a	2.3	1.8	12.6 min	1.5 min	112
000614a	2.2	1.7	12.6 min	1.09 min	112
000615a	3.7	3.2	6.35	24.38	223
000619a	2.0	1.3	12.6 min	0.3 min	113
000620a	2.2	1.5	12.6 min	0.56 min	112
000621a	2.4	2.0	7.84	0.84	180
000703a	2.5	1.9	10 min	1.1 min	142
000709b	1.9	1.4	10 min	0.23 min	141
000801a	1.9	1.4	10 min	0.24 min	142
000809a	1.6	1.0	12.6 min	0.11 min	113
000816a	2.5	2.0	11.4	2.5	124
000816b	1.9	1.2	10 min	0.11 min	139
000831a	1.1	0.7	12.6 min	0.042 min	112
000902a	1.3	0.8	12.6 min	0.062 min	112
000905a	1.6	1.1	12.6 min	0.18 min	96
000921a	2.7	2.1	12.6 min	4.19 min	112
000927b	3.1	2.3	12.6 min	9.48 min	112
001010a	2.3	1.7	12.2	1.18	115
001012a	2.5	1.8	12.6 min	1.48 min	112
001014a	1.9	1.5	11.5	0.42	123
001017a	1.1	0.4	12.6 min	0.015 min	113
001019b	2.0	1.3	12.6 min	0.36 min	112
001022a	2.1	1.5	12.6 min	0.7 min	112
001026a	2.3	1.6	12.6 min	1.03 min	112
001103b	2.3	1.8	12.6 min	1.49 min	112
001201a	2.4	1.6	12.6 min	0.81 min	112
001204a	2.4	2.0	8.3 min	1.05 min	170
001212b	2.3	1.6	8 min	0.24 min	177

Table 5.1: Parameters determined from Direct method.

* 'min' indicates that a minimum corner frequency was assigned.

Filename	MN	M	fo [Hz]	Stress Drop [bars]	Brune Radius [m]
001215a	1.1	0.7	12.6 min	0.035 min	112
001224a	2.2	2.0	8.7	1.08	163
010112b	1.3	1.0	9.1	0.028	182
010131a	2.1	1.5	9.78	0.32	50
010213a	1.1	0.7	12.6 min	0.043 min	113
010215a	2.1	1.6	12.6 min	0.82 min	112
010219a	2.2	1.5	12.6 min	0.59 min	112
010306a	2.2	1.5	12.6 min	0.54 min	113
010428a	2.1	1.6	12.6 min	0.9 min	112
010503b	2.2	1.9	9.92	1.22	145
010513a	1.5	1.0	12.6 min	0.1 min	113
010522a	2.1	1.8	10.2	0.86	138
010522b	3.5	2.9	6.92	13	204
010522c	3.1	2.5	8.62	5.89	164
010526a	1.1	0.4	12.6 min	0.016 min	112
010527b	1.8	1.4	13.1	0.57	108
010529a	1.6	1.2	10 min	0.2 min	112
010606a	2.1	1.4	12.6 min	0.4 min	112
010610b	2.8	2.4	7.77	3.36	182
010615a	1.3	0.8	12.6 min	0.05 min	112
010619a	2.5	2.0	11.2	2.17	127
010622a	2.0	1.4	12.6 min	0.39 min	112
010705a	2.3	1.7	12.6 min	1.21 min	112
010710b	2.2	1.4	12.6 min	0.47 min	112
010727a	2.1	1.1	12.6 min	0.14 min	113
010811a	1.8	0.9	10 min	0.088 min	112
010820a	1.7	1.0	12.6 min	0.094 min	112
010902a	1.0	0.6	12.6 min	0.028 min	112
010908a	2.5	2.0	12.6 min	3.94 min	112
010920a	2.1	1.6	12.6 min	0.81 min	112
010921a	2.5	1.8	12.6 min	1.97 min	112
010921b	1.2	0.8	12.6 min	0.055 min	113
011003a	2.9	2.5	5 min	1.06 min	282
011025a	2.3	1.6	12.6 min	0.96 min	112
011026a	2.3	1.9	10.6	1.55	134
011026b	2.5	1.8	12.6 min	2.03 min	112
011109a	2.2	1.5	10 min	0.35 min	141
011111a	2.5	2.1	12.6 min	4.33 min	112
011202a	2.0	1.3	12.6 min	0.31 min	112
011205a	1.7	1.1	12.6 min	0.15 min	112
011205b	2.4	1.8	8 min	0.46 min	177
011207a	1.7	0.9	12.6 min	0.075 min	112
011213a	2.5	2.1	12.6 min	4.42 min	112
011222a	1.1	0.6	12.6 min	0.029 min	113
011224a	2.1	1.7	12.6 min	1.43 min	112
020115a	2.3	1.6	12.6 min	1 min	112
020119a	2.6	2.0	12.6 min	3.76 min	112
020119c	2.0	1.6	12.6 min	0.88 min	112
020130a	1.2	0.6	12.6 min	0.029 min	112

Table 5.1: Parameters determined from Direct method.

* 'min' indicates that a minimum corner frequency was assigned.

Filename	MN	M	fo [Hz]	Stress Drop [bars]	Brune Radius [m]
020131a	2.5	1.8	12.6 min	1.94 min	112
020203a	1.4	0.8	12.6 min	0.048 min	113
020203b	1.0	0.5	12.6 min	0.022 min	113
020213b	2.1	1.4	12.6 min	0.38 min	112
020215a	2.1	1.5	12.6 min	0.57 min	112
020215b	0.8	0.6	12.6 min	0.023 min	113
020225a	2.2	1.8	8 min	0.29 min	177
020309a	2.1	1.5	12.6 min	0.61 min	113
020320a	1.0	0.5	12.6 min	0.017 min	112
020323b	1.5	0.9	12.6 min	0.078 min	112
020403a	2.1	1.5	8 min	0.15 min	176
020404a	2.4	1.7	12.6 min	1.09 min	112

Figure 5.4: Apparent Source displacement spectra for the Au Sable Forks, M5.0 event, from the Direct method as compared to the Brune source model and the two-corner model, after Atkinson and Sonley (2003). The spectral 'sag' is more faithfully reproduced in the two-corner model. The upper panel is vertical components only, the lower panel is horizontal components only.

between the source spectra derived from the horizontal and vertical components, as seen in the two panels. Comparison of the observed spectra to the Brune source model shows a significant overestimation of the displacement spectrum between 1 and 5 Hz for the vertical components and a somewhat smaller overestimation for the horizontal components. The overestimation may be a result of the spectral ‘sag’ in the calculated source spectra, described by Atkinson and Sonley (2003). A M5.0 event is no longer reasonably represented by a point source as the source has both a discernible area and duration. Source complexity results in a poor agreement between the apparent source spectrum and that given by the Brune model. The two-corner model (Atkinson, 1993) more faithfully reproduces the sag, as well as the absolute level of the average horizontal component spectrum. Finite fault effects explain this source complexity, where the size of the subfaults or asperities comprising the total fault governs the location of the sag within the earthquake spectrum. The Au Sable Forks, M5.0 event may have significant source complexity, typical of moderate to large magnitude events (see Atkinson and Silva, 1997), whereas the remainder of the events in this study show little evidence of source complexity in the apparent source spectrum and can thus be modeled by a simple point source model.

5.2 From the Empirical Green's Function Method

In this section, the source spectra determined by the EGF method are described. Recall that the EGF method requires a group of two or more co-located earthquakes of similar focal mechanisms, to ensure that the path effects will be identical within the group. Similarity of waveforms can be used to infer similarity of focal mechanism. Waveforms that meet these conditions are termed multiplets according to Lamontagne (1999), as used in Sonley and Atkinson (2001). The smaller magnitude events within the group can then be used to approximate the Green's function, describing the response of the Earth to the incoming wave, along the path between the hypocentre and the recording station.

For this study, we considered events to be co-located if they occurred within 0.1 degrees of each other (~10 km). These events were checked for similarity of waveform (which is a subjective test) if they met the location condition. Very few multiplets were eliminated on this basis; therefore there is some uncertainty in the similarity of focal mechanisms. CSZ focal mechanisms are typically thrust (Lamontagne, 1999), and strike generally NE/SW.

Spectral ratios of the EGF event to the mainshock event can be used to obtain the apparent source spectrum according to:

$$\frac{\Omega_{R=d,MAIN}(f,d)}{\Omega_{R=d,EGFj}(f,d)} = \frac{\Omega_{R=1,MAIN}(f)P_i(f,d)S_i(f)I_i(f)}{\Omega_{R=1,EGFj}(f)P_i(f,d)S_i(f)I_i(f)} \quad (5.6)$$

where $\Omega(f)$ is the displacement spectrum, described by the subscript with EGFj representing the jth EGF event within the multiplet. $P_i(f,d)$ represents path effects between the hypocentre and the ith station, $S_i(f)$ represents site effects at the ith site, and $I_i(f)$ represents the instrument response at the ith station (after Haddon, 1996; Sonley and

Atkinson, 2001; Atkinson and Sonley, 2003.) The instruments considered in this study are well calibrated and instrument response can easily be removed (CNSN autodrm, Bill Shannon pers. comm.), which is a necessary step if the response has changed over the timespan of the multiplet. For co-located events, the path effects will be identical and their ratio will be unity. Since the observations are made at the same site, the ratio of site effects will also be unity, leaving only the ratio of source spectra.

$$\frac{\Omega_{R=1,MAIN}(f)}{\Omega_{R=1,EGFj}(f)} = \frac{\Omega_{R=d,MAIN}(f,d)}{\Omega_{R=d,EGFj}(f,d)} \quad (5.7)$$

This ratio will exhibit the spectral shape of the apparent source spectrum, but not the absolute level. At frequencies below the EGF corner frequency, Equation 5.7 can be normalized by the long-period displacement level of the EGF event to obtain the correct absolute level for the target spectrum of the large magnitude event. Recall that the apparent source spectra of small magnitude events have a constant flat displacement level over a broad frequency range, as shown in Figure 5.2, panel B. Therefore $\Omega_{R=1,EGFj}(f)$ is constant over all frequencies of interest (<10 Hz) and by simple multiplication by this constant level (Equation 5.7) the absolute level of the mainshock source spectrum is obtained. The N normalized spectra at each station are then log-averaged to determined the calculated source spectrum for the mainshock, given EGFj, according to:

$$\log(\Omega_{MAIN}) = (\sum_i \log(\Omega_{MAIN(EGFj),i})) / N \quad (5.8)$$

Figure 5.5 illustrates the resulting averaged spectra for a multiplet containing one EGF event, compared to the Brune source model derived from the Direct method levels. Both methods of deriving the source spectrum agree within reasonable scatter and the Brune model is a good approximation of the apparent source displacement spectrum.

Figure 5.5: Example of EGF method apparent source spectrum. Brune source model, derived from the equivalent Direct method source spectrum, is shown for reference.

5.3 Comparison of Source Spectra from Direct and EGF Methods

Seventy-nine events of $M > 2.0$ were recorded in the CSZ, 27 of which fall into multiplets. Specific examples are instructive; Figure 5.6a shows the source displacement spectrum for the mainshock within a multiplet where the Direct method and the EGF method produce very similar results, both in spectral shape and in absolute level (MAIN 001022a, MN2.1; EGF0 011222a, MN1.1; EGF1 020323b MN1.5). Figure 5.6b shows the source displacement spectrum for the mainshock within a multiplet where the two methods agree overall, but with some significant discrepancies in shape (MAIN 001103b, MN2.3; EGF0 010710b, MN2.2). Such differences are to be expected, as the Direct method takes into consideration the average effects of attenuation over many paths, while the EGF method considers attenuation along a specific path, as described by the Empirical Green's Function. Source spectra obtained from the EGF method are compared to the corresponding source spectra derived from the Direct method for the largest magnitude event in the multiplet in Appendix 3.

The Au Sable Forks, M5.0 event merits further scrutiny as a detailed case study. The six aftershock events prove to be an effective set of EGF events to obtain the source spectra of the mainshock. The resulting comparison between the Direct method and EGF method source acceleration spectra show very good agreement, as shown in Figure 5.7, particularly for the vertical component. The horizontal component spectra are more strongly influenced by site response. The Direct method does not remove the site response while the EGF method does. This explains the larger discrepancies between the EGF and Direct methods observed for the horizontal components. The average source spectra derived from the EGF method show strong agreement with the average source

Figure 5.6a: Comparison between source displacement spectra determined by both the EGF and Direct methods. Direct Method reproduces the EGF results within the uncertainty of Direct method.

Figure 5.6b: Comparison between source displacement spectra determined by both the EGF and Direct methods. Direct method does not produce the same shape as the EGF method, but still agrees overall within the uncertainty of the Direct method.

Figure 5.7: Apparent Source spectra from the EGF method as compared to the Direct method, Brune model and two-corner model, after Atkinson and Sonley (2003). Upper panel is vertical components only, lower panel is horizontal components only.

spectrum derived from the Direct method, both in spectral shape and in absolute level. The spectral 'sag' (after Atkinson and Sonley, 2003) featured in the average source spectrum derived from the Direct method is reproduced in the source spectra derived from the EGF method for each aftershock. The 'sag' is most likely a result of significant source complexity. It is also noteworthy that there is no dependence of the results on the magnitude of the EGF event, as all six EGF events (ranging from M2.1 to M3.3) produce very similar mainshock spectra.

