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SOURCE SCALING OF EARTHQUAKES IN THE NORTHEASTERN UNITED STATES: COLLABORATIVE RESEARCH WITH COLUMBIA UNIVERSITY AND BOSTON UNIVERSITY

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Technical Abstract

High-quality digital data with a high sample rate (200 samples/s) from the Mw 5.0 Au Sable Forks, NY earthquake sequence in April – November 2002, provided useful data to determine accurate source parameters and to validate previous regional wave studies in NE United States. The regional and local waveform data analysis indicates that the relation between corner frequency and seismic moment of Au Sable Forks, NY sequence does not separate into two regions along the line with the seismic moment about 2×10^{13} Nm (~magnitude 3) as reported in Shi, Kim and Richards (1998), rather the corner frequency measurements of Au Sable Forks, NY sequence fill the gap in the corner frequency and seismic moment relationship at around the moment 2×10^{13} Nm. The breakdown in self-similarity below a threshold moment about 2×10^{13} Nm reported by Shi, Kim and Richards (1998) is not observed in the 2002 Au Sable Forks data set. The stress drops are high, confirming previous work suggesting high stress drops for intraplate continental earthquakes. The direct and regional wave methods yield inconclusive results as to the scaling of stress drop at small magnitudes; the regional waves suggest that self-similarity breaks down but the direct wave analyses imply that this is simply an artifact of the limited frequency bandwidth.

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Non-Technical Abstract

Earthquakes in the Northeastern United States are rare but have the potential to cause catastrophic damage and numerous causalities. Few earthquakes have been well recorded in the Northeastern U.S., to provide useful ground motions for the research community. As a result, earthquakes and seismic wave propagation in the region are poorly understood. The magnitude 5 Au Sable Forks earthquake on 20 April 2002 was one of the strongest earthquakes in the northeastern United States in the past 20 years or so. The earthquake caused substantial damage above several million US dollars in Clinton and Essex Counties, NY. The aftershocks of the 2002 Au Sable Forks earthquake are by far the best recorded earthquakes to occur in the Northeastern US to date. High-quality digital seismogram data with a high sample rate from the Au Sable Forks, NY earthquake sequence in April – November 2002, provided useful data to determine accurate source parameters and to validate previous regional wave studies in Northeastern US. The seismogram data analysis suggests that the relation between corner frequency and seismic moment of Au Sable Forks, NY sequence does not separate into two regions along the line with the seismic moment at about magnitude 3 as reported in Shi *et al.* (1998) and others, rather the corner frequency measurements of Au Sable Forks, NY sequence imply that the corner frequency continuously increases with decreasing seismic moment. We compare the method used by Shi *et al*. (1998), with the methods used in California and other regions with better recorded seismicity than the NE USA. We find that the stress drops for the earthquakes are higher than in more active tectonic locations, but the Shi et al. method suggests scaling breaks down for the smallest earthquakes whereas the other methods imply that they are self-similar. These results have significant implication on evaluating the earthquake hazards in the Northeastern US, because ground shaking is directly proportional to the stress drop of the earthquake.

Introduction

Although small earthquakes are not themselves a serious hazard, they provide essential information about the earthquake rupture process on all scales. For example: How do earthquake ruptures start and grow? How do they interact with one another? What is the energy budget and stress level? Studies of small earthquakes form a vital link between even smaller scale laboratory studies and large damaging earthquakes. Abercrombie and Leary (1993) and Abercrombie (1995) compiled measurements of earthquake source parameters, mainly from active tectonic regions and found that the static stress drop was not magnitude dependent, at least above -1M. It is unclear whether these are directly relevant to Northeastern USA. Comparison of earthquakes in different tectonic settings provides an opportunity to investigate the factors governing the earthquake slip, and hence learn about the physics of the earthquake rupture process. For example, studies of a small number of larger earthquakes in the Northeastern USA predict a larger average stress drop (and higher shaking) than in the western USA. Shi *et al*. (1998) also find an apparent breakdown in constant stress drop below about 2×10^{13} Nm. At present it is unclear whether this is a real effect or a result of the different data and methods used.

The importance of reliable estimates of radiated seismic energy for understanding the dynamics of frictional slip has become recently apparent (e.g. Kanamori 1994, Kanamori and Heaton 2000). The need for more precise measurements of source parameters, in particular radiated energy and stress drop, in a range of tectonic settings is clear (e.g. Abercrombie and Rice, 2005; Ide and Beroza 2001, Izutani and Kanamori 2001, Kim and Mori 2001). Shi *et al.* (2000) has developed a method of measuring radiated energy from regional *Lg* waves in the Northeastern USA but it has yet to be validated with more commonly used local recordings.

Earthquake source models are an essential component of seismic hazard estimation. The low seismicity rate in the Northeastern USA (and other stable continental regions) results in a scarcity of ground motion recordings from which empirical relationships can be developed (e. g. Atkinson 1993, Atkinson and Boore 1995, Atkinson and Sonley, 2003). For example, Somerville *et al.* (2002) use the recordings of only 3 moderate sized earthquakes to propose source scaling relationships for earthquakes in the Northeastern USA and other stable continental regions. Their results imply that earthquakes in the Northeastern USA have relatively high stress drops (as previously suggested, e. g. Atkinson 1993), and significantly larger slip displacements (2.5 times) than earthquakes in tectonically active western North America. These results are consistent with the observations of the 2001, M7.7 Bhuj earthquake (Johnston, 2003) which is also interpreted to be an intraplate earthquake.

Preliminary work on the 20 April 2002, Mw 5 Au Sable Forks earthquake suggests that it has a relatively high stress drop (~10 MPa, Atkinson and Sonley 2003, Kim *et a*l. (2002), consistent with the predictions of Somerville *et al.* (2002). The aftershock sequence of the 2002 Au Sable Forks earthquake was recorded by broadband seismometers in the distance range 5 to 500 km (Figures 1). These recordings provide an unprecedented opportunity to use local recordings to calibrate previous regional work in the region. Three large aftershocks (M > 3) and a total of about 70 aftershocks have been recorded. We used the local recordings to calculate the moment, radius, stress drop and radiated energy in the same manner used in more active tectonic regions (e. g. Abercrombie 1995, Abercrombie and Rice 2005). We also analyzed the regional recordings using the methods developed by Shi et al. (1996, 1998, 2000). The aim of the this study is to characterize the source processes of at least 50 small earthquakes in the Northeastern USA, including the aftershocks of the 2002 Au Sable Forks, New York (Mw 5) earthquake (Figures 1).