5.4 Inferred Source Parameters from CSZ events

Based on the apparent source spectra obtained by the Direct method, moment magnitude (M , see Equation 5.5) was determined for a large set of small events in the CSZ. The GSC determines either MN or ML for all located earthquakes, with ML generally reserved for very small or offshore events. Both MN and ML are determined from the observed maximum amplitudes of the earthquake, in the time domain. Since no transformation is required, either magnitude scale can be calculated in near-real-time. M is calculated from the frequency domain of the observed source spectra, requiring a significant number of calculations, delaying the result. However, M is a more direct measure of the physical size of the earthquake, since it relates directly to seismic moment. Hence relating MN (or ML) to M through empirical relationships has become useful (see Atkinson, 1993). The Atkinson (1993) empirical relationship giving M as a function of MN;

$$M = 0.98MN - 0.39 \quad (5.9)$$

was determined from a set of events within the magnitude range $4 < M < 6$. The results of this study can be used to extend this relation over a broader M range, from $M \geq 0.8$. A linear least-squares regression was performed, from the dataset shown in Table 5.1 expanded to include the Atkinson (1993) study events ($M > 4$), to determine the empirical relationship:

$$M = 1.03MN - 0.61 \quad (5.10)$$

The two empirical relationships (Equations 5.9 and 5.10) are nearly identical as shown in Figure 5.8. This is remarkable, considering the very different magnitude ranges of the two studies, and suggests that this empirical relationship is well constrained over a broad

Figure 5.8: Empirical relationship between M and M_N . Atkinson (1993) equation corresponds to Equation 5.8, Equation 5.9 gives the regression results from this study (shown as black line). Note the similarity of the two empirical relationships, despite the vastly different magnitude ranges.

magnitude range. An insufficient number of events where ML was the given magnitude exist to consider the relationship between ML and M.

The stress drop parameter ($\Delta\sigma$) is derived from the high-frequency level of the source spectra obtained by the Direct method, once the seismic moment has been determined (Equations 5.3 and 5.4). Table 5.1 gives the values of $\Delta\sigma$ determined in this study, with a minimum value given when the corner frequency is beyond the available bandwidth. A high-frequency level was defined by taking the log average of the spectral acceleration amplitudes over the flat portion of the spectrum above the corner frequency. A level was determined only if at least three points defined the flat portion. The values determined by Atkinson (1993) for higher magnitude events in ENA are also listed.

The top panel of Figure 5.9 shows that corner frequency (Equation 5.3) is inversely dependent on M; that is, higher magnitude events will have lower corner frequencies. Note that the corner frequency occurs at very high frequencies for small earthquakes. The data collected in this study is limited in bandwidth (~ 0.5 Hz – 20 Hz), due to the moderate sampling rates of the instruments in the CSZ (especially pre-October 2000). Since the corner frequency is above the instrument bandwidth for most small magnitude events, the high-frequency acceleration level cannot be obtained. In such cases a minimum corner frequency is assigned. Examples for which the high-frequency acceleration level can be obtained are shown in Figure 5.10, with the source acceleration spectra for all events shown in Appendix 2. In some instances, the departure from the constant long-period displacement level is visible, but the high frequency acceleration level is not. This may be related to source complexity, where a small sag has been introduced at the moderate frequencies. The bottom two panels of Figure 5.10 illustrate

Figure 5.9: Top panel shows Brune corner frequencies, determined from the source displacement and acceleration spectra (Equation 5.3) as a function of M . Bottom panel shows associated stress drop values. Minimum stress is given when the long period level of the source acceleration spectra is beyond the available bandwidth.

NOTE: The Mont Laurier earthquake of 1990 values have been corrected as per Atkinson (1998). Shi et al (1998) values are calculated from f_c^0 of same.

Figure 5.10: Top four panels show examples of acceleration spectra for which Brune high frequency level can be determined. Bottom two panels exhibit problem discussed in text. The high frequency acceleration level can not be determined from this graph. The arrows indicate possible introduction of a spectral sag. Spectra for the entire dataset are shown in Appendix 2.

an example of this phenomenon, where the arrows point out the small sag. Such events were assigned a minimum corner frequency.

The bottom panel of Figure 5.9 illustrates the dependence of $\Delta\sigma$ on M , for low M and the constant level at higher magnitudes. The plotted data points are from this study, plus previous studies by Atkinson (1993) and Shi et al. (1998). The arrows represent minimum values determined from the lower-bound corner frequencies (this study only). It is important to note that Shi et al. (1998) used three methods of calculating the corner frequency. The first is identical to that used in this study and will be used for the sake of consistency. The second uses an EGF deconvolution method, where optimization is used to find the parameters Ω_0^L , Ω_0^S , f_c^L , f_c^S in:

$$r(f) = \frac{\Omega_0^L}{\Omega_0^S} \cdot \frac{1 + (f/f_c^S)^2}{1 + (f/f_c^L)^2} \quad (5.11)$$

where $r(f)$ is the spectral ratio of the large (L) and the small (S) events, Ω_0 represents the low frequency asymptote of the displacement spectrum of each event and f_c is the corner frequency of each event (after Shi et al., 1996). The third method used by Shi et al. (1998) fits an optimum Brune source model to the observed data, resulting in determinations of both Ω_0 and f_c . This method was considered and rejected for data in this study, as it is too subjective and may result in a false corner frequency determination. The dependence of $\Delta\sigma$ on seismic moment (M_0), and therefore M , is controversial. For larger values of M_0 (or M), above the M range of this study but shown in the Atkinson (1993) data, it has been observed that $\Delta\sigma$ becomes constant (~ 100 bars). However, special cases have shown higher than average $\Delta\sigma$, such as the 1988 Saguenay earthquake (Atkinson, 1993). Some studies (e.g. Boore, 1986; Abercrombie and Leary, 1993) have

cited bandwidth limitations as the source of the magnitude dependence of stress drop ($\Delta\sigma$). It is important to note that the high frequency constant level of the source acceleration spectrum for all stress drops reported in this study is below the high frequency cut-off of the instruments. Thus, the dependence of $\Delta\sigma$ on M does not appear to be a bandwidth effect. On the other hand, the corner frequencies shown in Figure 5.9 (top) are pushing up against the bandlimits for the smallest moment events, and so there may be some influence of bandwidth.

The decrease of $\Delta\sigma$ with decreasing M at low magnitudes implies a breakdown in the self-similarity of earthquakes. It has long been held (e.g. Aki, 1967) that earthquake spectra scale with magnitude in a self-similar manner, but are otherwise identical in terms of physical mechanism. The implication of self-similarity is that while the fault area increases, the applied force must also increase, resulting in constant stress drop over the fault, regardless of earthquake magnitude. Thus, small magnitude earthquakes have a smaller fault area, but would maintain the level of stress drop as magnitude decreases. Empirical determinations of $\Delta\sigma$ at low M have not reproduced this relationship (e.g. Shi et al., 1998; Atkinson, 1993; Dysart et al., 1988; this study), although a satisfactory physical explanation remains elusive. The results of this study do not support this possibility, as corner frequencies are determined for only those events where the high frequency constant level is observed, within the bandwidth of the instruments.

One possible explanation borrows the concept of ‘quantization’ from particle physics. An earthquake ‘quantum’, or ‘seismon’ (after Wu et al., 1996), may be restricted in dimensions, possibly related to the crystal or grain size of the rock (Sacks and Rydelek, 1995), though determined to be much larger (~1-5 m in length) by Iio (1991). Every

earthquake larger than the earthquake quantum must be made up of a whole number of quanta. While the area increases in discrete steps that are determined by the size of the earthquake quantum, the force required for failure depends only on the material strength and thus, the constant stress drop level is no longer achieved. This hypothesis provides a physical explanation for the breakdown in self-similarity and can be empirically tested with the determination of source size; one would expect the size to reach a constant level at low magnitudes.

The Brune model source radius is the radius of the point source of an earthquake, determined according to (Brune, 1970):

$$M_0 = (16/7)10^6(\Delta\sigma)a^3 \quad (5.12)$$

where M_0 is the seismic moment in dyne-cm, $\Delta\sigma$ is the stress drop in bars and a is the source radius in cm. If quantization were occurring, one would expect to find a constant value of a at low magnitudes, corresponding to the minimum size of an earthquake. Figure 5.11 suggests that the results of this study are ambiguous with respect to a minimum source radius. While the event radius continues to decrease with decreasing magnitude, below magnitude 2 the error bars also allow an interpretation of a fixed minimum radius between 100 and 120 m. Thus the quantization issue requires further study.

The error bars in Figure 5.11 were produced by varying the corner frequency, creating a limiting envelope of suitable Brune models. Figure 5.12 illustrates this procedure. The initial corner frequency is given by the high frequency level of the acceleration spectrum, shown as a black line in Figure 5.12. By iteratively increasing the corner frequency, keeping the seismic moment fixed, the Brune model meets those points

Figure 5.11: Top panel shows Brune source radii, determined using Equation 5.11, as a function of M . Note the cloud at $3 < M < 4$ and the increasing trend at $M > 4$. The bottom panel shows the data at low M values determined in this study in more detail. Note the apparent increase in the low magnitude range (approximately 50 m per unit M). Below magnitude 2, a constant value could be assigned given the error bars. Note that where several datapoints have the same magnitude, the points have been displaced for visual reasons only.

Figure 5.12: Example of method used to determined error bars in Figure 5.11. Corner frequency was increased and decreased by eye (gray curves) to encompass all data points, both above and below the Brune model. The upper curve corresponds to the lowest possible source radius, the lower curve corresponds to the highest possible source radius.

slightly above the initial Brune model producing the upper grey line in Figure 5.12. The same procedure is applied to meet those points below the initial Brune model, producing the lower grey line in Figure 5.12. The values determined as the highest and lowest reasonable corner frequencies were then used in Equation 5.12 to infer limits on the associated Brune source radius (a).

The Brune source radius appears to increase slightly with magnitude for small events (~ 50 m per unit magnitude) in contrast to the results of Sacks and Rydelek (1995) shown in Figure 5.13. Figure 5.13 illustrates the change in behaviour of the source size (given by Brune source radius) at $M3.5$, as described by Sacks and Rydelek (1995); the constant radius for $M < 3.5$ is interpreted as an effect of quantization, while the increase of radius with M above 3.5 suggests self-similarity. This same change in behaviour is noted in the Atkinson (1993) study, shown in Figure 5.11.

If all observed earthquakes are self-similar, then the log of the number of these events per year should fall in a straight line, following the Gutenberg-Richter relation (Sacks and Rydelek, 1995). Deviations from the straight line indicate either an incomplete data set or a departure from self-similarity. Figure 5.14 gives the magnitude recurrence relationship for the CSZ over the time period 1983-2003 (from GSC), within the detection confidence limit of $M_N \geq 2.0$ as determined by GSC. Linear least-squares regression produced the black line shown in the figure. Using Equation 5.10 and Figure 5.9 as a guide, departure from the Gutenberg-Richter relation corresponding to the change in the behaviour of the Brune radius with increasing M , might be expected at

(a)

(b)

Figure 5.13: Figure 1 of Sacks and Rydelek (1995). Top panel shows Brune radii determined from Equation 5.12. The corresponding stress drop values appear in the bottom panel. The change in behaviour at $M \sim 3.5$ may be an effect of earthquake quantization.

Figure 5.14: Cumulative number of earthquakes per year as a function of magnitude (MN) for the Charlevoix Seismic Zone within detection confidence limit for the time period 1983-2003 (GSC). No departure from the Gutenberg-Richter relation is observed between MN 3.5 and 4.0. The departure from the Gutenberg-Richter relation at $\sim MN$ 4.0 is a product of the occurrence of one event of $MN > 5$.

about M_N 3.5 to 4.0. No departure from a Gutenberg-Richter relation is observed, perhaps implying that the change in Brune source radius and in the corresponding stress drop values with M is not related to a breakdown in self-similarity. Thus, the explanation for the apparent decrease in stress drop with decreasing moment for events of $M \geq 3.5$ remains enigmatic.

6. Attenuation Results using the RTSM Method

6.1 Reverse-Two Station Method in the Charlevoix Seismic Zone

The importance of determining attenuation accurately has been described in detail in chapter 2, with various methods described in chapter 3. The preferred method for the purposes of this study is a modified version of the Reverse-Two Station Method (RTSM) of Chun et al. (1987). The RTSM calculates attenuation along a specific path, between two stations. Conditions are placed on the location of the events relative to the station pair to ensure similarity of path effects. Figure 6.1 shows schematically how the selection of event pairs was made. The events must lie within a threshold distance (0.1 degrees in the case of CSZ, 1 degree for station pairs in the remainder of Eastern Canada) of the line connecting the two stations and must fall outside the pair (filled circles in Figure 6.1).

The main difference between the method applied here and that of Chun et al. (1987) is as follows: Chun et al. (1987) modeled attenuation as $R^{-B}\exp(\gamma R)$. For an assumed rate of geometric attenuation (B) they solved for the coefficient of anelastic attenuation (γ). However, the contribution of anelastic attenuation to the total attenuation in the CSZ is not significant. Earthquakes in the CSZ are measured at stations less than 70 km distant, where geometric spreading dominates the total attenuation, as shown in Figure 6.2. Therefore, in this study the goal is to determine the total attenuation, R^{-b} . By limiting the dataset to observations made at distances $R < 70$ km, the coefficient of total attenuation (b), is nearly equal to the geometric spreading coefficient (B). Equation 3.3 can be modified as follows:

Figure 6.1: Schematic of event selection for RTSM attenuation calculation for a station pair in Eastern Canada. Events that fall within the threshold distance (0.1 degrees for pairs within CSZ, 1 degree everywhere else) of the line connecting the two stations but beyond either station are selected (shown as filled circles). Events are rejected when the distance to the closest station is larger than the inter-station distance (shown as open circles).

Figure 6.2: Attenuation models, after Atkinson and Mereu (1992). At low frequencies and short distances, attenuation is dominated by geometric spreading. At higher frequencies and larger distances, the effect of anelastic attenuation becomes more important. This is a schematic drawing only, showing attenuation for an arbitrary source level. The distance range for study events in the CSZ is highlighted in Panel B.

$$\begin{aligned}
\frac{\Omega_{11} \cdot \Omega_{22}}{\Omega_{12} \cdot \Omega_{21}} &= \frac{\Omega_{1(R=1)}(f)P(f, d_{11})S_1(f) \cdot \Omega_{2(R=1)}P(f, d_{22})S_2(f)}{\Omega_{1(R=1)}P(f, d_{12})S_2(f) \cdot \Omega_{2(R=1)}P(f, d_{21})S_1(f)} \\
&= \frac{P(f, d_{11}) \cdot P(f, d_{22})}{P(f, d_{12}) \cdot P(f, d_{21})} \\
&= \left(\frac{d_{11}d_{22}}{d_{12}d_{21}} \right)^{-B} \exp[-\gamma\Delta]
\end{aligned}$$

$$\gamma \approx 0 \text{ \& } b \approx B$$

thus

$$b = \frac{\log\left(\frac{\Omega_{11} \cdot \Omega_{22}}{\Omega_{12} \cdot \Omega_{21}}\right)}{\log\left(\frac{d_{12} \cdot d_{21}}{d_{11}d_{22}}\right)} \quad (6.1)$$

where Ω_{ij} is the observed displacement spectrum at station i of event j , $\Omega_{j(R=1)}$ is the source spectrum of event j , $P=d_{ij}^{-B}\exp(-\gamma d_{ij})$ is the path transfer function modified to $P=d_{ij}^{-b}$ for total attenuation. γ is the coefficient of anelastic attenuation (a function of frequency), d_{ij} is the hypocentral distance between event j and station i and S_i is the site effect function at station i . Δ is the station separation (modified after Chun et al., 1987). We use the notation b to indicate that the coefficient of total attenuation is related to B , the coefficient of geometric spreading, but not identical. At short inter-station distances, $b \approx B$, but b will grow with increasing pathlength and increasing frequency, as anelastic attenuation becomes a significant addition to the total attenuation.

Although the dataset comprises several hundred earthquakes, the inclusion of events is limited by the geometry requirements. Within the CSZ, the 410 study events (listed in Table 4.1) are reduced to ~ 180 for each station pair. The specific numbers of events for each station pair, as a function of frequency, are listed in Table 6.1. The total number of calculations for each station pair is limited to the number of possible earthquake pairs times the number of frequency bins (24). It is necessary to impose the further limiting condition that the signal to noise ratio for each spectral value be greater

Station 1	Station 2	# left	# right	Distance [km]	Mean b	ST DEV	ST ERR
A11	A16	35	141	32.7	1.6	0.31	0.031
A16	A54	35	78	42.5	1.28	0.62	0.022
A16	A61	47	32	26	1.47	0.53	0.016
A16	LMQ	59	72	34.1	1.16	0.71	0.03
A61	A64	306	14	23	2.13	0.7	0.046
A64	LMQ	109	99	28.2	1.34	1.05	0.017

Table 6.1: Station names, number events to the left and right of the station pair, Inter-station distance, Mean value of coefficient of total attenuation (b) with standard deviation and standard error for pairs in the Charlevoix Seismic Zone.

than 2. Since each calculation of the coefficient of total attenuation (b) requires four observed data points at each frequency bin, the number of calculated values is decreased further. This method requires a high volume of reliable data for a single calculation, decreasing the effective scope of the method, but increasing the certainty in its applications. Overall there is a decrease in the uncertainty in the total rate of attenuation for this method, relative to the empirically derived attenuation model of Atkinson and Mereu (1992). This method also provides a more path-specific determination of attenuation and thus, has a different range of applicability.

The RTSM method requires the isolation of the path between the two stations. This is not achieved for events where the distance from the station pair is much greater than the inter-station distance. The net attenuation between the stations is overwhelmed by small variations along the path leading to the pair. It is therefore necessary to remove all such event pairs. This method is also limited to a narrow corridor surrounding the line that connects two stations. If the corridor is too wide, the paths travelled will not be the same. Valid events from the data set are shown in Figure 6.1 where the filled circles represent events with the nearest station at a distance less than the inter-station distance.

The likelihood that the path taken by the waves will be similar between the two stations decreases as the inter-station distance nears the average earthquake depth, as shown schematically in Figure 6.3. The paths taken by the waves travelling in opposite direction overlap in the bottom panel, where the inter-station distance is much larger than the average earthquake depth. In the top panel, the inter-station distance is approximately equal to the average earthquake depth; here the wave paths cross, but do not overlap significantly. While eliminating events at the very near distances would eliminate this

Figure 6.3: Schematic drawing in cross-section of wave paths for inter-station distance near average earthquake depth. Bottom schematic shows the desired situation. Boxes represent stations, circles represent hypocentres. Scale is not conserved between pictures, distances are given between points.

effect, only one station pair is affected (A54, LMQ with inter-station distance 13.4 km). Figure 6.4 shows the histogram of b determinations for this pair. The distribution of the coefficient b is too broad to be meaningful. The mean b value does not represent the attenuation rate in this particular case.

Figure 6.5 shows a more typical attenuation result for the CSZ. The station separation is 33 km, approximately twice the average earthquake depth. The wavepath is essentially the same in both directions through the station pair at this inter-station distance. Histograms of b calculations with an overlying normal distributions from all station pairs listed in Table 6.1 are given in Appendix 4. Table 6.1 gives the mean values of b , standard deviation and standard error for each station pair. The average value of b , determined by fitting a normal distribution to the histogram of observed b values, is 1.36 ± 0.01 (standard error reported) within the CSZ as shown in Figure 6.6. Figure 6.7 shows the average b for stations pairs as a function of inter-station distance and frequency. Apparent trends with distance are weak and not statistically compelling, as indicated by the slope and error of the least-squares fit given in each panel. Because of the relatively short inter-station spacings (< 50 km), this value of $b = 1.36$ is a very good estimate of the geometric spreading rate of direct waves. This b value is significantly higher than the b value of 1.0 typically given for Eastern North America (ENA) for distances less than 70 km (Atkinson and Mereu, 1992). This may be specific to the CSZ, where attenuation may be higher than elsewhere in ENA, due to the complicated tectonic history of the region, including a meteorite impact structure. It may also be due to an increased dataset at these distances. The standard error in the calculations of Atkinson and Mereu (1992) is significantly higher near the source than at regional distances. A

Figure 6.4: Histogram of b values for short interstation spacing (see Figure 6.3). Solid line shows normal curve fit to histogram.

Figure 6.5: Typical histogram of b determinations for all earthquakes recorded across a station pair in the CSZ. Solid line shows normal curve fit to histogram.

Figure 6.6: Histogram of b values for all frequencies within the Charlevoix Seismic Zone, omitting poor geometries such as those illustrated in the top panel of Figure 6.3 and the distribution shown in Figure 6.4. Mean value corresponds to total attenuation. In this case, where all observations are made at distances less than 70 km, the total attenuation can be approximated by geometric spreading alone, $\therefore b \approx B$.

Figure 6.7: Average values of total attenuation slope for the CSZ. Panels B, C and D show the mean values of b for one frequency bin. There is no significant dependence on frequency or inter-station distance for pathlengths less than 60 km. Slopes given with standard error are not significantly different than zero. Black line represents average of b values in b .

more recent study using ENA seismographic data (Atkinson, 2004) reports $b=1.3$ for $R<70$ km, implying that the CSZ results may be fairly typical of regional attenuation of direct waves in ENA.

6.2 Other regions

The modified method was also applied to larger station separations, considering paths between stations for all of Eastern Canada. At larger distances, the coefficient of total attenuation, b , represents the combined effects of geometric spreading, anelastic attenuation and any Moho bounce effects. The assumption that the contribution of anelastic attenuation is small is not valid at these distances. However, we can still consider the overall attenuation modeled by the function R^{-b} . Because the results at larger inter-station distances (i.e. $\Delta > 70$ km) include a significant contribution from anelastic attenuation, b should not be considered as an estimate of the geometric spreading coefficient, B , in such cases. At the larger inter-station distances, the S window is most likely contaminated with surface waves. The net effect of the inclusion of some surface wave energy is a reduction of the coefficient of geometric spreading (~ 0.5). It should be noted that the coefficient of total attenuation determined in this study incorporates all changes in amplitude with distance into a single model of the form R^{-b} .

Throughout Eastern Canada, the 470 recorded events (listed in Appendix 1B) are reduced to an average of ~ 20 events for each station pair, specifically listed in the second part of Table 6.2. Panel A of Figure 6.8 shows a typical histogram of b values for Eastern Canada, where the standard deviation is slightly larger than that of the CSZ, but still reasonable, given the larger pathlength. Panel B shows a poor distribution of b . Many calculations are erroneous (i.e. less than 0, indicating that wave amplitudes have been amplified over the pathlength). In this instance, the event distribution is very uneven, as shown Figure 6.9. Ground motions recorded at one station for one of the two events to the west of station CRLO was anomalously high, possibly due to a temporary

Table 6.2: Station pairs, number of events to the left and right of the station pair, inter-station distance, mean value of coefficient of total attenuation (b) as a function of frequency with standard error reported in brackets. * indicates no data in frequency bin.

Pair Name	# left	# right	Inter-Station Distance [km]	Average b [2 Hz]	Average b [4 Hz]	Average b [8 Hz]	Average b [10 Hz]
A11CNQ	11	6	248.1	0.5(0.1)	0.8(0.03)	1.3(0.04)	1.4(0)
A11DPQ	15	11	289.3	0.9(0.11)	0.8(0.04)	1.1(0.04)	1.2(0)
A11GAC	5	12	496.6	0.7(0.11)	0.8(0.06)	0.9(0.07)	1.4(0.2)
A11GRQ	10	12	620.1	0.5(0.06)	0.7(0.03)	1(0.03)	1.2(0)
A11GSQ	25	16	271.3	0.7(0.09)	1.1(0.04)	1.2(0.07)	1.4(0.1)
A11ICQ	15	9	271.9	0.6(0.12)	0.9(0.06)	1.2(0.05)	1.2(0)
A11MNT	25	20	338.4	1.1(0.16)	0.9(0.16)	1.3(0.15)	1.3(0.1)
A11MOQ	6	12	262.3	1(0.09)	1.2(0.05)	1.5(0.05)	1.8(0.1)
A11OTT	6	13	471.5	1.1(0.07)	*	*	*
A11TRQ	12	9	461.3	0.6(0.09)	0.7(0.04)	1(0.06)	1.2(0.1)
A11WBO	10	16	392.4	1.1(0.08)	1.6(0.13)	*	*
A16CNQ	14	6	213.4	0.7(0.09)	0.8(0.03)	1.4(0.03)	1.4(0)
A16DPQ	16	10	319.5	1.1(0.12)	1.2(0.14)	1.3(0.07)	1.5(0.1)
A16GAC	6	12	557.6	0.7(0.1)	1.1(0.15)	1.1(0.34)	0.8(0.2)
A16GRQ	10	8	654.5	0.6(0.14)	0.8(0.07)	1.1(0.13)	1.1(0.2)
A16GSQ	34	14	222.7	0.8(0.08)	0.9(0.04)	1.4(0.03)	1.4(0)
A16ICQ	18	9	235.4	0.6(0.13)	0.7(0.04)	1.1(0.04)	1.2(0.1)
A16MNT	22	18	389.7	1(0.16)	1.2(0.14)	1.5(0.17)	1.9(0.3)
A16MOQ	6	9	303.1	1.4(0.24)	1.2(0.11)	1.7(0.1)	*
A16OTT	5	14	540	0.9(0)	1.9(0.16)	*	*
A16TRQ	13	10	505.1	0.6(0.13)	1(0.12)	1.3(0.17)	1.3(0.2)
A16WBO	10	17	459.7	1.1(0.06)	1.6(0.12)	*	*
A21CNQ	17	5	180.6	0.8(0.1)	0.7(0.03)	1.3(0.03)	1.4(0)
A21DPQ	17	10	360.3	0.6(0.18)	1.2(0.04)	1.9(0.07)	2(0.1)
A21GAC	7	11	627.2	0.6(0.1)	1.4(0.11)	1.2(0.14)	*
A21GRQ	10	5	695.3	0.2(0.17)	0.9(0.06)	*	*
A21GSQ	35	14	172.2	0.7(0.12)	0.9(0.03)	1.3(0.03)	1.3(0)
A21ICQ	21	9	203	0.5(0.14)	0.7(0.04)	1(0.04)	1.1(0)
A21MNT	20	12	450.7	0.7(0.14)	1.1(0.09)	1.5(0.17)	*
A21MOQ	6	6	352.8	1.4(0.04)	1.8(0.1)	2.7(0.05)	2.7(0.1)
A21OTT	5	10	617.2	0.8(0.05)	1.8(0.15)	*	*
A21TRQ	14	8	558	0.2(0.17)	1(0.07)	1.3(0.08)	1.3(0.1)
A21WBO	10	14	536.1	1.1(0.07)	1.9(0.05)	*	*
A54CNQ	16	10	220	0.7(0.03)	0.8(0.03)	1.4(0.04)	1.3(0)
A54DPQ	17	15	275.9	0.5(0.06)	0.6(0.03)	1(0.03)	1.2(0)
A54GAC	7	17	519.1	0.3(0.08)	0.8(0.05)	1.1(0.06)	1.3(0.1)
A54GRQ	10	8	609.5	0.3(0.04)	0.6(0.03)	1(0.04)	1.2(0.1)
A54GSQ	29	11	241	0.8(0.06)	1.1(0.03)	1.3(0.04)	1.4(0)
A54ICQ	19	8	240	0.8(0.08)	0.7(0.05)	1(0.06)	1(0.1)
A54MNT	21	17	358.2	0.8(0.07)	1.4(0.16)	1.7(0.17)	1.6(0.2)
A54MOQ	5	8	282	1(0.04)	1.3(0.05)	1.4(0.03)	1.7(0)
A54OTT	5	16	505.8	0.8(0.06)	2(0.04)	*	*
A54SMQ	16	5	312.6	*	1.4(0.1)	*	*
A54TRQ	13	14	462.3	0.1(0.07)	0.8(0.05)	1.1(0.05)	1.3(0.1)
A54WBO	11	22	433.9	1.1(0.07)	1.4(0.06)	2.1(0.19)	*
A61CNQ	18	9	183.9	0.6(0.1)	0.6(0.04)	1.1(0.03)	1.2(0)
A61DPQ	19	13	318.2	1.2(0.11)	1.1(0.06)	1.2(0.06)	1.4(0.1)

Table 6.2: Station pairs, number of events to the left and right of the station pair, inter-station distance, mean value of coefficient of total attenuation (b) as a function of frequency with standard error reported in brackets. * indicates no data in frequency bin.