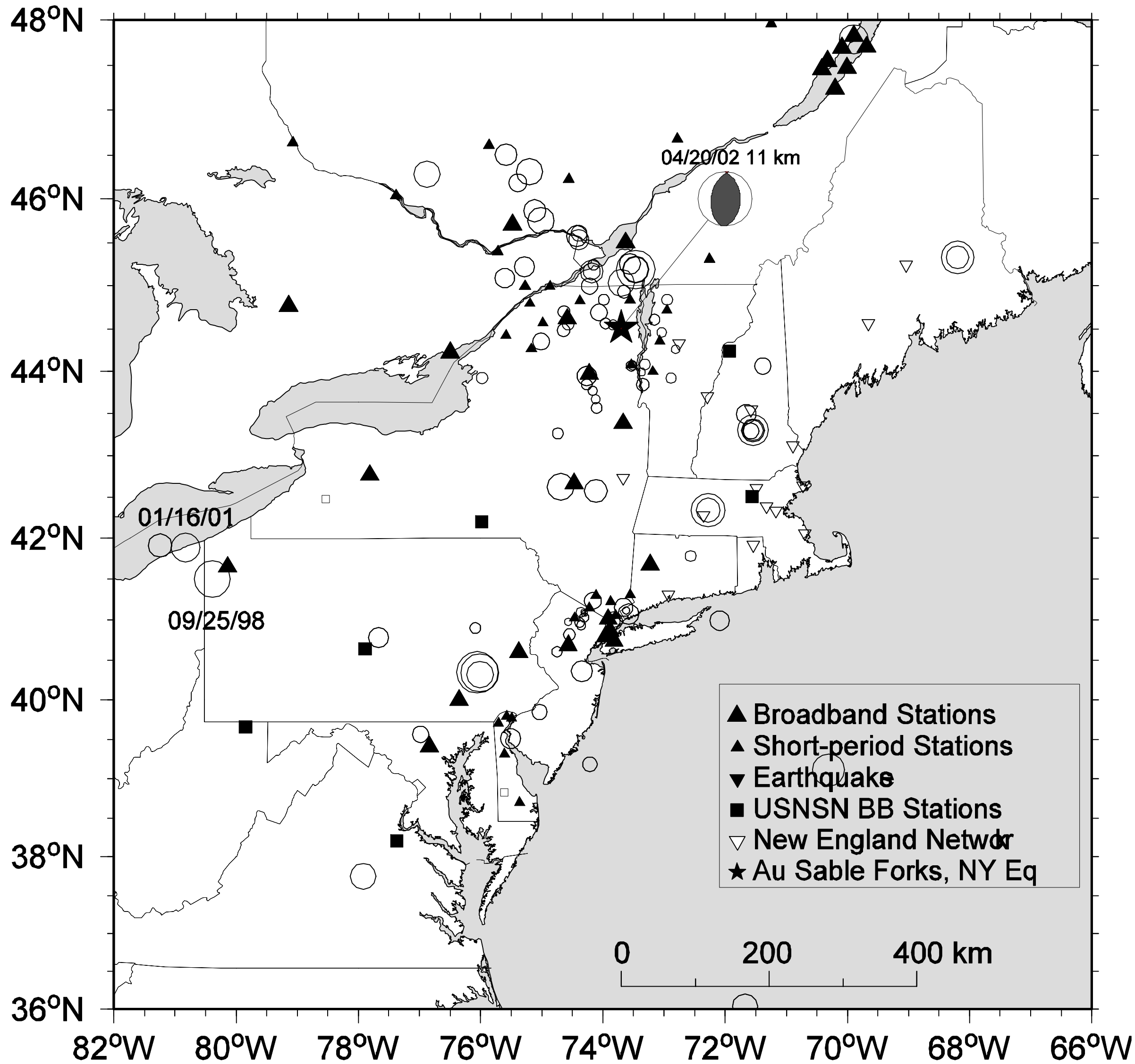

Figure 1. Epicenters of the earthquakes that have been studied by Shi *et al*. (1996, 1998 and 2000) as well as other significant earthquakes in the region that we attempted to analyze and to validate their source parameters. Au Sable Forks, NY earthquake is plotted with a star. Eight mainshock-aftershock pairs that have been used in empirical Green's function method (Shi *et al.*, 1998) and other earthquakes are plotted with circles with size proportional to magnitudes of the earthquakes. The focal mechanism for the Au Sable Forks earthquake is from Seeber *et al.* (2002).

Au Sable Forks, New York Earthquake Sequence

On April 20, 2002 at 06h 50m 47s (EDT), a moderate earthquake of magnitude M_L 5.3 occurred about 29 km SW of Plattsburgh, New York in northeastern Adirondack Mountains (Figure 1). The epicenter of the mainshock is about 8 km north of town of Au Sable Forks and the focal depth of the mainshock is about 11 km from the surface. Hence, the earthquake on April 20, 2002 is formally called *Au Sable Forks* earthquake. The mainshock was felt widely by residents in New York and adjacent states. It was felt from Maine, Boston, Massachusetts, metropolitan New York City area, down to Baltimore, Maryland. It is also widely felt in Ottawa and Montreal, Canada. The felt radius is several hundred km and is consistent with the low attenuation typical of the region. Residents in the two counties -- Clinton and Essex Counties, around the epicenter felt intensity VI (MMI) and up to VII at close to the epicenter. The earthquake caused substantial damage and on May 16, 2002, Presidential disaster declaration was issued for Clinton and Essex Counties, NY.

There was damage to roads, bridges, chimneys and water mains in Clinton and Essex Counties, NY. Many people reported cracked walls and foundations, small items knocked from shelves and some broken windows. Local magnitude (= Richter scale), M_L, of the mainshock is $M_L = 5.3$, measured from the three component seismograms at 12 stations in the distance ranges of 73 to 715 km from the source. The main shock is followed by aftershock of magnitude M_L 3.7 at 11:04:42 and many smaller aftershocks followed.

Instrument Deployment and Aftershocks*:* Following the mainshock, LDEO (Lamont-Doherty Earth Observatory) deployed digital portable seismographs to monitor aftershocks. The first station was installed within a day after the mainshock and four more stations were installed the next day. Additional portable digital seismographs were deployed through collaborative efforts with earthquake research organizations in the US and in Canada. By April 27, 2002, a week after the mainshock on 20 April, 15 portable, digital seismographic stations were deployed at 13 sites for monitoring the aftershocks in the epicentral area (Table 1; Figure 2). The local network spans an area about 24 by 20 km with an average inter-station spacing of 4 – 6 km, smaller than the source depth. Between April 22 and November, 2002, we detected and located 74 small aftershocks from the epicentral area, including six local earthquakes that occurred in Adirondacks slightly outside of the Au Sable Forks epicentral area.

Mainshock and Large Aftershocks: The mainshock as well as a dozen aftershocks that occurred within the first 24 hours following the mainshock were only recorded by a set of 25 regional seismic stations in the distance range 37 – 550 km, including a dozen stations in southeastern Canada. However, six large aftershocks with magnitude mostly greater than 2 that occurred during April 21 – June 25, 2002 were well recorded by both the temporary local network and by the regional seismic stations. Hence, these six aftershocks are accurately located. We thus relocated the mainshock and its first day aftershocks by using the master event location technique. The M_L 3.1 event on 05/24/2002 (23:46:00) is used as the master event. The results of the master event location using JHD (joint hypocenter determination) algorithm are plotted in Figure 3 and are listed in Table 2. The aftershock hypocenters from the Au Sable Forks local network covering the period April – November, 2002 are plotted in Figure 3 and are listed in Appendix 1. Mainshock rupture size (assuming circular shape), geometry and reverse slip kinematics were inferred from regional waveforms and are shown as a thick bar and slip-direction arrows. They generally correlate well with aftershock distribution. Some aftershocks, however, are located a significant distance from the rupture suggesting a large aftershock volume and the activation of secondary faults.