Pair Name	# left	# right	Inter-Station Distance [km]	Average b [2 Hz]	Average b [4 Hz]	Average b [8 Hz]	Average b [10 Hz]
A61GAC	6	13	587.7	0.6(0.11)	1.2(0.09)	1.2(0.07)	1.4(0.1)
A61GRQ	10	9	651.5	0.4(0.07)	0.7(0.03)	0.9(0.04)	1(0.1)
A61GSQ	29	10	185.1	0.7(0.1)	0.8(0.04)	1.1(0.05)	1.1(0.1)
A61ICQ	26	7	204.8	0.8(0.14)	0.7(0.04)	1(0.05)	1.1(0.1)
A61MNT	19	11	417.3	0.7(0.13)	1.2(0.11)	1.5(0.1)	1.3(0.1)
A61MOQ	6	5	328.6	1.1(0.18)	1.6(0.17)	1.7(0.12)	1.8(0.2)
A61OTT	5	13	581.3	1.3(0.17)	1.9(0.28)	*	*
A61SMQ	19	5	297.2	*	1.4(0.13)	1.7(0.18)	1.5(0.1)
A61TRQ	15	14	515.4	0.5(0.08)	1.1(0.05)	1.5(0.06)	1.5(0.1)
A61WBO	11	18	507.6	1.6(0.22)	2.2(0.17)	1.2(0.21)	*
A64CNQ	21	8	165.9	0.8(0.07)	0.8(0.03)	1.1(0.02)	1.2(0)
A64DPQ	20	11	342.1	0.9(0.13)	1.1(0.04)	2(0.06)	2.2(0.1)
A64GAC	6	11	626.4	0.5(0.07)	1(0.09)	1.2(0.15)	1.4(0.1)
A64GRQ	9	8	673.3	0.3(0.09)	0.6(0.03)	1(0.05)	1(0.1)
A64GSQ	29	10	155.8	0.9(0.09)	1.1(0.03)	1.2(0.03)	1.2(0)
A64ICQ	29	7	188.4	0.9(0.11)	0.7(0.04)	1(0.03)	1.1(0)
A64MNT	19	8	452	0.9(0.06)	0.9(0.07)	1.6(0.1)	*
A64OTT	6	11	624.4	0.7(0.04)	1.6(0.13)	*	*
A64SMQ	22	5	289.6	1.1(0.19)	1.3(0.1)	*	*
A64TRQ	15	11	545	0.4(0.06)	0.8(0.05)	1.4(0.07)	1.4(0.1)
A64WBO	11	16	550.8	1(0.07)	1.6(0.11)	*	*
CNQDAQ	18	11	150.1	0.6(0.07)	0.9(0.03)	1.7(0.05)	1.9(0.1)
CNQDPQ	26	10	445.9	0.8(0.04)	1.1(0.02)	1.9(0.03)	2(0.1)
CNQGAC	8	15	861.8	*	1.3(0.1)	*	*
CNQGRQ	8	10	655.2	0.6(0.03)	1(0.02)	1.9(0.05)	1.9(0.1)
CNQICQ	13	10	63.4	*	0.7(0.13)	*	*
CNQLMQ	16	10	205.8	0.6(0.03)	0.9(0.03)	1.6(0.04)	1.5(0)
CNQMNT	16	9	727.1	0.8(0.07)	1.1(0.04)	*	*
CNQMOQ	6	6	635.8	*	1.5(0.05)	2.4(0.11)	2.6(0.1)
CNQOTT	9	15	934	0.8(0.03)	1.7(0.05)	*	*
CNQTRQ	16	15	671.5	0.8(0.08)	1.2(0.04)	1.8(0.04)	1.7(0)
CNQWBO	10	7	930.8	0.9(0.06)	1.6(0.05)	*	*
CRLOTT	18	5	77.4	*	0.7(0.08)	1.4(0.04)	1.3(0)
CRLOWBO	11	5	115.4	0.9(0.07)	1(0.05)	1.6(0.03)	1.8(0)
DAQGAC	9	12	515.6	0.6(0.11)	1.1(0.05)	1.3(0.08)	1.6(0.1)
DAQGRQ	7	20	527.8	0.6(0.04)	0.7(0.02)	1.3(0.02)	1.5(0)
DAQICQ	21	10	174.2	*	1(0.05)	1.5(0.15)	1.6(0.1)
DAQOTT	10	8	531.3	0.8(0.1)	1.4(0.15)	*	*
DAQSMQ	22	9	317.9	*	1.5(0.1)	1.8(0.04)	1.9(0.1)
DAQTRQ	19	13	415.3	0.5(0.05)	0.8(0.02)	1.3(0.02)	1.4(0)
DAQWBO	8	6	486.6	*	1.1(0.04)	1.6(0.2)	1.7(0.2)
DPQGAC	7	21	209	0.2(0.07)	0.8(0.07)	0.7(0.05)	1(0.1)
DPQGRQ	10	19	303.6	0.4(0.03)	0.5(0.03)	0.9(0.02)	1(0)
DPQGSQ	20	10	550.7	0.9(0.05)	1.6(0.03)	1.9(0.05)	2(0.1)
DPQICQ	25	14	465.2	*	1.5(0.04)	1.9(0.04)	*
DPQLMQ	19	17	288.5	0.9(0.02)	0.9(0.02)	1.1(0.02)	1.3(0)
DPQOTT	6	22	208.4	*	*	1.4(0.18)	1.4(0.2)

Table 6.2: Station pairs, number of events to the left and right of the station pair, inter-station distance, mean value of coefficient of total attenuation (b) as a function of frequency with standard error reported in brackets. * indicates no data in frequency bin.

Pair Name	# left	# right	Inter-Station Distance [km]	Average b [2 Hz]	Average b [4 Hz]	Average b [8 Hz]	Average b [10 Hz]
DPQTRQ	13	18	162.6	0.2(0.07)	0(0.04)	0.5(0.04)	0.5(0)
DPQWBO	9	16	202.3	0.9(0.08)	1.2(0.09)	1.5(0.06)	1.7(0.1)
GACGRQ	8	6	103.2	-0.1(0.11)	0.3(0.05)	0.6(0.03)	0.7(0)
GACGSQ	6	10	980.1	0.9(0.07)	1.4(0.07)	*	*
GACICQ	7	14	909.2	*	1.1(0.08)	*	*
GACLMQ	7	16	542.4	0.5(0.09)	1(0.04)	1.2(0.04)	1.5(0.1)
GACMOQ	5	7	46.4	1.1(0.09)	1.4(0.07)	2(0.06)	2(0.1)
GRQGSQ	9	10	821.8	0.6(0.03)	1.2(0.03)	1.7(0.08)	1.9(0.1)
GRQICQ	8	10	648.3	0.7(0.08)	1(0.04)	2(0.23)	1.9(0.2)
GRQLMQ	10	9	622.3	0.6(0.04)	0.8(0.02)	1.2(0.03)	1.4(0)
GRQMNT	7	6	171.1	0.7(0.07)	0.5(0.04)	0.9(0.03)	1.2(0)
GRQMOQ	5	10	213.8	0.9(0.04)	1.2(0.03)	1.8(0.04)	2(0.1)
GRQSMQ	8	5	489.9	*	1(0.03)	*	*
GRQTRQ	14	9	117.8	0.5(0.08)	0.3(0.04)	0.6(0.02)	0.8(0)
GSQLMQ	26	10	220.2	0.7(0.09)	1.3(0.03)	1.6(0.03)	1.6(0)
GSQMNT	23	16	813.8	1.1(0.06)	1.5(0.07)	*	*
GSQMOQ	9	11	696.9	1.2(0.08)	1.6(0.05)	2.2(0.08)	2.4(0.1)
GSQOTT	5	10	1031.7	0.9(0.06)	*	*	*
GSQTRQ	14	10	803.8	0.8(0.07)	1.4(0.04)	1.7(0.08)	*
GSQWBO	10	14	993.6	1.1(0.08)	*	*	*
ICQLMQ	23	7	225.7	0.8(0.09)	0.8(0.04)	1.3(0.05)	1.4(0.1)
ICQMNT	19	5	790.5	0.9(0.06)	1.1(0.04)	*	*
ICQMOQ	7	8	706.2	*	1.3(0.05)	*	*
ICQOTT	9	14	997.1	0.8(0.04)	1.4(0.06)	*	*
ICQTRQ	16	13	696.7	0.8(0.07)	1.2(0.06)	1.4(0.04)	*
LMQMNT	19	14	378	0.8(0.07)	1(0.06)	1.4(0.11)	1.7(0.1)
LMQMOQ	5	8	297.7	*	1.2(0.04)	1.3(0.04)	1.6(0)
LMQOTT	5	16	532	*	2(0.04)	*	*
LMQTRQ	14	15	479.2	0.5(0.04)	1(0.02)	1.3(0.03)	1.5(0)
LMQWBO	11	22	459.8	*	1.4(0.07)	1.6(0.12)	1.4(0.1)
MNTTRQ	6	14	85.9	*	0.2(0.09)	0.5(0.05)	0.9(0)
MOQTRQ	5	18	114.7	0.8(0.06)	1.5(0.03)	2(0.04)	1.9(0.1)
MOQWBO	5	5	134.2	*	1.6(0.08)	2(0.14)	2(0.1)

Figure 6.8: Histograms of b determinations in Eastern Canada. Panel A is a typical result. Panel B is the result of an uneven event distribution with one poorly constrained observation. Event distributions are shown in Figure 6.8. All other histograms are given in Appendix 4.

Figure 6.9: Event distributions corresponding to histograms in Figure 6.8.

change in instrument response (i.e. temporary error in instrument response) or an overlay of the signal with some temporary cultural noise, affecting only that particular recording. The one anomalous (and possibly erroneous) recording is then used many times, as it is paired with every event to the east of stations A11. To reduce the impact of these possible anomalies or errors, paths with fewer than five events recorded to one side of the station pair were eliminated from the study. While this phenomenon may still be present in other pairs, the weight of an anomalous value is significantly less and mostly affect the standard deviation. All histograms are given in Appendix 4, excluding those with uneven event distributions.

Figure 6.10a shows the mean values of b for all stations pairs in Eastern Canada, including the CSZ pairs, determined by fitting a normal distribution to the histogram of observed b values for each station pair. The overall effects of attenuation appear to be modelled as approximately $R^{-1.2}$. This model would incorporate geometric spreading, anelastic attenuation and smooth out many important features such as the Moho bounce. However, it is apparent in Figures 6.10b-d that it is not appropriate to average over all frequencies, as b is highly dependent on frequency, as total attenuation includes the effects of anelastic attenuation.

By incorporating anelastic attenuation into the model implicitly, a dependence on both distance and frequency has been introduced to the value of b . The net increase in b with frequency is obvious (as are the effects of distance). This effect is explored in more detail in Figure 6.11, which plots the average b value, for path lengths < 700 km, as a function of frequency. The least-squares fit is given by:

$$b = 0.542 + 0.908 \log f \quad (6.2)$$

Figure 6.10: Average values of coefficient, b , of total attenuation. Panels B, C and D show the mean values of ' b ' for one frequency bin. Note the increase in the average value with increasing frequency.

Figure 6.11: Frequency dependence of calculated b values. Thick line is given by Equation 6.2 in text.

The overall attenuation rates determined by the RTSM compare remarkably well with those of Atkinson and Mereu (1992) when considered on a frequency-specific basis, simply smoothing over detailed attenuation changes with distance. This is illustrated in Figure 6.12. Figure 6.12 was constructed such that the two curves would meet at $\log R=1.25$; the correct total attenuation b for each frequency (from Equation 6.2) is plotted. The tri-linear function proposed by Atkinson and Mereu (1992) features a prominent flat portion, related to the Moho bounce. This feature is not reproduced in the RTSM results due to the geometric constraints. However, since the RTSM results include the contribution of anelastic attenuation implicitly, the average decay with distance matches the net decay of the tri-linear function. The differences between these models are not great; they are simply indicative of how different models can reproduce different features of the observations.

Aside from the dependence of b on pathlength, the location of the station pair may play a role in the value of b . Many of the station pairs in Eastern Canada are generally parallel to the St. Lawrence River. No significant trends in the determined value of b are apparent at either 2 Hz or 10 Hz, as shown in Figures 6.13a and 6.13b respectively. At the lower frequency (2 Hz), all station pairs at angles to the river, either straddling it or simply not at the same azimuth, appear to show low values of b . At higher frequencies (10 Hz) there are no apparent geographic patterns in the observed b values. This is surprising. It has been suggested, based on elongated isoseismal contours along the St. Lawrence in past historical earthquakes, that attenuation may be stronger across the structural grain of the St. Lawrence than along it. The results of this study, though not conclusive, appear to suggest the opposite. However, it is noteworthy that the high

Figure 6.12: RTSM total attenuation results compared to Atkinson and Mereu (1992). Note the general similarity, but features, such as the Moho bounce at approximately 100 km, are smoothed out of the RTSM method results.

Figure 6.13a: Average b value as a function of path location. Note higher coefficient of total attenuation values for paths along the St. Lawrence River. Note that b represents total attenuation.

Figure 6.13b: Average b value as a function of path location. There is no discernable pattern in the distribution of b at this frequency. Note that b represents total attenuation.

attenuation paths all connect to stations in the CSZ. It may be that the attenuation within the CSZ is a significant factor in these high b values.

6.3 Sensitivity of Direct Method to Choice of Attenuation Model

The source spectra obtained by the Direct method may be very sensitive to the choice of attenuation model. The model chosen to obtain the source spectra for this study (after Atkinson and Mereu, 1992) is described in chapter 3 with results presented in chapter 5. For comparison, consider the Atkinson (2004) model, where the apparent source spectrum is determined for observations made at hypocentral distances less than 70 km according to:

$$\Omega_{\text{source}}(f) = \Omega_{\text{main}}(f) R^{-B} \exp[\pi R f / (\beta Q)] \quad (6.3)$$

where $\Omega_{\text{source}}(f)$ is the source displacement, $\Omega_{\text{main}}(f)$ is the observed displacement, R is the hypocentral distance in km, f is the frequency, β is the shear wave velocity in km/s (3.8 km/s for Eastern North America after Atkinson and Mereu, 1992). The determined values from regression of a large ENA dataset are $B = 1.3$ and:

$$Q = 893 f^{0.32} \quad (6.4)$$

for frequencies less than 1 Hz or:

$$Q = 3.052 - 0.393 \log f + 0.945 (\log f)^2 + 0.327 (\log f)^3 \quad (6.5)$$

for all frequencies (Atkinson, 2004). For the purposes of direct comparison in this study, Equation 6.4 will suffice, as data from this study is unreliable at frequencies less than 1 Hz. At large distance the form is modified to accommodate the Moho bounce and Lg propagation effects. The earthquakes from the CSZ used in chapter 5 are all measured at hypocentral distances less than 70 km; thus there is no need to consider the modifications to the model at greater distances.

Differences between the source spectra derived using the two attenuation models will illustrate the sensitivity of the Direct method to model choice. Figure 6.14 shows the

Figure 6.14: Sensitivity of the Direct method to the choice of attenuation model. The new attenuation model of Atkinson (2004) (A04) predicts slightly larger attenuation at distances less than 70 km, as compared to the Atkinson and Mereu(1992) (AM92) model. Note that the corresponding differences in the Direct method derived source spectra are small.

source displacement spectra for one mainshock event (000131a, M1.7), as determined by the EGF method (symbols), the Direct method using the Atkinson and Mereu (1992) attenuation model (black line) and the Direct method using the Atkinson (2004) attenuation model (grey line). Because the net effects of both attenuation models are quite similar, there are only small differences between the resulting source spectra derived from the Direct method. Note that the apparent source spectrum obtained from the Atkinson, 2004 (A04) attenuation model is slightly lower and smoother than the apparent source spectrum obtained from the Atkinson and Mereu, 1992 (AM92) attenuation model. Both of these source spectra (AM92 and A04) exceed the source spectra derived from the EGF method. The source spectra derived from the EGF method may be more reliable because path effects are removed on a more specific basis. However, even for the EGF spectra, the absolute level is derived from the seismic moment value determined for the small event, by means of the Direct method. The overall level for the EGF method is therefore subject to the same attenuation sensitivity as are the Direct method source spectra. However, calibration of the overall levels for the EGF events using seismic moment determined independently from waveform modelling (such as CMT solutions) is possible. Atkinson (2004) has shown that moments determined from the Direct method are in good agreement with such independent estimates.

7. Conclusions

An accurate attenuation model is an essential building block for the development of regional ground motion relations and seismic hazard analysis. It is also needed in order to determine the apparent source spectra of earthquakes from seismographic observations. Source spectra can be used to determine important parameters such as seismic moment (M_0), corner frequency (f_0), and from M_0 , moment magnitude (M) and stress drop ($\Delta\sigma$) can be determined.

The purpose of this study was to evaluate different means of determining the source spectrum of an earthquake as well as different methods of calculating attenuation. In order to calculate the source spectrum, path effects and site effects must be removed from the observed spectrum; thus source, attenuation and site issues are linked. Geometric spreading and anelastic attenuation are the dominant path effects. Site effects, the result of the overlying soil column at the recording site, were not treated in detail as all study records were obtained on rock sites. The study therefore focused on attenuation and source properties.

Alternative methods of determining attenuation were examined. By modifying the Reverse Two-Station Method (RTSM) of Chun et al. (1987), the coefficient of total attenuation, given by R^{-b} , was calculated for specific travel paths in the Charlevoix Seismic Zone (CSZ), where the inter-station distance is small ($\Delta < 50$ km). For such cases, the determination of b is approximately equal to the coefficient of geometric spreading. This method was then applied to larger inter-station distances, determining the total attenuation, for paths in the remainder of Eastern Canada. While the total attenuation in this instance has the same functional form as geometric spreading, it is

important to note that anelastic attenuation is implicitly included within the coefficient (b).

The following conclusions were reached:

- 1) The apparent source spectra of small magnitude earthquakes follow the Brune point-source model, whereas other models (such as the two-corner model of Atkinson, 1993) are more appropriate for larger magnitude earthquakes. These results are similar to those found in previous studies for southeastern Canada (e.g. Atkinson, 1993; Sonley and Atkinson, 2001).
- 2) The Empirical Green's Function method of determining the apparent source spectrum provides results that are in good agreement, within uncertainty, with the source spectra derived from the Direct method. This result is in agreement with conclusions reached with other datasets (e.g. Hough et al., 2000; Sonley and Atkinson, 2001).
- 3) A new empirical relationship between M_N and M was determined (Equation 5.10): $M = 1.03M_N - 0.61$, valid over the magnitude range $0.8 < M < 6.0$. This relationship is nearly identical to that determined by Atkinson (1993) for earthquakes of $M > 4$. the agreement is remarkable given the different magnitude ranges of the datasets used.
- 4) An apparent failure of self-similarity was observed, in the form of a linear increase of stress drop with increasing M for events with M 1 to 3. The associated Brune radii do not appear to support quantization as an explanation for the failure of self-similarity, but due to uncertainty the data do not exclude this possibility. Previous studies have also noted this breakdown in self-similarity for small magnitude events, and suggested that it may be due to a minimum earthquake size, or "quanta" (Sacks and Rydelek, 1995). This issue requires further study.

- 5) Attenuation in the Charlevoix Seismic Zone (CSZ) was found to be higher than previously determined regional values. With total attenuation modelled as R^{-b} , b was found to be 1.36 ± 0.01 (standard error reported) on average. The coefficient $b=1.36$ represents geometric attenuation rates for direct waves in the CSZ, due to the short path lengths (<70 km) involved.
- 6) Total attenuation coefficients were determined for specific paths throughout Eastern North America, as tabulated in Table 6.1 and 6.2. These coefficients were found to be frequency dependent, largely due to the influence of anelastic attenuation on higher frequencies for long path lengths involved.

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Appendix 1A: Study events for extended CSZ dataset.

Note: 'g' in depth column indicates depth assigned by a geophysicist because it could not be determined from data. Magnitude values are calculated at the GSC, with MN being the preferred scale for moderate sized earthquakes, and ML for very small (ML<1.0) or off-shore events.

Date	Time	Latitude	Longitude	Depth	Magnitude
[yyymmdd]	[hh:mm:ss]	[°N]	[°W]	[km]	[GSC listed]
19990609	01:35:01	47.7	69.89	11.2	2.8
19990810	02:45:25	47.59	70.17	14.3	1.5
19990812	03:09:28	47.57	70.00	15.4	2.3
19990813	05:03:33	47.45	70.02	11.4	2.1
19990821	00:24:54	47.60	70.27	6.3	1.3
19990823	22:34:48	47.35	70.14	7.1	1.6
19990824	08:26:22	47.38	70.28	14.6	1.7
19990824	00:29:59	47.61	70.16	13.5	1.4
19990824	07:20:10	47.62	70.23	9.1	1.3
19990828	07:59:14	47.46	70.12	16.4	1.8
19990831	09:20:10	47.41	70.33	10.1	1.2
19991002	09:45:36	47.42	70.12	9.0	3.0
19991002	10:58:43	47.42	70.11	9.5	1.3
19991005	09:10:21	47.45	70.33	7.9	1.1
19991013	12:41:49	47.39	70.13	15.8	1.6
19991013	11:34:27	47.63	70.29	11.8	1.0
19991015	14:13:59	47.41	70.45	5.3	1.8
19991015	07:52:12	47.48	70.38	2.6	1.2
19991028	01:52:08	47.71	69.86	15.3	2.8
19991028	02:06:57	47.71	69.87	15.4	1.9
19991031	06:20:30	47.41	70.45	9.0	1.7
19991105	06:32:07	47.47	69.99	12.8	0.5
19991106	05:08:04	47.38	70.14	17.1	1.4
19991120	04:47:16	47.43	70.45	3.0	1.5
19991120	17:37:14	47.41	70.15	9.6	1.0
19991120	14:29:07	47.50	70.04	12.1	0.5
19991130	05:33:40	47.44	70.16	23.0	0.2
19991209	07:29:51	47.58	70.21	7.6	1.4
19991210	02:24:11	47.44	70.11	7.8	2.1
19991210	22:05:51	47.55	70.06	10.2	1.5
20000106	18:56:29	47.39	70.22	12.6	2.0
20000110	16:55:00	47.69	69.88	14.6	2.6
20000111	06:31:23	47.44	70.24	24.5	1.7
20000111	19:32:46	47.49	70.08	8.5	1.6
20000111	19:35:37	47.56	70.36	18.0g	1.3
20000115	04:50:52	47.45	70.23	24.0	2.8
20000115	13:30:35	47.58	69.95	11.0	1.3
20000115	16:14:11	47.49	70.41	6.9	0.4
20000117	08:50:20	47.39	70.49	10.3	0.7
20000121	04:54:35	47.54	70.40	0.0	0.6
20000123	10:05:59	47.43	70.54	8.8	2.5
20000123	10:26:27	47.52	70.22	13.8	1.0
20000124	14:32:00	47.71	69.86	15.2	1.3
20000131	02:26:20	47.42	70.44	4.8	2.0
20000201	11:59:34	47.53	70.05	13.3	1.5
20000203	02:46:29	47.42	70.45	5.7	2.1

Date	Time	Latitude	Longitude	Depth	Magnitude
20000205	15:39:04	47.38	70.26	15.7	1.5
20000209	23:42:22	47.48	69.98	13.1	2.5
20000209	23:59:07	47.48	69.97	13.0	1.1
20000210	00:37:41	47.48	69.98	13.1	1.7
20000214	04:43:26	47.42	70.43	5.9	0.7
20000218	03:55:19	47.51	70.39	5.8	1.0
20000224	02:01:04	47.51	70.04	12.1	2.0
20000224	02:19:14	47.51	70.04	12.1	2.0
20000225	07:13:09	47.68	69.89	10.6	1.1
20000225	06:36:44	47.53	70.29	10.6	1.0
20000227	11:43:28	47.52	69.93	10.8	1.9
20000228	14:37:08	47.77	69.95	14.5	0.9
20000301	21:56:13	47.63	70.11	19.5	1.7
20000302	19:40:08	47.49	70.39	3.8	0.7
20000308	14:33:57	47.60	69.94	12.2	2.0
20000308	03:41:02	47.66	69.96	12.7	1.3
20000308	08:58:41	47.53	70.41	10.5	0.9
20000311	02:21:17	47.39	70.30	11.7	1.3
20000313	04:26:17	47.58	70.26	4.8	1.2
20000313	10:54:54	47.60	70.29	3.4	1.2
20000314	00:37:21	47.62	69.89	14.8	2.3
20000317	08:34:35	47.42	70.33	8.7	1.3
20000326	02:07:46	47.52	69.95	9.8	1.4
20000327	14:51:27	47.42	70.32	10.7	1.9
20000329	02:33:42	47.75	69.74	18.0g	1.6
20000410	05:59:55	47.38	70.14	12.6	1.3
20000413	14:28:02	47.52	70.29	11.9	1.5
20000417	22:30:15	47.34	70.20	15.8	2.4
20000417	06:43:59	47.49	70.09	14.3	2.1
20000421	18:16:50	47.45	70.03	10.2	1.5
20000424	10:00:22	47.39	70.13	15.6	1.2
20000429	01:51:08	47.48	70.14	21.8	2.3
20000429	23:52:53	47.47	70.31	11.0	1.6
20000506	08:00:45	47.66	69.89	12.8	0.9
20000507	14:31:18	47.65	69.99	23.7	1.3
20000508	00:16:46	47.39	70.40	13.8	1.4
20000511	14:44:16	47.59	69.97	10.5	1.4
20000518	13:27:39	47.60	70.18	9.1	1.2
20000520	15:43:48	47.50	70.14	8.8	1.9
20000523	13:26:11	47.60	70.21	15.5	1.6
20000526	15:47:10	47.72	70.03	10.2	1.9
20000529	21:37:09	47.97	70.09	18.0g	1.0
20000604	07:36:20	47.41	70.06	8.2	1.1
20000610	22:33:40	47.53	70.04	6.5	1.0
20000612	20:36:56	47.67	70.15	11.7	1.4
20000614	20:02:24	47.33	70.11	19.0	2.2
20000615	09:25:53	47.67	69.80	11.4	3.7
20000619	03:02:44	47.55	70.05	14.0	2.0
20000619	05:31:24	47.60	69.94	11.1	1.3
20000620	20:12:05	47.41	70.09	8.5	2.2
20000621	12:16:44	47.65	69.91	13.1	2.4
20000622	01:49:50	47.72	70.22	4.8	1.2