Table 1. Local seismic network for April 2002 Au Sable Forks, New York earthquake sequence*

Station (code)	Latitude (N)	Longitude (W)	Elev (m)	Datalogger (type)	Sensor (type)	Operation (start date)	(end date)	Affiliation
FORD	44.510	73.770	365	DM24	CMG-40T	2002-04-21	2002-04/30	ISTI
JEEP	44.480	73.630	144	RT 262	L22	2002-04-21	2002-11-14	LDEO
SCRF	44.560	73.630	333	RT 526	L22	2002-04-21	2002-06/20	LDEO
LAKE	44.495	73.716	354	RT 524	L28	2002-04-21	2002-11-14	LDEO
MESS	44.571	73.715	283	RT 232	L22	2002-04-21	2002-11-14	LDEO
BARN	44.593	73.629	256	RT 240	L28	2002-04-22	2003-01-25	LDEO
				RT 240	CMG-40T	2002-11-14	2003-01-25	LDEO
				DM24	CMG-40T	2002-04-25	2002-06-20	CERI
BILL	44.482	73.806	408	RT 6115	L22	2002-04-23	2002-08-16	LDEO
				K2	L28	2002-04-25	2002-06-20	CERI
SKUN	44.535	73.594	180	K2	L28	2002-04-25	2002-06-20	CERI
GREE	44.425	73.629	238	RT 479	L22	2002-04-25	2002-11-14	IRIS
				K2	L28	2002-04-25	2002-06-20	CERI
OREB	44.586	73.781	280	K2	L4C	2002-04-25	2002-06-20	CERI
BROK	44.462	73.749	300	RT 393	L22	2002-04-25	2002-09-08	IRIS
HALL	44.519	73.521	210	RT 117	L22	2002-04-27	2002-11-14	IRIS
KSVO	44.552	73.686	381		CMG-3ESP	2002-04-28	2004-09-24	
	POLARIS							
						2002-11-15	2003-07-25	
						2003-07-25	2004-05-06	

*) Affiliation: IRIS= PASSCAL program of the Incorporated Research Institutions for Seismology (IRIS); ISTI = Instrumental Software Technologies Inc.; CERI = Center for Earthquake Research and Information, University of Memphis; and the POLARIS Consortium, Canada CGS (Canadian Geologic Survey); DM24= 24-bit A/D system made by Guralp Systems Inc., RT=Refraction Technology Inc.; K2= 19-bit A/D accerelometer from Kinematrics, Inc.; CMG-40T, broadband seismometer with T_0 = 20 s and gain= 800 V/(M/s); L22 = short-period seismometer with T_0 = 0.5 s, gain = 88 V/(M/s); L28 = short-period seismometer with T_0 = 0.22 s, gain = 30.4 V/(M/s); L4C = short-period seismometer with T_0 = 1 s, gain = 166.54 V/(M/s); CMG-3ESP = broadband seismometer with T_0 = 30 s and gain= 2,000 V/(M/s).

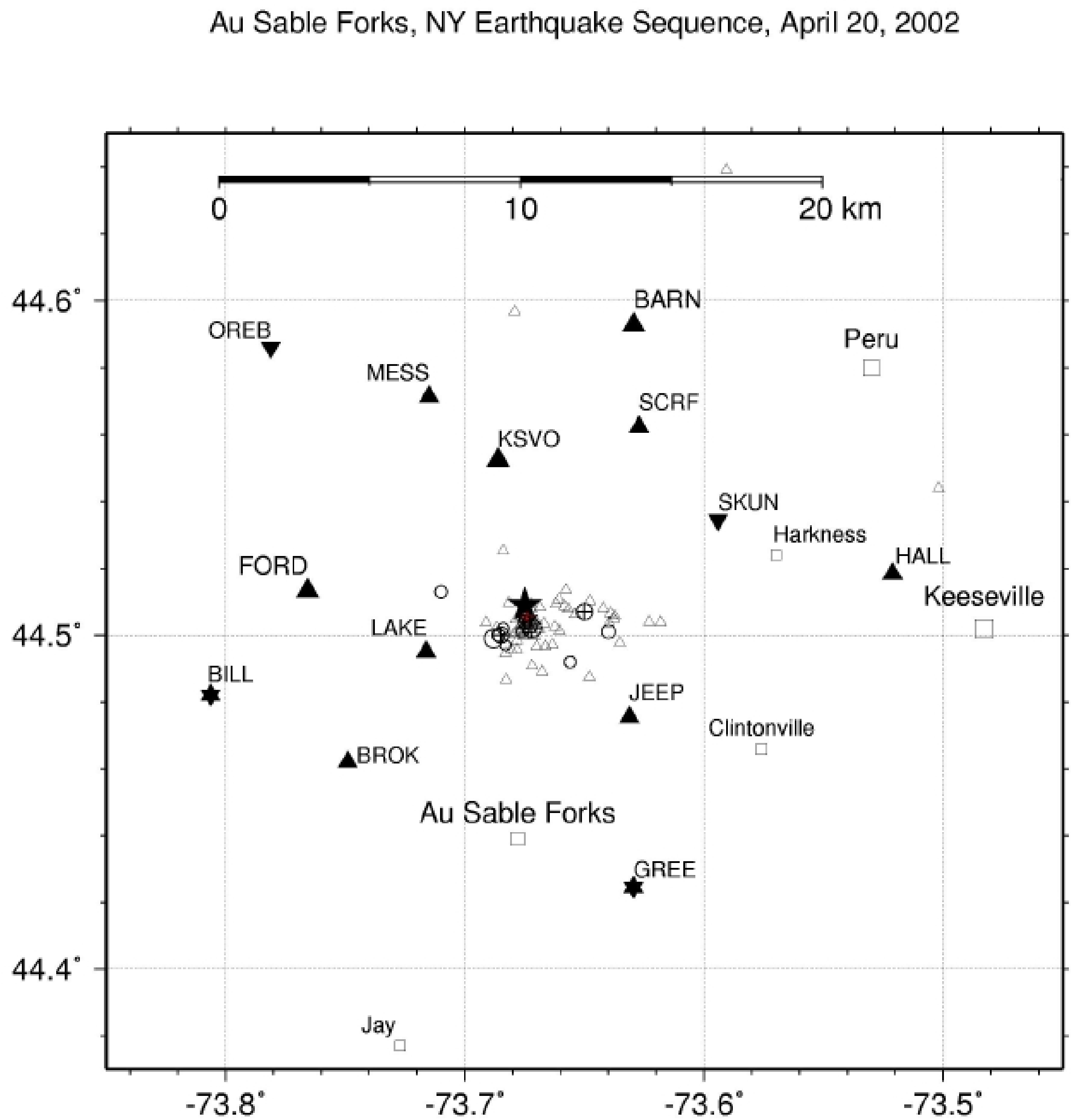

Figure 2. Map of the Au Sable Forks epicentral area in northeastern Adirondacks showing the temporary monitoring stations and aftershock epicenters. The epicentral area is indicated in Figure 1. A *large solid star* indicates the mainshock, *small open circles* are epicenters of aftershocks located by using the regional station data (Table 3); *open triangles* are aftershocks located by the local stations. *Solid triangles* indicate short-period seismographs (LAKE, JEEP, HALL, SCRF); *large triangles* denote broadband seismographs (BARN, FORD, & KSVO); *inverted triangles* are strong motion accelerometers (BILL, GREE, OREB and SKUN; some are co-located with velocity sensors). *Open squares* indicate towns in the area (e.g., Keeseville, Au Sable Forks etc.).