Date	Time	Latitude	Longitude	Depth	Magnitude
20000624	02:12:46	47.39	70.13	15.6	0.9
20000625	06:19:20	47.41	70.23	12.8	0.9
20000628	09:37:38	47.33	70.49	12.8	1.3
20000702	02:01:07	47.73	70.12	7.9	1.0
20000703	11:01:43	47.43	70.16	11.6	2.5
20000704	06:35:15	47.54	70.18	25.2	1.2
20000706	10:17:56	47.44	70.19	13.0	1.4
20000709	13:34:51	47.48	69.98	13.1	1.9
20000709	21:12:22	47.42	70.35	13.6	1.3
20000709	00:24:04	47.54	70.28	13.1	1.1
20000713	00:11:19	47.60	70.28	13.6	1.3
20000714	02:42:03	47.80	69.81	18.4	1.3
20000716	03:43:36	47.53	70.07	10.6	1.0
20000718	00:16:03	47.65	69.89	13.2	1.3
20000720	19:36:19	47.61	70.23	5.8	1.1
20000723	12:41:39	47.22	69.94	23.1	1.5
20000727	01:45:24	47.21	70.70	18.0g	1.5
20000729	00:34:46	47.44	70.38	9.6	1.4
20000729	22:05:51	47.46	70.01	10.4	1.2
20000731	23:27:19	47.87	70.02	10.0g	1.4
20000801	04:27:51	47.42	70.44	5.9	1.9
20000802	01:42:44	47.44	70.39	5.4	1.4
20000803	20:14:01	47.79	69.91	14.6	1.6
20000804	02:42:52	47.42	70.51	13.3	0.8
20000809	22:05:55	47.50	70.05	10.5	1.6
20000812	13:11:39	47.51	70.36	4.1	1.2
20000812	09:34:59	47.42	70.36	93.4	0.7
20000814	04:25:22	47.94	69.74	20.2	1.2
20000814	17:11:04	47.55	70.23	12.2	1.2
20000814	01:53:02	47.59	70.19	16.1	0.1
20000815	02:33:14	47.77	70.11	12.8	1.2
20000816	11:52:26	47.79	69.93	15.7	2.5
20000816	16:33:13	47.42	70.44	4.1	1.9
20000818	22:52:32	47.51	70.10	21.1	1.1
20000818	07:59:43	47.65	69.98	20.5	0.9
20000819	08:53:31	47.72	70.07	9.7	0.9
20000829	23:26:23	47.43	70.05	11.3	1.2
20000831	06:15:27	47.74	69.91	24.7	1.2
20000831	03:06:31	47.59	69.99	10.2	1.1
20000902	02:02:44	47.43	70.04	6.8	1.3
20000903	18:37:51	47.78	69.87	22.9	1.6
20000905	07:00:40	47.49	70.08	12.2	1.6
20000906	17:44:33	47.78	69.84	21.4	1.4
20000908	11:42:01	47.50	70.39	4.3	1.2
20000910	07:00:45	47.54	70.26	10.3	1.7
20000910	17:43:22	47.76	69.76	17.3	1.7
20000911	16:24:26	47.48	70.37	3.5	1.6
20000914	16:34:12	47.68	70.05	8.9	1.3
20000918	06:38:05	47.44	70.01	12.5	1.4
20000920	02:03:53	47.49	70.37	0.0	1.2
20000920	02:16:06	47.57	70.07	10.4	0.9
20000921	20:26:31	47.48	69.97	12.6	2.7

Date	Time	Latitude	Longitude	Depth	Magnitude
20000921	09:51:56	47.55	70.20	20.4	1.4
20000924	04:27:50	47.53	70.17	12.7	1.8
20000924	13:19:36	47.47	70.32	10.8	1.1
20000925	11:25:01	47.49	69.98	11.7	1.4
20000927	12:42:01	47.47	70.04	8.1	3.0
20000927	04:52:41	47.70	70.07	9.8	1.8
20000930	19:00:36	47.41	70.42	6.2	1.4
20001002	01:54:48	47.36	70.52	0.7	1.8
20001003	01:22:33	47.61	70.20	13.7	1.3
20001008	08:40:28	47.59	70.31	11.2	1.4
20001009	03:21:11	47.46	70.09	10.0	1.1
20001010	22:20:14	47.38	70.45	12.8	2.3
20001012	14:16:11	47.59	70.00	11.7	2.5
20001013	17:54:09	47.44	70.35	7.6	1.3
20001014	22:11:52	47.59	70.00	11.5	1.9
20001015	21:28:20	47.45	70.04	5.9	1.5
20001017	03:33:40	47.42	70.44	4.5	1.1
20001018	02:22:15	47.59	70.31	11.1	1.5
20001019	20:02:14	47.61	69.97	9.4	2.0
20001019	16:15:01	47.58	69.95	10.6	1.5
20001022	15:21:52	47.40	70.41	4.9	2.1
20001026	09:24:52	47.28	70.22	8.5	2.3
20001102	03:25:25	47.62	70.24	16.7	0.8
20001103	17:21:03	47.42	70.06	11.6	2.3
20001103	01:05:27	47.69	70.07	12.1	0.9
20001104	02:59:42	47.66	69.96	16.6	1.2
20001115	08:03:58	47.55	70.37	5.4	1.1
20001117	10:48:39	47.41	70.20	13.3	1.3
20001130	14:45:57	47.46	70.01	10.1	1.3
20001130	20:54:00	47.69	70.08	5.4	1.2
20001201	02:50:16	47.52	70.21	13.3	2.4
20001204	06:44:54	47.40	70.17	10.3	2.4
20001204	21:55:29	47.58	69.96	10.3	1.9
20001204	00:36:49	47.48	70.28	12.1	1.3
20001205	06:40:30	47.43	70.31	11.7	1.2
20001206	09:17:54	47.53	70.29	10.9	1.5
20001212	13:48:24	47.57	70.20	1.6	2.3
20001212	02:38:43	47.54	70.17	15.1	1.2
20001215	11:12:16	47.47	70.11	7.6	1.1
20001217	06:27:29	47.49	70.10	7.3	1.9
20001219	17:33:11	47.49	70.37	9.8	1.8
20001224	00:19:49	47.31	70.44	20.0	2.2
20001226	19:55:01	47.49	70.40	0.0	1.0
20001227	16:23:30	47.51	70.44	17.5	0.8
20010101	05:41:53	47.54	70.19	23.8	1.5
20010103	07:30:03	47.67	70.28	8.3	1.1
20010106	15:55:25	47.44	70.07	8.9	1.0
20010111	03:02:11	47.53	70.01	14.4	1.3
20010112	18:22:39	47.47	70.06	6.4	1.8
20010112	18:39:16	47.47	70.05	7.7	1.3
20010114	17:56:02	47.40	70.37	7.4	1.1
20010115	05:15:19	47.81	69.82	24.7	1.4

Date	Time	Latitude	Longitude	Depth	Magnitude
20010121	01:46:10	47.45	70.37	6.1	0.7
20010127	02:38:47	47.42	70.36	6.5	0.9
20010129	05:11:44	47.55	70.24	12.1	1.4
20010131	13:52:30	47.53	70.13	14.9	2.1
20010131	19:29:48	47.49	69.97	12.8	0.0
20010203	13:00:58	47.80	69.80	20.3	1.1
20010204	08:09:46	47.53	70.00	8.6	1.0
20010205	23:07:00	47.43	70.38	5.6	1.4
20010207	12:22:06	47.50	70.12	8.1	1.3
20010213	19:25:18	47.43	70.45	2.6	1.1
20010215	07:47:20	47.59	69.98	9.9	2.1
20010215	18:49:26	47.54	70.05	7.4	0.0
20010219	03:39:57	47.82	70.16	25.6	2.2
20010225	00:01:24	47.67	69.80	11.3	1.9
20010306	02:09:03	47.49	70.08	7.9	2.2
20010306	04:32:18	47.42	70.42	6.4	0.8
20010311	23:44:06	47.61	70.19	10.5	1.9
20010312	13:44:06	47.42	70.35	7.2	1.1
20010316	04:29:04	47.39	70.30	6.4	0.7
20010317	17:48:36	47.63	70.25	5.7	0.8
20010318	20:19:47	47.36	70.50	16.5	1.1
20010318	06:45:56	47.59	70.20	9.4	0.9
20010318	10:16:23	47.58	69.88	18.0	0.1
20010319	13:04:34	47.63	70.21	13.9	1.1
20010323	11:18:27	47.68	69.92	12.9	1.6
20010325	07:20:08	47.38	70.24	20.9	1.4
20010326	23:54:45	47.45	70.07	5.8	1.4
20010329	08:17:58	47.47	70.12	15.1	1.7
20010331	15:52:59	47.60	69.92	12.4	1.4
20010401	04:19:56	47.61	69.91	12.4	1.6
20010403	17:28:43	47.38	70.26	13.3	1.3
20010403	07:54:55	47.46	70.29	13.8	1.1
20010403	23:39:23	47.37	70.61	12.2	0.9
20010406	03:57:42	47.51	70.03	12.8	1.3
20010407	16:50:00	47.58	69.97	10.6	1.5
20010409	10:37:50	47.53	70.14	17.6	1.0
20010409	10:38:02	47.53	70.14	17.3	0.9
20010414	16:02:13	47.48	70.05	5.7	1.4
20010415	12:06:05	47.33	70.27	9.4	1.1
20010416	08:31:52	47.53	70.39	3.1	1.3
20010418	04:52:21	47.48	70.05	15.6	1.7
20010421	20:09:07	47.72	69.92	19.5	1.9
20010421	21:07:03	47.46	70.05	13.9	0.1
20010427	23:33:01	47.49	70.11	4.3	1.6
20010428	07:10:43	47.41	70.30	13.4	2.1
20010503	20:07:44	47.43	70.16	11.3	2.2
20010503	09:46:04	47.45	70.02	10.9	0.5
20010504	18:48:41	47.40	70.42	5.8	1.9
20010504	06:56:42	47.69	70.21	2.6	0.3
20010509	01:59:37	47.44	70.34	9.3	0.9
20010513	22:22:25	47.46	70.05	12.2	1.5
20010514	04:08:59	47.42	70.42	6.2	1.3

Date	Time	Latitude	Longitude	Depth	Magnitude
20010516	06:59:34	47.69	70.08	12.1	1.2
20010518	17:26:49	47.41	70.42	5.3	1.5
20010519	09:36:09	47.69	69.95	24.6	0.9
20010522	00:33:29	47.65	69.92	11.4	3.5
20010522	00:36:47	47.65	69.92	10.9	3.1
20010522	00:31:55	47.66	69.92	8.9	2.1
20010524	23:46:54	47.52	70.02	8.9	1.7
20010526	11:41:27	47.71	69.74	28.5	1.3
20010526	10:19:57	47.55	70.03	13.6	1.1
20010527	15:03:35	47.49	70.08	14.9	1.8
20010527	01:54:11	47.47	70.06	17.8	1.0
20010528	10:27:29	47.46	70.12	8.1	1.5
20010529	06:18:40	47.31	70.44	7.6	1.6
20010606	05:51:57	47.54	70.11	10.5	2.1
20010608	07:10:31	47.52	70.03	16.4	1.0
20010610	15:59:32	47.29	70.21	16.8	2.8
20010610	18:23:52	47.43	70.30	12.7	1.2
20010610	04:49:45	47.56	70.22	4.5	0.8
20010615	23:58:16	47.44	70.06	8.2	1.3
20010619	05:21:54	47.69	70.10	11.3	2.5
20010620	14:13:06	47.56	70.03	7.4	1.7
20010622	03:29:02	47.39	70.13	16.0	2.0
20010622	15:17:14	47.50	70.02	16.5	1.2
20010624	13:32:19	47.80	69.82	21.7	1.2
20010626	03:31:00	47.57	70.35	17.0	1.3
20010701	10:35:32	47.63	70.19	15.4	1.6
20010705	10:32:55	47.24	70.34	8.6	2.3
20010706	15:22:03	47.40	70.38	8.3	1.7
20010710	12:30:19	47.43	70.06	18.0	2.2
20010710	06:37:32	47.59	70.23	12.1	1.0
20010719	01:16:13	47.53	70.36	6.0	1.0
20010721	13:11:55	47.73	70.11	9.7	1.3
20010721	06:52:00	47.41	70.26	16.0	0.9
20010723	10:36:39	47.51	70.20	14.2	1.5
20010724	06:49:38	47.49	70.20	17.3	1.9
20010727	23:12:41	47.69	69.86	14.4	2.1
20010728	10:56:50	47.62	70.16	14.4	1.4
20010803	04:31:53	47.61	70.22	13.8	1.9
20010806	11:58:03	47.46	70.38	15.6	1.6
20010811	14:36:35	47.51	70.04	11.9	1.8
20010814	09:24:17	47.61	69.89	14.8	1.4
20010817	21:44:23	47.56	69.97	16.8	1.3
20010820	07:16:48	47.43	70.16	10.4	1.7
20010826	00:02:22	47.68	69.92	9.1	1.4
20010826	16:41:26	47.50	70.07	10.4	1.2
20010830	07:59:58	47.70	69.89	8.4	1.5
20010902	01:29:07	47.44	70.16	11.4	1.0
20010907	03:38:41	47.58	70.25	6.5	1.4
20010907	23:42:08	47.53	70.20	16.0	1.1
20010908	05:31:21	47.79	69.86	23.0	2.5
20010909	08:43:44	47.65	69.96	13.1	1.5
20010909	10:41:16	47.40	70.38	7.8	1.2

Date	Time	Latitude	Longitude	Depth	Magnitude
20010910	19:51:50	47.74	69.77	5.4	1.2
20010911	14:32:12	47.42	70.44	6.0	1.9
20010915	05:36:47	47.50	69.97	8.8	1.9
20010917	14:29:58	47.22	70.30	12.3	1.4
20010920	22:33:11	47.41	70.08	21.6	2.1
20010921	04:43:04	47.69	70.10	4.8	2.5
20010921	05:20:58	47.41	70.30	13.2	1.2
20010928	08:32:53	47.56	70.27	16.6	0.9
20010930	21:00:39	47.57	69.99	8.9	1.1
20011003	05:29:20	47.40	70.48	9.9	2.9
20011022	09:43:24	47.59	69.88	15.8	1.8
20011025	08:11:59	47.34	70.20	23.6	2.3
20011026	12:57:41	47.39	70.11	17.5	2.4
20011026	05:08:30	47.36	70.23	12.9	2.3
20011027	15:49:29	47.60	70.25	11.8	1.6
20011029	21:38:37	47.68	70.18	8.1	1.7
20011103	14:46:32	47.42	70.42	6.0	1.7
20011103	11:45:44	47.41	70.34	9.4	1.6
20011106	20:09:37	47.81	69.82	22.0	1.7
20011109	10:23:48	47.51	69.96	7.2	2.2
20011111	13:22:22	47.86	69.93	25.9	2.5
20011111	14:46:08	47.86	69.92	25.1	1.2
20011116	07:29:52	47.79	69.91	24.1	1.7
20011118	00:44:51	47.33	70.49	12.6	1.3
20011118	15:57:48	47.43	70.40	13.9	1.1
20011119	02:08:08	47.38	70.51	5.9	1.1
20011120	08:38:18	47.48	70.39	4.4	1.4
20011123	10:41:08	47.59	70.17	10.3	1.2
20011202	08:38:29	47.59	70.05	24.9	2.0
20011205	18:48:27	47.55	70.25	9.2	2.4
20011205	04:57:56	47.57	70.00	13.1	1.7
20011207	06:44:55	47.57	70.00	13.4	1.7
20011212	09:51:38	47.80	69.82	23.0	1.4
20011213	07:56:48	47.23	70.53	26.0	2.5
20011214	10:04:46	47.40	70.20	8.9	0.8
20011219	07:52:52	47.65	70.01	27.8	1.9
20011219	04:24:01	47.54	70.16	18.8	1.1
20011222	19:06:56	47.41	70.41	5.7	1.1
20011223	23:10:57	47.48	70.15	19.4	0.8
20011224	02:36:22	47.49	70.16	15.1	2.1
20011224	19:32:57	47.48	70.05	17.1	1.9
20011226	10:47:16	47.38	70.25	12.7	1.4
20011230	11:45:37	47.62	69.79	20.0	1.0
20011231	16:30:31	47.39	70.40	7.6	0.8
20020101	02:16:35	47.60	70.19	10.5	1.5
20020101	05:27:36	47.43	70.45	4.9	0.6
20020106	22:26:05	47.30	70.38	3.3	1.1
20020107	01:54:02	47.49	70.20	16.5	1.3
20020112	03:39:56	47.45	70.06	21.8	1.6
20020113	15:33:54	47.86	69.95	21.8	1.3
20020115	04:31:49	47.55	70.03	8.5	2.3
20020119	01:18:05	47.48	70.11	22.9	2.6