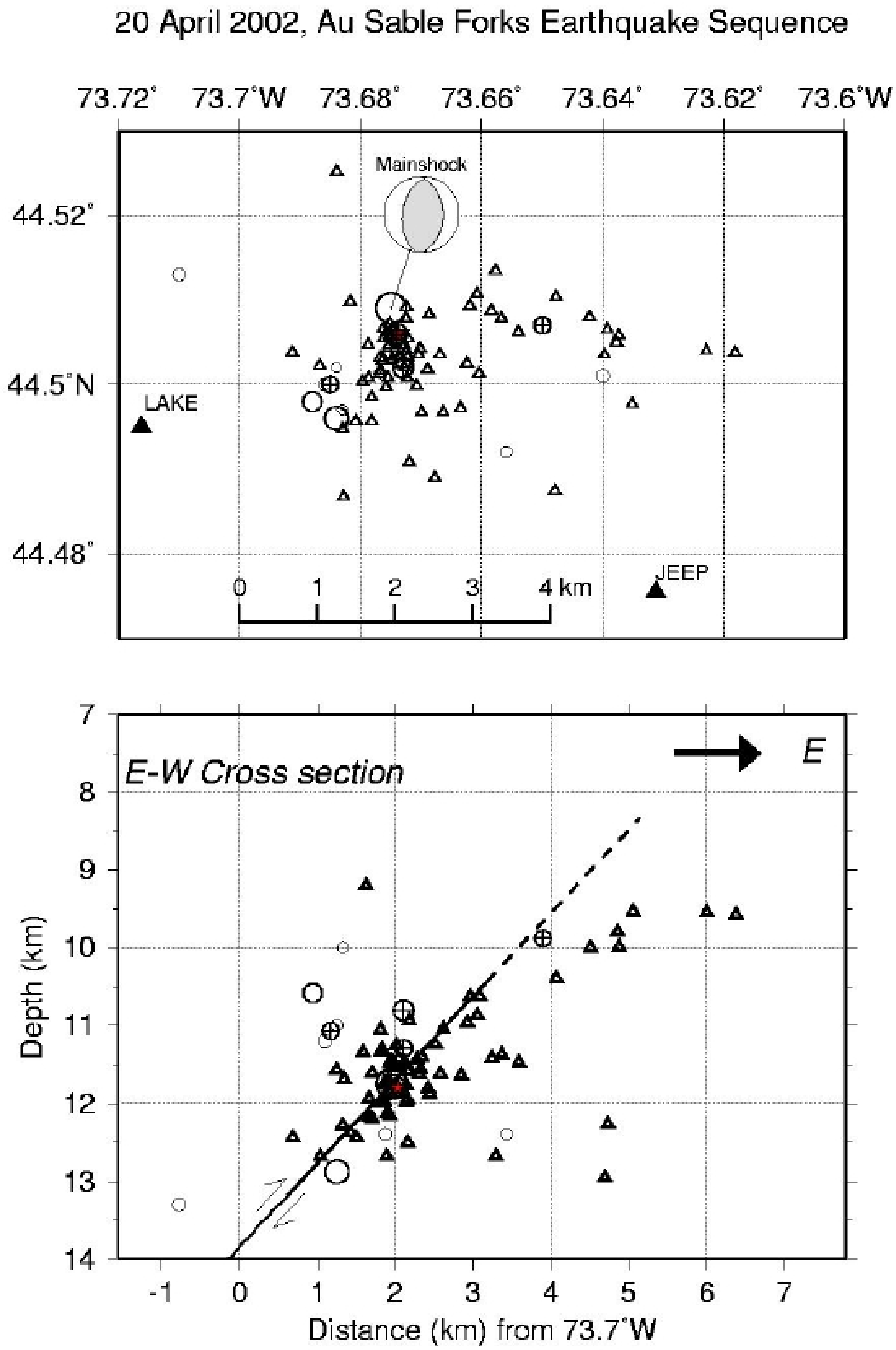

Figure 3. (*top panel*) Epicenters of the Au Sable Forks earthquake sequence during April – November, 2002. The mainshock and its large aftershocks that are recorded both by the local and regional network stations are plotted by *circles*, whereas small aftershocks that are only recorded locally are plotted by *triangles*. (*bottom panel*) Hypocenters of the mainshock and its aftershocks determined from the local network data are plotted as EW cross-section. Mainshock rupture size (assuming circular shape), geometry and reverse slip kinematics were inferred from regional waveforms and are shown as a thick bar (2.6 km diameter for the 2002 rupture) and slip-direction arrows. They generally correlate well with aftershock distribution.

Analysis of Regional Recordings.

We used the spectrum fitting method developed by Shi *et al.* (1996 and 1998) to determine the source parameters of the dozen largest aftershocks in the Au Sable Forks earthquake sequence. We measured seismic moment, source radius, stress drop and radiated seismic energy using the broadband and short-period recordings of the *Sg* and *Lg* waves recorded at local and regional distances (few kilometers to about 200 km) by the broadband networks and temporary local network stations. The key in this analysis is the availability of the high-frequency broadband recordings of a set of about 10 earthquakes (M>2) recorded at both local and regional distances. These recordings enable us to estimate amplitude decay along the propagation paths to the regional stations.

Figure 4 shows spectral fitting method deployed in this study for event on 04/25/2002 13:39 (Table 2). The *S* wave train and their displacement spectra with the best fit ω^{-2} source at different local stations are plotted to illustrate essence of the method used. In each plot, the *S* waves within the group velocity window used were marked and its displacement spectrum was plotted with the fitted source curve. The corner frequencies and seismic moment estimated from the simulated spectrum are written at the left corner of each plot. The vertical records from six local stations in the hypocentral distance range 12 - 15.7 km and a permanent regional station with short-period seismometer at about 39.5 km are used for analysis. This is one of the largest event (Mw ~ 2.3) that has unclipped data from all local stations. All local stations recorded signals with 200 samples per seconds, and hence the data can provide opportunity to determine spectral source parameters with less bias due to limited frequency band available for previous studies in the ENA.

Table 2. List of regionally recorded earthquakes in the 2002 Au Sable Forks sequence

Date (year-mo-dy)	Time (hh:mm:sec)	Lat. (ºN)	Long. (ºW)	Depth (km)	Magnitude (Mc)	
2002-04-20	10:50:47.1	44.509	73.675	11.8	5.3 (M_L)	Mainshock
2002-04-20	11:04:42.0	44.496	73.685	12.8	3.7 (M_L)	aftershock
2002-04-20	11:08:25.8	44.500	73.686	11.2	1.7	
2002-04-20	11:45:28.4	44.499	73.688	10.5	2.6 (M_L)	
2002-04-20	12:03:19.8	44.513	73.710	13.3	1.6	
2002-04-20	12:05:17.0	44.502	73.684	11.0	1.3	
2002-04-20	17:08:43.0	44.501	73.676	12.4	1.5	
2002-04-20	23:05:41.7	44.501	73.640	06.3	1.9	
2002-04-20	23:38:34.9	44.497	73.683	10.0	1.2	
2002-04-20	23:50:04.5	44.492	73.656	12.4	1.4	
2002-04-21	11:47:09.9	44.507	73.650	10.0	2.3	
2002-04-21	12:39:10.6	44.500	73.685	11.1	2.3	
2002-04-25	13:39:55.8	44.504	73.675	11.6	1.8	
2002-05-24	23:46:00.0	44.505	73.674	11.7	3.1 (M_L)	Master event
2002-05-25	04:48:56.8	44.503	73.673	11.3	2.4	
2002-06-25	13:40:27.9	44.502	73.672	10.7	3.0	

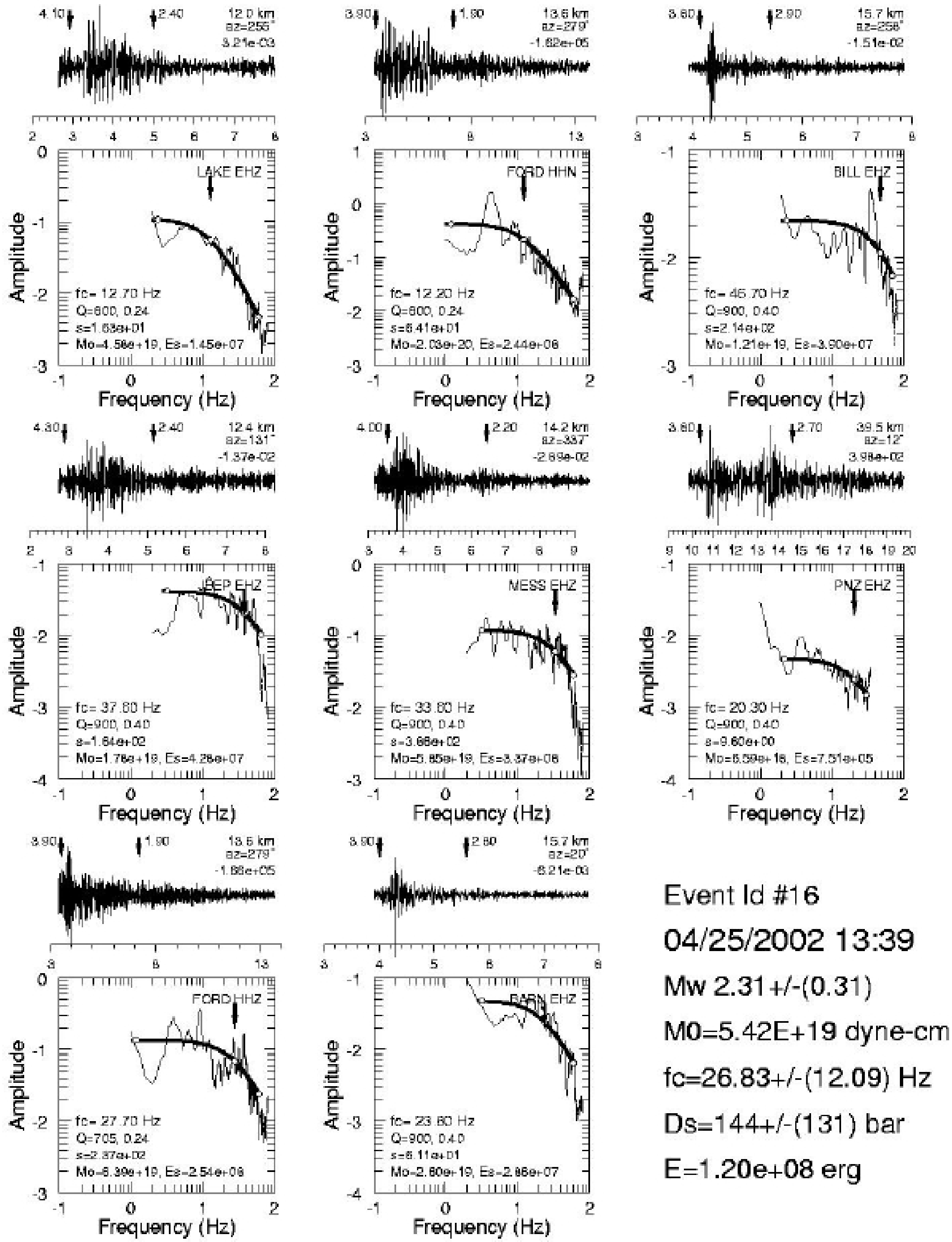

Figure 4. The *S* wave train and their displacement spectra with the best fit ω-square source at different local stations for event on 04/25/2002 13:39. In each plot, the *S* waves within the group velocity window used were marked by two arrows in the above time series trace.

The attenuation correction is applied with a quality factor Q which is frequency dependent and its frequency dependence can be written as $Q = Q_0 (f/f_0)^{\eta}$, where f_0 = 1 Hz, $Q_0 = Q$ at this reference frequency, and η = constant (e. g., Shi *et al*., 1996). In our previous study of the region of present interest (Figure 1), we used empirical Green's function analysis from broadband data and obtained the attenuation factor Q in the Northeastern United States (Shi *et al*., 1996). The attenuation factor Q varies in different tectonic regions, with average values given by Q_0 = 705 and η = 0.24 around Au Sable Forks, NY region. We use this result in the following analysis for the attenuation correction.

Source spectrum corner frequency determination: The result of the source spectrum corner frequency estimates employing the spectral fitting method indicates that the corner frequencies are nearly a factor of two greater than the corner frequencies from similar sized events previous studied by Shi *et al.* (1998). Results of the corner frequency measurements are plotted in Figure 6 and are listed in Table 3. Corner frequencies from 13 selected events are about a factor of two greater than previously reported values in the seismic moment (M_0) range $1 \times 10^{11} – 1 \times 10^{16}$ Nm (Figure 6).

Analysis of Direct Waves using Local Recordings.

We calculate the source parameters using two methods commonly applied to direct waves recorded at local stations: spectral modeling of the three-component P and S waves (e.g. Abercrombie, 1995), and the Empirical Green's Function (EGF) method (e.g. Abercrombie and Rice, 2005). Both methods require high frequency content data to work well. Many studies consider the EGF method superior as it corrects for all path and site effects by using a smaller, collocated earthquake as an EGF. The high degree of cross-correlation found between many aftershocks of the AU Sable Forks earthquake means that there are many candidates for this approach. We model the spectra obtained by dividing the spectrum of the large earthquake by the smaller one. We also tested all EGF deconvolutions by transforming back to the time domain and checking that we were able to resolve a clear source pulse. We measured corner frequency and source duration of the aftershocks, using local and regional recordings of the P and S waves.

We followed Abercrombie (1995) to calculate and model the individual P and S spectra, using the following equation (Boatwright 1980),

$$\Omega(f) = \Omega_0 \exp(-\pi f t/Q)/[1+(f/f_c)^4]^2, \quad (1)$$

where Ω_0 is the long period amplitude, f the frequency, t the travel time of the considered wave, Q the frequency independent quality factor, and f_c the corner frequency.

We obtain reasonable results for Q from the modeling, of the order of 1200 for P and 800 for S. We then modeled the source spectra determined from the EGF using the same equation, but in this case, Ω_0 becomes the amplitude (or moment) ratio of the two earthquakes and the exponential attenuation factor is set to 1.

Figure 5 shows the application of the two methods to 2 earthquakes that occurred on 04/25/2002 (events #15 and #16 in Table 4). The top plots show the vertical displacement seismograms and fitted P and S spectra of events #16 and #15 at 3 stations. The bottom plots show the resulting EGF spectral ratio and source time function for the event pair. Note that the spectral ratios of event 16/15 show only one clear corner and are still decreasing at high frequencies. This implies that the corner frequency of Earthquake 15 is outside our bandwidth, and hence above 80Hz.