Date	Time	Latitude	Longitude	Depth	Magnitude
20020119	13:32:47	47.44	70.04	14.7	2.0
20020119	12:06:43	47.72	69.96	23.5	1.5
20020119	23:56:00	47.63	69.91	11.7	1.4
20020123	04:51:47	47.52	70.36	4.2	1.1
20020123	17:40:10	47.50	70.39	3.5	1.1
20020125	06:54:09	47.41	70.43	10.4	0.7
20020126	06:13:59	47.53	70.18	15.4	1.8
20020126	06:25:35	47.53	70.18	15.2	1.1
20020127	00:45:01	47.54	70.30	8.3	1.0
20020130	04:53:04	47.53	70.13	16.9	1.2
20020130	21:10:34	47.70	70.03	15.1	1.1
20020131	20:51:54	47.35	70.40	11.9	2.5
20020202	03:40:47	47.35	70.33	10.6	1.9
20020203	13:27:33	47.54	70.05	7.7	1.4
20020203	22:17:40	47.39	70.12	8.7	1.0
20020206	23:39:49	47.56	70.28	9.1	1.1
20020208	22:21:29	47.50	70.06	15.8	1.6
20020209	01:00:38	47.53	70.03	7.5	0.9
20020211	13:53:22	47.53	70.40	0.7	0.2
20020213	22:48:34	47.46	70.05	12.3	2.1
20020213	02:29:05	47.57	70.30	10.7	1.3
20020214	11:14:36	47.50	70.11	11.1	1.3
20020214	08:21:41	47.62	69.98	6.1	1.0
20020215	11:00:10	47.50	70.04	11.9	2.1
20020215	22:50:51	47.57	70.20	10.9	0.8
20020216	21:49:55	47.82	69.79	22.7	1.2
20020217	04:44:41	47.49	70.06	15.8	1.2
20020218	04:12:38	47.57	70.30	5.5	1.1
20020219	03:18:14	47.49	70.07	15.7	1.7
20020220	23:20:26	47.61	70.21	12.7	0.0
20020222	12:51:12	47.59	69.93	11.3	1.7
20020223	18:46:30	47.48	70.18	8.4	1.2
20020225	23:37:36	47.56	70.30	9.8	2.4
20020225	06:09:14	47.52	70.19	17.4	2.2
20020225	23:38:26	47.56	70.30	9.4	0.5
20020303	13:10:26	47.42	70.15	20.1	1.3
20020307	02:50:48	47.60	69.90	13.3	1.4
20020309	00:55:22	47.67	70.15	10.9	2.1
20020309	19:45:21	47.78	70.08	10.7	1.1
20020311	16:33:57	47.64	70.30	6.0	1.4
20020313	04:19:13	47.67	70.13	10.9	0.8
20020316	06:13:00	47.58	70.01	6.3	1.1
20020320	05:37:05	47.47	70.11	10.6	1.0
20020323	00:59:26	47.41	70.40	6.2	1.5
20020323	02:47:44	47.40	70.40	6.1	1.5
20020325	08:47:30	47.38	70.23	13.1	0.8
20020403	18:09:13	47.44	70.41	7.7	2.1
20020404	22:37:34	47.21	70.40	11.4	2.4
20020406	23:11:12	47.70	70.09	9.5	0.9

Appendix 1B: Study events for Eastern North America, as listed at www.seismo.nrcan.gc.ca.

Note: 'g' in depth column indicates depth assigned by a geophysicist because it could not be determined from data. Magnitude values are calculated at the GSC, with MN being the preferred scale for moderate sized earthquakes, and ML for very small ($ML < 1.0$) or off-shore events.

Date	Time	Latitude	Longitude	Depth	Magnitude
[yyymmdd]	[hh:mm:ss]	[°N]	[°W]	[km]	[GSC listed]
19980518	15:41	45.18	74	18g	2.5
19980521	2:05	57.83	60.94	18g	4
19980614	8:48	53.09	79.9	18g	2.6
19980615	8:51	59.68	75.94	18g	3.6
19980617	20:06	45.95	74.9	18g	2.8
19980629	12:11	59.92	73.98	18g	3.1
19980709	1:52	44.8	73.74	18g	2.5
19980713	14:20	49.36	66.14	18g	3.1
19980715	7:08	47.03	66.62	5g	4
19980729	3:32	48.39	104.77	0g	3.4
19980730	8:57	46.19	74.8	10g	4.4
19980730	2:22	46.35	76.15	18g	2.7
19980730	10:29	46.19	74.8	10g	2.5
19980808	8:23	49.05	68.34	18g	2.9
19980824	19:27	43.87	75.76	18g	3.1
19980905	5:19	44.2	68.71	18g	2.5
19980913	6:23	46.86	76.95	18g	2.7
19980916	7:49	44.92	67.21	5g	2.6
19980918	21:30	49.06	67.59	18g	3.6
19980924	18:15	46.5	76.31	18g	2.8
19980925	19:52	41.52	80.53	5g	5.4
19980927	8:18	46.47	76.21	18g	2.7
19980929	1:03	45.88	75.35	18g	2.8
19981005	9:22	45.14	75.52	18g	2.5
19981008	18:13	46.39	74.01	18g	2.5
19981021	7:44	47.56	70.28	9.8	2.6
19981022	9:43	49.34	66.88	18g	4.1
19981023	7:02	45.71	73.82	18g	2.5
19981105	1:33	49.06	67.89	18g	2.5
19981111	11:59	48.49	103.99	10g	3.5
19981125	2:55	41.1	82.63	5g	3.2
19981128	16:38	45.78	77	18g	2.5
19981201	5:02	46.59	74.29	18g	2.6
19981207	13:37	52.68	79.83	18g	3.3
19981225	13:30	43.83	77.91	18g	3.6
19981229	23:15	47.03	66.56	5g	3
19990110	10:52	42.87	71	2g	3.1
19990110	15:20	42.86	70.96	2g	3
19990119	6:23	45.44	74.53	18g	3
19990122	4:27	49.13	67.09	18g	3.5
19990125	20:12	42.79	77.82	5g	2.7
19990126	8:14	45.92	74.85	18g	2.9
19990127	1:38	42.33	82.3	5g	2.6
19990127	1:57	42.31	82.31	5g	2.5
19990201	22:22	49.26	80.94	18g	3.4
19990203	22:48	49.74	66.98	18g	2.5

Date	Time	Latitude	Longitude	Depth	Magnitude
19990223	1:10	48.02	70.67	18g	2.7
19990223	11:12	47.61	65.99	5g	2.7
19990226	3:38	44.62	69.67	18g	3.8
19990308	11:38	46.04	74.99	18g	2.8
19990309	12:07	44.77	73.83	10g	3
19990315	14:32	45.89	74.38	18g	2.8
19990316	12:50	49.61	66.32	18g	5.1
19990316	15:04	49.62	66.34	18g	2.6
19990316	17:33	49.61	66.31	18g	2.6
19990317	8:55	49.62	66.32	18g	2.5
19990317	14:26	49.61	66.29	18g	2.5
19990322	6:03	49.62	66.38	18g	2.5
19990325	14:06	45.96	74.86	18g	3
19990330	13:30	59.81	72.94	18g	3.3
19990330	15:51	49.63	66.39	18g	2.7
19990418	20:21	47.44	70.47	9.2	2.5
19990515	3:21	46.98	79.07	18g	3
19990525	16:28	47	66.6	5g	2.7
19990530	9:30	47.11	76.37	18g	2.9
19990530	14:33	46.55	78.39	18g	2.6
19990609	1:35	47.7	69.89	11.2	2.8
19990618	23:19	46.47	75.1	18g	3.5
19990623	20:06	50.12	71.22	18g	2.5
19990707	6:37	49.63	66.41	18g	2.7
19990714	11:11	46.59	75.39	18g	2.9
19990726	17:35	47.48	70.12	20.5	2.6
19990727	12:23	46.57	69	5g	2.7
19990729	20:00	49.27	67.64	18g	2.5
19990729	19:12	43.53	79.35	5g	2.4
19990815	17:12	46.28	75.58	18g	2.9
19990818	5:05	53.27	78.85	18g	3
19990821	6:38	49.45	66.45	18g	2.6
19990828	23:01	42.56	77.97	5g	2.6
19990902	16:17	41.7	89.4	5g	3.5
19990910	13:41	46.99	66.01	5g	3.2
19990918	16:09	47.51	70.04	12.2g	2.7
19990922	13:09	47.61	66.38	5g	3.2
19990922	10:02	41.83	81.48	18g	2.8
19990928	18:47	47	66.6	5g	3
19991002	9:45	47.42	70.12	8.7	3
19991002	14:37	49.02	67.56	18g	2.7
19991028	1:52	47.71	69.86	15.3	2.8
19991031	20:14	45.86	74.3	18g	4.2
19991101	2:21	46.85	78.86	18g	2.9
19991101	10:12	42.78	78.93	18g	2.7
19991107	23:02	50.03	65.41	18g	2.5
19991121	1:40	59.36	73.24	18g	3.2
19991124	19:08	49.12	67.56	18g	2.9
19991126	22:33	43.7	78.98	5g	3.8
19991212	6:21	46.84	75.86	18g	2.9
19991217	21:00	51.58	89.64	18g	3.9

Date	Time	Latitude	Longitude	Depth	Magnitude
19991218	21:57	51.6	89.91	18g	3
19991221	9:17	46.78	76.6	18g	3
19991225	0:21	44.91	69.25	18g	3
20000101	11:22	46.84	78.93	12g	5.2
20000103	21:05	44.31	70.17	10g	3.5
20000106	21:03	49.4	65.91	18g	2.5
20000108	1:25	49.56	66.76	18g	2.5
20000110	16:55	47.69	69.88	14.6	2.6
20000114	12:14	46.96	76.25	18g	2.5
20000115	4:50	47.45	70.23	24	2.8
20000117	8:16	44.6	70.47	10g	3.6
20000121	5:59	42.99	71.18	5g	2.6
20000123	10:05	47.44	70.54	8.7	2.5
20000124	7:27	47	76.69	18g	2.7
20000127	14:49	43	71.18	5g	3
20000127	13:21	48.32	69.25	18g	2.7
20000207	11:59	49.07	66.99	18g	3.1
20000207	2:36	45.97	75.44	18g	2.9
20000209	23:42	47.48	69.98	13.1	2.5
20000216	16:55	47.38	65.1	18g	2.5
20000219	17:10	49.75	66.5	18g	2.5
20000221	11:30	47.18	76.56	18g	2.7
20000302	20:48	46.12	75.7	18g	3
20000312	16:16	50.13	71.35	18g	2.7
20000320	1:04	46.54	76.64	18g	3.2
20000321	12:02	58.5	71.88	18g	2.8
20000405	8:19	46.52	72.28	18g	3.1
20000408	10:35	48.18	90.97	18g	2.5
20000409	17:29	60	71.02	18g	3.3
20000416	18:59	43.98	74.26	5g	2.7
20000420	8:46	44.01	74.32	18g	4
20000504	22:45	51.34	77.63	18g	2.9
20000508	12:56	46.97	78.6	18g	2.5
20000518	11:41	59.78	108.12	18g	2.6
20000519	19:54	50.31	64.99	18g	3
20000524	10:22	43.78	79.09	5g	3.1
20000528	20:26	44.43	77.5	10g	2.7
20000531	5:36	44.42	77.51	18g	2.5
20000607	2:56	49.57	66.93	19.4	2.6
20000608	11:59	46.85	71.41	18g	2.8
20000610	11:01	51.07	62.94	18g	3.1
20000615	9:25	47.67	69.8	11.4	3.7
20000616	4:02	42.12	72.85	10g	3.3
20000628	10:04	51.88	93.06	18g	3
20000629	8:15	46.91	70.77	18g	3.2
20000630	18:44	51.86	92.72	18g	3.1
20000703	11:01	47.43	70.16	11.6	2.5
20000703	23:05	50.2	60.77	18g	2.5
20000711	20:13	45.34	75.3	18g	2.5
20000712	15:01	47.56	71.06	18g	4.2
20000712	15:07	47.55	71.08	18g	2.5