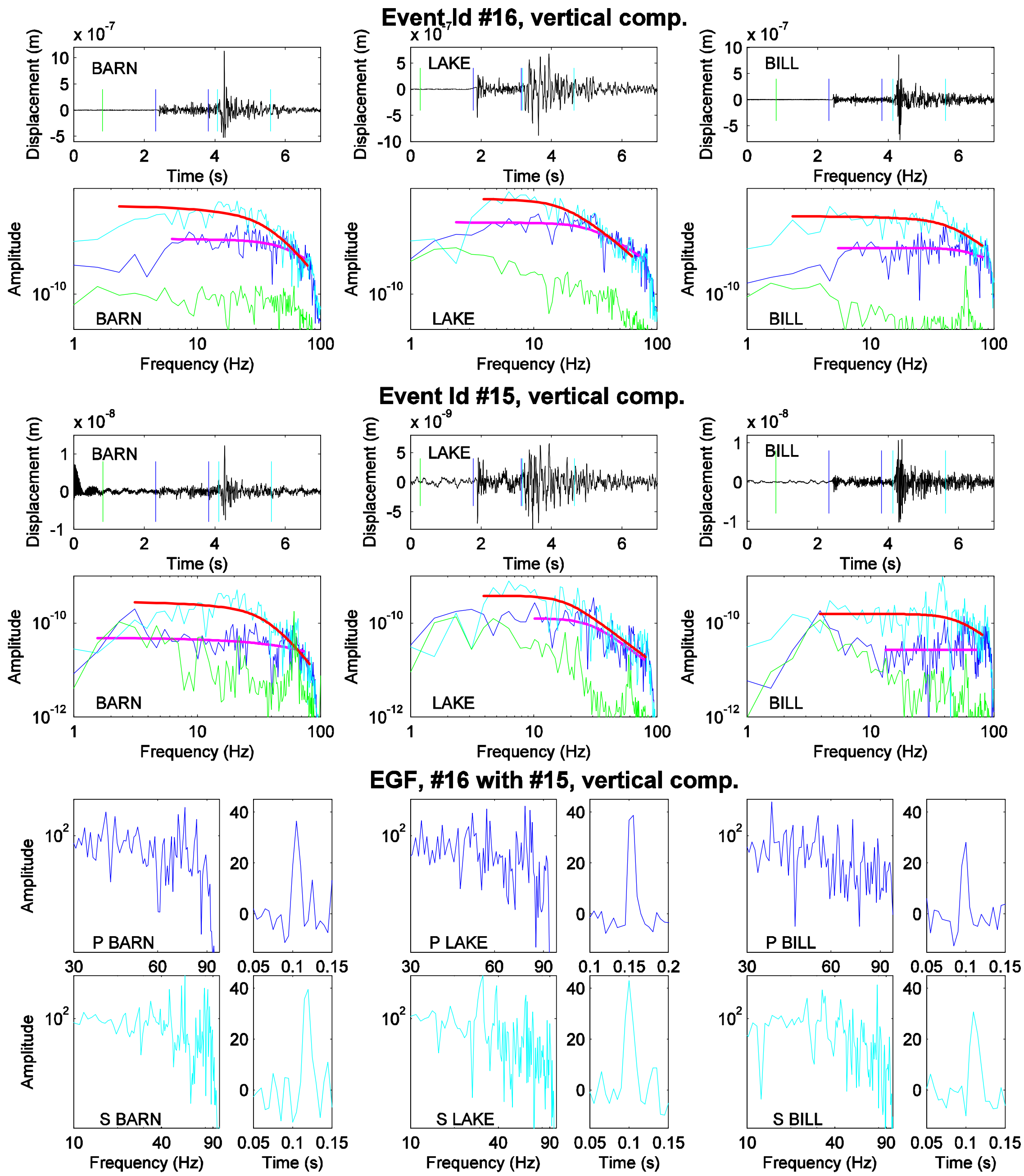

Figure 5. Application of the direct wave methods to earthquakes #15 and #16 (04/25/2002). ***Top plots*:** vertical displacement seismograms and fitted P and S spectra of the two earthquakes at stations BARN, LAKE and BILL. Green is pre-P noise, dark blue is P wave and cyan is S wave. Time windows used for spectra are indicated in the seismogram by vertical lines with correspondent colors. The results of fitting the spectra using equation 1 are shown in magenta (P waves) and red (S waves). ***Bottom plots*:** EGF spectral ratio and source time functions for the #16 and #15 pair. Same color definitions as above plots.

Source Parameter Results from Analysis of Regional and Direct Wave Methods.

We plot the results of our two independent analyses in Figure 6. It is obvious that the relationship between corner frequency and seismic moment does not clearly separate into two regions along the line with the seismic moment about 2 $\times 10^{13}$ Nm (~magnitude M_w 3) as implied by Shi *et al.* (1998). It is less clear, however, whether there is any change in relationship between moment and corner frequency for the smaller earthquakes. The results of the regional analysis suggest that the smaller earthquakes have lower corner frequencies than would be predicted from extrapolation of the results from the larger ones. The analysis of the local, direct waves is less clear, however. The EGF approach clearly implies that the corner frequency of the smallest earthquake (#15) is above 80 Hz and cannot be resolved by any of the data in this stuffy. This suggests that the apparent change in slope of the regional results is an artifact of the bandwidth. The highest frequencies that can be analyzed are only 80 Hz, and so identifying a corner frequency higher than about 50 Hz is very hard and there are possible trade-offs between site effects and source processes.

Table 3. Source parameters of selected earthquakes of the Au Sable Forks sequence from Regional wave analysis.

Event id	Date (mo-dy)	Time (hh:mm:sec)	Magnitude (Mw)	Moment (Nm)	f_c (Hz)	$\Delta\sigma$ (MPa)	N (obs)
1001	04-20	10:50:47.1	4.90±0.10	2.61±0.87 $\times 10^{16}$	3.2±1.4	96.6±89.6	2
1006	04-20	11:04:42.0	3.58±0.17	3.18±2.42 $\times 10^{14}$	8.8±2.7	34.9±20.8	8
1016	04-21	11:47:09.9	2.53±0.56	2.70±3.87 $\times 10^{13}$	15.9±7.2	5.3±5.2	8
1017	04-21	12:39:10.6	2.58±0.43	2.10±2.85 $\times 10^{13}$	16.0±4.7	7.5±6.1	6
3	04-23	00:40:17.6	1.80±0.33	9.45±9.88 $\times 10^{11}$	26.4±12.2	1.7±1.3	10
5	04-23	20:49:52.5	1.93±0.37	1.70±1.90 $\times 10^{12}$	23.8±12.6	1.6±0.9	8
15	04-25	08:53:43.0	1.10±0.26	7.61±7.80 $\times 10^{10}$	35.4±17.1	0.4±0.4	12
16	04-25	13:39:55.8	2.31±0.31	5.42±6.37 $\times 10^{12}$	26.8±12.1	14.4±13.1	8
17	04-26	10:41:16.7	1.19±0.29	1.08±1.18 $\times 10^{11}$	29.1±14.7	0.3±0.3	12
19	04-27	15:51:48.4	1.34±0.30	1.92±2.13 $\times 10^{11}$	31.8±15.2	0.8±1.1	10
44	05-24	23:46:00.0	3.10±0.14	5.50±2.32 $\times 10^{13}$	10.8±4.1	20.8±28.6	9
45	05-25	04:48:56.8	2.36±0.23	4.96±0.43 $\times 10^{12}$	19.2±3.4	8.9±12.6	4
56	06-25	13:40:27.9	3.06±0.27	7.27±1.12 $\times 10^{13}$	11.3±3.1	24.6±49.0	9

Table 4. Source parameters of selected earthquakes of the Au Sable Forks sequence from local direct wave analysis.

Event id/Phase	Ind. Moment (N.m)	Q	Ind. f_c (Hz)	Ind. $\Delta\sigma$ (MPa)	EGF f_c (Hz)	EGF $\Delta\sigma$ (MPa)
1006 S	6.15×10^{14}	1391	5.8	104.5	3.5	23.6
1007 S	4.30×10^{13}	1200	13.4	92.5	20.0	307.5
15 P	1.87×10^{10}	1269	>80.0	>2.4	>80.0	>2.4
15 S	1.87×10^{10}	1164	>30.4	>0.5	>80.0	>8.5
16 P	1.76×10^{12}	1406	42.3	33.6	35.6	20.0
16 S	1.76×10^{12}	642	30.0	42.5	35.0	67.3
56 P	1.90×10^{13}	854	21.2	45.4	17.7	26.7

Stress drop calculation: We measured seismic moment from the low frequency spectral level Ω_0 of the displacement spectra as discussed in Shi *et al.* (1998) for the regional analysis and following Abercrombie (1995) for the local direct wave analysis. The geometrical spreading correction is applied for amplitude measurements. For the regional wave analysis we assume a circular fault model (Brune, 1970; 1971), and estimate the source radius, r_0, from the corner frequency, f_c, through the relation, $r_0 = 2.34\ \beta/(2\pi f_c)$, where β = shear wave speed in the source region and 3.6 km/s is assumed. For the local and direct wave analysis we also assume a circular model but use the relationship of Madariaga (1976) where $r_0 = k\beta/f_c$, and k=0.32 for P waves and 0.21 for S waves. The static stress drop, $\Delta\sigma$, is then estimated from the standard circular static crack solution (Eshelby, 1957), $\Delta\sigma = (7/16)(M_0/r_0^3)$.

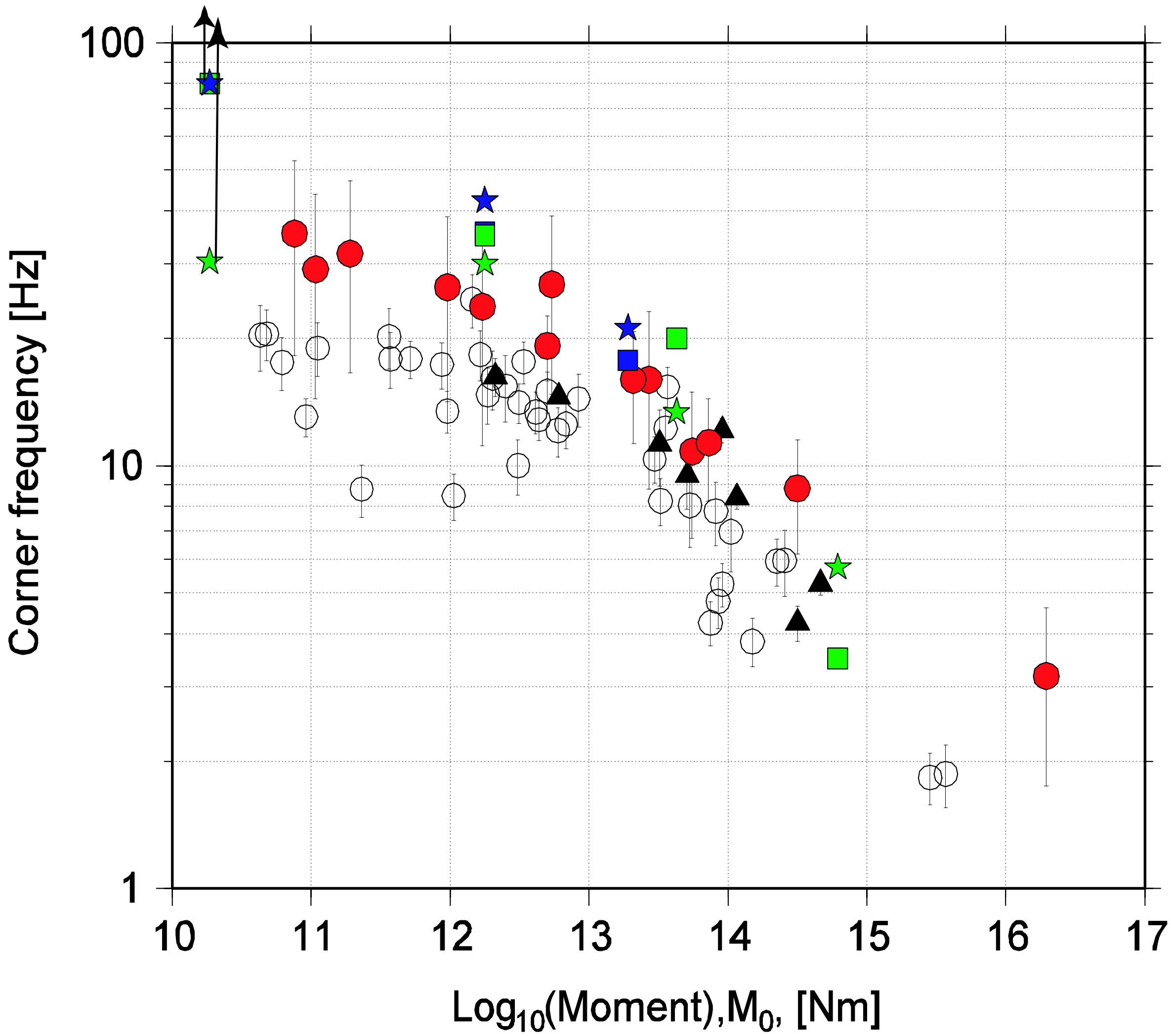

Figure 6. Corner frequencies of 13 selected Au Sable Forks earthquake sequence obtained in this study by using regional spectral model fitting (f_c) are plotted with *red circles*. The local direct results are plotted in *blue* (P waves) and *green* (S waves); the *stars* are from fitting the individual spectra and the *squares* from the EGF. The *vertical arrow* indicates that we can only estimate a minimum corner frequency. Corner frequencies from the EGF analysis of the eight events in the northeastern USA from Shi *et al.* (1998) are plotted as filled *triangles*. Other corner frequency measurements in the northeastern USA reported in Shi *et al.* (1998) are plotted as *open circles*. The difference in corner frequency estimates from the Shi *et al.* (1998) and this study suggest that the nearly constant corner frequency for events with moment below 2 x 10^{13} Nm reported by Shi *et al.* might be due to band limited data used in earlier studies. Each corner frequency and source radius is plotted with an error bar which indicates the error of the mean of values for the event across the network. Those of the local direct wave analysis are similar size.

In Figure 7, we plot static stress drops with their error bars (the mean of error in the stress drop calculation) for the Au Sable Forks earthquakes together with 49 events studied by Shi *et al*. (1998). As expected, the static stress drops are highly variable and largely scattered. The estimates of the stress drop for most of the events fall between 0.1 and 100 MPa (Figure 7). The relation of stress drop and seismic moment show that the breakdown in self-similarity below a threshold moment about 2×10^{13} Nm reported by Shi *et al*. (1998) is not clear in this data set. The results of the regional analysis suggest that the stress drops of 13 Au Sable Forks sequence increase with increasing moment in the moment range 1×10^{13} to 1×10^{15} Nm (Figure 7), but the results of the EGF study imply that this apparent increase is an artifact of the upper frequency limit.