Date	Time	Latitude	Longitude	Depth	Magnitude
20000714	1:40	51.88	92.67	18g	2.9
20000722	5:02	43.47	75.24	18g	2.7
20000727	19:28	46.91	76.5	18g	2.9
20000806	8:52	46.19	74.97	18g	4.2
20000806	6:21	44.33	74.46	18g	3.2
20000807	2:02	40.89	81.22	18g	3.3
20000816	11:52	47.79	69.93	15.7	2.5
20000901	9:10	44.4	74.92	18g	2.6
20000903	5:31	51.62	89.85	18g	2.7
20000907	10:07	44.4	69.52	18g	3.3
20000920	4:59	43.99	73.23	18g	2.6
20000921	21:41	47.75	80.57	18g	3
20000921	20:26	47.49	69.98	7.4	2.7
20000927	12:42	47.47	70.04	8.1	3
20001002	14:55	46.74	76.41	18g	2.8
20001005	22:39	44.43	77.5	5g	2.5
20001006	13:59	45.1	74.02	18g	3.8
20001006	2:41	46.31	75.14	18g	2.4
20001009	23:22	43.63	78.36	18g	2.8
20001009	19:00	52.68	80.29	18g	2.7
20001010	19:46	46.28	76.9	18g	3
20001012	14:16	47.59	70	11.7g	2.5
20001015	23:49	43.69	71.38	5g	2.6
20001020	23:26	41.93	80.78	5g	2.5
20001023	10:03	45.82	77.35	18g	2.9
20001023	10:25	45.64	75.2	18g	2.6
20001023	12:12	50.01	64.66	18g	2.6
20001101	15:30	47.13	76.5	18g	2.7
20001105	16:14	49.67	81.47	18g	2.7
20001106	12:16	42.76	74.07	8g	3.1
20001108	3:16	49.29	65.7	18g	2.6
20001110	7:40	45.74	75.3	18g	3.3
20001201	4:48	49.63	66.94	18g	2.8
20001208	4:40	50.33	64.97	18g	2.8
20010106	9:10	51.91	92.72	18g	2.8
20010109	16:23	50	82.34	18g	2.5
20010114	11:03	45.94	74.97	18g	3.3
20010126	3:03	41.93	80.72	5g	4.4
20010126	5:36	41.98	80.7	5g	3.2
20010203	20:15	42.44	77.48	5g	3.2
20010203	20:15	42.44	77.48	5g	3.2
20010203	0:34	46.06	75.01	18g	2.6
20010206	14:44	46.05	75	18g	3
20010319	10:40	47.05	76.28	18g	3.9
20010324	11:57	50.03	63.35	18g	4.2
20010411	21:30	47.05	76.1	18g	3.6
20010522	0:36	47.65	69.92	10.9	3.1
20010612	16:45	47	76.36	18g	3.4
20010726	10:46	41.2	82.51	5g	3.1
20010727	13:57	45.95	74.81	18g	3.4
20010818	9:41	49.61	66.51	18g	3

Date	Time	Latitude	Longitude	Depth	Magnitude
20010915	15:14	59.2	71.39	5g	4.1
20010916	6:20	50.64	63.35	5g	3.7
20010924	4:24	45.87	82.26	5g	3.2
20010926	21:06	46.49	80.07	5g	3.1
20011025	0:24	45.01	68.18	18g	3.2
20011110	5:18	46.44	76.32	18g	3.2
20011114	20:21	46.51	77.37	18g	3.2
20011115	7:06	46.74	76.12	18g	3.2
20011129	7:35	52.11	107.07	0.4	3.1
20011224	16:58	46.87	76.49	18g	3.8
20020120	14:11	49.49	66.95	30g	4.1
20020211	11:41	46.06	73.46	10g	3.8
20020224	21:38	45.29	75.17	18g	3.1
20020301	13:52	46.75	76.13	18g	2.8
20020312	7:13	41.19	69.12	18g	3
20020401	16:05	46.3	75.76	18g	3.1
20020420	10:50	44.53	73.73	18g	5.5
20020420	11:45	44.58	73.69	18g	3.1
20020420	11:08	44.53	73.7	18g	3
20020420	11:08	44.53	73.7	18g	3
20020425	12:51	46.22	72.73	18g	3.1
20020427	7:09	46.97	76.25	18g	3.1
20020503	17:07	46.11	75.02	18g	2.7
20020514	7:26	47.66	69.97	14.1	3.1
20020521	6:04	50.1	92.72	5g	3.2
20020524	23:45	44.5	73.68	10g	3.5
20020528	9:15	45.63	76.62	18g	3.4
20020601	11:35	45.59	73.86	18g	3.2
20020605	20:17	52.85	74.35	5g	4.5
20020612	17:14	47.51	70.02	7.8	3.1
20020625	13:40	44.53	73.67	10g	3.4
20020723	2:08	49.59	66.95	18g	4
20020726	8:32	44.4	98.74	18g	3.1
20020817	5:53	47.33	70.51	13.3	3.8
20020824	6:47	47.43	74.88	18g	3.1
20020907	21:27	46.96	76.29	18g	3.7
20021019	20:57	47.44	65.95	5g	3.1
20021107	16:55	44.06	77.43	18g	3
20021121	11:41	53.22	80.81	18g	3

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

000106a; M1.7, f_0 min 10 Hz

000110a; M2.1, f_0 min 12.6 Hz

000111b; M1.1, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

000115a; M2.3, f_0 min 10 Hz

000123a; M2.1, f_0 8.1 Hz

000131a; M1.7, f_0 min 10 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

000203a; M1.8, f_0 min 10 Hz

000209a; M1.8, f_0 min 12.6 Hz

000210a; M1.2, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

000224b; M1.4, f_0 min 12.6 Hz

000308c; M1.1, f_0 min 12.6 Hz

000314a; M1.4, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

000417b; M2.1, f_0 min 10 Hz

000429a; M1.8, f_0 min 12.6 Hz

000614a; M1.7, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

000615a; M3.2, f_0 6.35 Hz

000619a; M1.3, f_0 min 12.6 Hz

000620a; M1.5, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

000621a; M2.0, f_0 7.84 Hz

000703a; M1.9, f_0 min 10 Hz

000709b; M1.4, f_0 min 10 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

000801a; M1.4, f_0 min 10 Hz

000809a; M1.0, f_0 min 12.6 Hz

000816a; M2.0, f_0 11.4 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

000816b; M1.2, f_0 min 10 Hz

000831a; M0.7, f_0 min 12.6 Hz

000902a; M0.8, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

000905a; M1.1, f_0 min 12.6 Hz

000921a; M2.1, f_0 14.0 Hz

000927b; M2.3, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

001010a; M1.7, f_0 12.2 Hz

001012a; M1.8, f_0 min 12.6 Hz

001014a; M1.5, f_0 11.5

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model
 Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

001017a; M0.4, f_0 min 12.6 Hz

001019b; M1.3, f_0 min 12.6 Hz

001026a; M1.6, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

001103b; M1.8, f_0 min 12.6 Hz

001201a; M1.6, f_0 min 12.6 Hz

001204a; M2.0, f_0 8.3 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

001212b; M1.6, f_0 9.79 Hz

001215a; M0.7, f_0 min 12.6 Hz

001224a; M2.0, f_0 8.7 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

010112b; M1.0, f_0 9.1 Hz

010131a; M1.5, f_0 9.8 Hz

010213a; M0.7, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

010215a; M1.6, f_0 min 12.6 Hz

010219a; M1.5, f_0 min 12.6 Hz

010306a; M1.5, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

010428a; M1.6, f_0 min 12.6 Hz

010503b; M1.9, f_0 9.9 Hz

010513a; M1.0, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

010522a; M1.8, f_0 10.2 Hz

010522b; M2.9, f_0 6.9 Hz

010522c; M2.5, f_0 8.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

010526a; M0.4, f_0 min 12.6 Hz

010527b; M1.4, f_0 13.1 Hz

010529a; M1.2, f_0 min 10 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

010606a; M1.4, f_0 min 12.6 Hz

010610b; M2.4, f_0 7.8 Hz

010615a; M0.8, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

010619a; M2.0, f_0 11.2 Hz

010622a; M1.4, f_0 min 12.6 Hz

010705a; M1.7, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

010710b; M1.4, f_0 min 12.6 Hz

010727a; M1.1, f_0 min 12.6 Hz

010811a; M0.9, f_0 min 10 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

010820a; M1.0, f_0 min 12.6 Hz

010902a; M0.6, f_0 min 12.6 Hz

010908a; M2.0, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

010920a; M1.6, f_0 min 12.6 Hz

010921a; M1.8, f_0 min 12.6 Hz

010921b; M0.8, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

011003a; M2.5, f_0 min 5.0 Hz

011025a; M1.6, f_0 min 12.6 Hz

011026a; M1.9, f_0 10.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

011026b; M1.8, f_0 min 12.6 Hz

011109a; M1.5, f_0 10.9 Hz

011111a; M2.1, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

011202a; M1.3, f_0 min 12.6 Hz

011205a; M1.1, f_0 min 12.6 Hz

011205b; M1.8, f_0 9.3 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

011207a; $M 0.9$, f_0 min 12.6 Hz

011213a; $M 2.1$, f_0 min 12.6 Hz

011222a; $M 0.6$, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

011224a; M1.7, f_0 min 12.6 Hz

020115a; M1.6, f_0 min 12.6 Hz

020119a; M2.0, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

020119c; M1.6, f_0 min 12.6 Hz

020130a; M0.6, f_0 min 12.6 Hz

020131a; M1.8, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

020203a; M0.8, f_0 min 12.6 Hz

020203b; M0.5, f_0 min 12.6 Hz

020213b; M1.4, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

020215a; M1.5, f_0 min 12.6 Hz

020215b; M0.6, f_0 min 12.6 Hz

020225a; M1.8, f_0 12.56 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

020309a; M1.5, f_0 min 12.6 Hz

020320a; M0.5, f_0 min 12.6 Hz

020323b; M0.9, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

020403a; M1.5, f_0 11.1 Hz

020404a; M1.7, f_0 min 12.6 Hz

990609a; M2.0, f_0 min 12.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

990812a; M1.7, f_0 min 12.6 Hz

990813a; M1.5, f_0 12.3 Hz

991002a; M2.5, f_0 6.7 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

+ Direct Method Displacement × Direct Method Acceleration — Brune Model

990813b; M1.1, f_0 min 12.6 Hz

990828a; M2.0, f_0 12.4 Hz

991120a; M1.0, f_0 9.6 Hz

Appendix 2: Source Displacement and Acceleration Spectra compared to Brune Model

Note: The Brune Model is a flat line when the high frequency level of the acceleration spectrum is beyond the bandwidth of available data.

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Appendix 3: Comparison of Source Spectra obtained from EGF and Direct methods.
 Multiplet events are listed in Table A3.1

Appendix 3: Comparison of Source Spectra obtained from EGF and Direct methods.
 Multiplet events are listed in Table A3.1

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 Multiplet events are listed in Table 3A.1

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 Multiplet events are listed in Table 3A.1

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 Multiplet events are listed in Table 3A.1

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Appendix 3: Comparison of Source Spectra obtained from EGF and Direct methods.
 Multiplet events are listed in Table 3A.1

Table A3.1: Multiplets within CSZ used in EGF method

	Type	Event Name	M
1	MAIN	000131a	1.7
	EGF1	000801a	1.4
	EGF2	000816b	1.2
	EGF3	001017a	0.4
2	MAIN	000203a	1.8
	EGF0	010213a	0.7
	EGF2	991120a	1.0
3	MAIN	000209a	1.8
	EGF0	000210a	1.2
	EGF1	000709b	1.4
4	MAIN	000224b	1.4
	EGF1	010811a	0.9
5	MAIN	000619a	1.3
	EGF0	020203a	0.8
6	MAIN	000703a	1.9
	EGF1	010820a	1.0
	EGF2	010902a	0.6
7	MAIN	000927b	2.3
	EGF0	010112b	1.0
8	MAIN	001012a	1.8
	EGF0	001014a	1.5
9	MAIN	001022a	1.5
	EGF0	011222a	0.6
	EGF1	020323b	0.9
10	MAIN	001103b	1.8
	EGF0	010710b	1.4
11	MAIN	001212b	1.6
	EGF0	020215b	0.6
12	MAIN	001224a	2.0
	EGF0	010529a	1.2
13	MAIN	010131a	1.5
	EGF0	020130a	0.6
14	MAIN	010215a	1.6
	EGF0	000831a	0.7
15	MAIN	010306a	1.5
	EGF0	000111b	1.1
	EGF1	000905a	1.1
	EGF2	010527b	1.4

	Type	Event Name	M
16	MAIN	010428a	1.6
	EGF0	010921b	0.8
17	MAIN	010503b	1.9
	EGF1	010820a	1.0
	EGF2	010902a	0.6
18	MAIN	010522b	2.9
	EGF0	010522a	1.8
	EGF1	010522c	2.5
19	MAIN	010522c	2.5
	EGF0	010522a	1.8
20	MAIN	010622a	1.4
	EGF2	020203b	0.5
	EGF3	991013b	1.1
21	MAIN	010710b	1.4
	EGF1	010615a	0.8
22	MAIN	020115a	1.6
	EGF0	010526a	0.4
23	MAIN	020119a	2.0
	EGF0	001215a	0.7
	EGF1	020320a	0.5
24	MAIN	020119c	1.6
	EGF0	000902a	0.8
25	MAIN	020213b	1.4
	EGF0	010112b	1.0
	EGF1	010513a	1.0
26	MAIN	020215a	1.5
	EGF1	000224b	1.4
	EGF2	000809a	1.0
	EGF3	010811a	0.9
27	MAIN	990812a	1.7
	EGF0	011205a	1.1
	EGF1	011207a	0.9

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^0 . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

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Path: A54 GAC
 $\Delta=519$ km

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Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-p} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

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Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

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Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^b . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^D . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-p} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^b . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^b . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^b . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

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Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-5} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^b . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^b . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^0 . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.

Appendix 4: Histogram of calculated b coefficients, where total attenuation is model as R^{-b} . Overlain is normal distribution fit to histogram data. Top left panel is all available calculations regardless of frequency, top right is for 2.5 Hz bin, bottom left for 5 Hz and bottom right for 10 Hz. NO DATA signifies an empty bin.