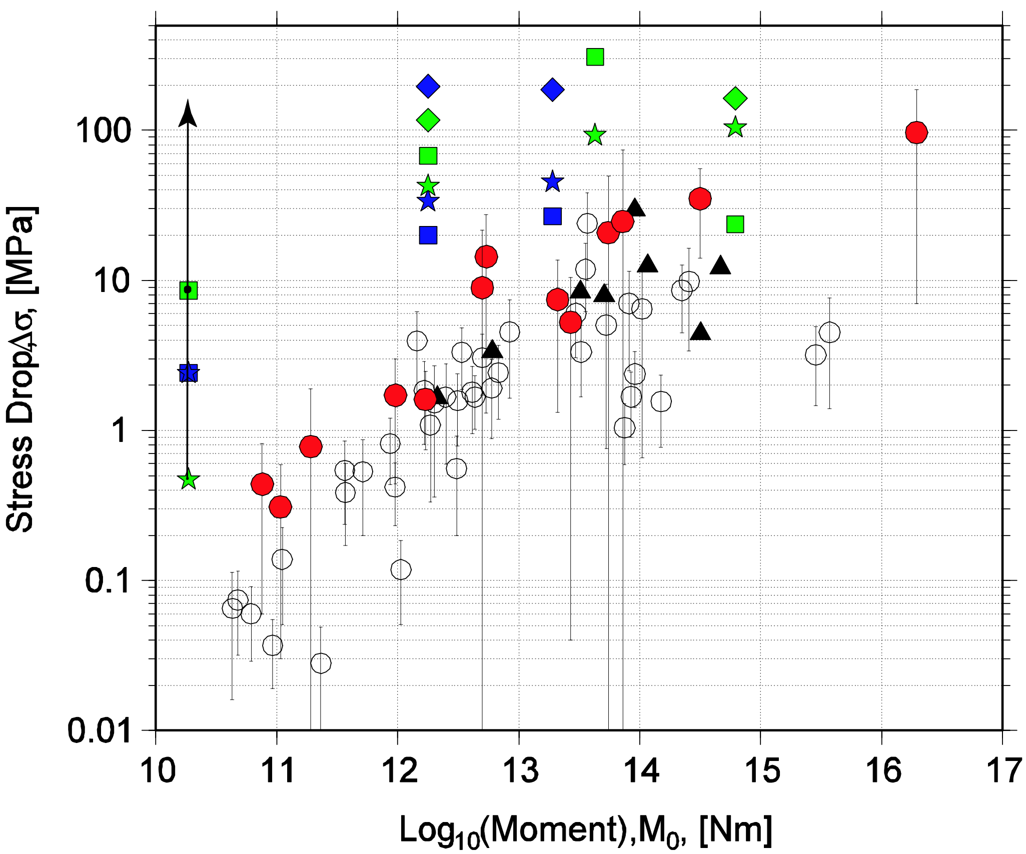

Figure 7. The relation between the static stress drop with seismic moment with the error bar (the mean of error in the event network average) for Au Sable Forks earthquake sequence for the regional wave analysis is plotted with *red circles*. The *blue* and *green* symbols are from the local direct wave analysis, and the *diamonds* are from the time domain EGF measurements. The *vertical arrow* indicates that we only estimate a minimum stress drop because we can only estimate a minimum corner frequency. As in Figure 6, the *open circles* are corner frequency of the 41 events in the northeastern US and southeastern Canada determined by Shi *et al*. (1998). The *filled triangles* are for the eight events whose corner frequencies were estimated from the empirical Green's function method in Shi *et al*. (1998).

Conclusions

The relation between corner frequency and seismic moment of Au Sable Forks, NY sequence does not separate into two regions along the line with the seismic moment about 2×10^{13} Nm (~magnitude 3) as reported in Shi *et al.* (1998), rather the corner frequency measurements of Au Sable Forks, NY sequence fill the gap in the corner frequency and seismic moment relationship at around the moment 2×10^{13} Nm, and make the corner frequency continuously increases with decreasing seismic moment, consequently the source radii for smaller events decrease with decreasing moment down to at least 1×10^{12} Nm (~Mw 2).

The results from both regional and local, direct wave analyses show that the stress drop is high for small and moderate sized earthquakes in NE USA (3-300 MPa). The scaling of stress drop at small magnitudes is less clear. The regional methods suggest a decrease, but the local empirical Green's function approach suggests that the source dimensions are too small to be resolved and that the relation of stress drop and seismic moment suggest that a breakdown in self-similarity below a threshold moment about 2×10^{13} Nm reported by Shi *et al*. (1998) is not obvious in the current data set. Stress drops of 13 Au Sable Forks sequence indicate that the stress drop increase with increasing moment in the moment range 1×10^{13} to 1×10^{15} Nm (Figure 7).

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Appendix 1. List of aftershocks of the 2002 Au Sable Forks sequence recorded by local seismic network during April – November, 2002*.

Id	Date (year-mo-dy)	Time (hh:mm:sec)	Lat. (°N)	Long. (°W)	Depth (km)	Phase (N)	Gap (°)	Dmin (km)	Q
1	2002-04-22	15:12:12.02	44.5018	73.6690	11.81	8	201	04.2	c
2	2002-04-22	23:26:05.78	44.5008	73.6787	11.93	10	132	03.0	b
3	2002-04-23	00:40:17.63	44.5013	73.6605	10.62	10	120	03.6	b
4	2002-04-23	03:20:42.97	44.5017	73.6768	11.05	7	129	03.2	b
5	2002-04-23	20:49:52.49	44.5038	73.6182	09.57	8	204	03.3	c
6	2002-04-23	23:40:16.59	44.5080	73.6422	10.00	6	252	06.0	c
7	2002-04-24	03:16:19.93	44.4977	73.6352	09.53	6	259	07.2	c
8	2002-04-24	09:20:34.94	44.5032	73.6768	11.33	10	128	04.7	b
9	2002-04-24	13:49:28.01	44.5040	73.6230	09.54	8	196	03.2	c
10	2002-04-24	16:32:38.67	44.4967	73.6700	11.40	10	135	03.8	b
11	2002-04-24	17:16:02.76	44.5038	73.6913	12.44	6	136	05.7	b
12	2002-04-25	02:52:17.35	44.5252	73.6840	11.57	12	096	04.2	b
13	2002-04-25	08:26:25.43	44.5008	73.6755	11.71	8	131	04.5	b
14	2002-04-25	08:26:29.73	44.5050	73.6378	09.80	8	164	03.3	b
15	2002-04-25	08:53:43.03	44.5028	73.6750	11.44	12	124	03.3	b
16	2002-04-25	13:39:55.97	44.5033	73.6738	11.41	12	123	03.4	b
17	2002-04-26	10:41:16.72	44.4947	73.6830	12.28	12	146	02.6	b
18	2002-04-27	14:34:01.33	44.4875	73.6480	05.95*	12	124	01.9	b
19	2002-04-27	15:51:48.43	44.5083	73.6687	11.88	10	172	04.7	b
20	2002-04-28	00:23:26.50	44.4972	73.6635	11.64	8	201	03.5	c
21	2002-04-29	15:50:36.02	44.5087	73.6585	11.42	12	144	04.8	b
22	2002-04-30	01:48:35.13	44.5062	73.6540	11.47	11	134	03.8	b
23	2002-04-30	22:53:23.13	44.4867	73.6828	11.69	13	142	02.8	b
24	2002-05-01	08:24:31.94	44.5023	73.6868	12.68	10	220	05.3	c
25	2002-05-03	18:00:49.29	44.5107	73.6608	10.87	8	163	06.3	b
26	2002-05-04	07:05:36.20	44.5092	73.6725	11.50	16	086	03.8	a
27	2002-05-04	15:38:59.00	44.5047	73.6788	12.17	9	287	05.3	c
28	2002-05-05	06:13:49.78	44.4957	73.6782	12.19	14	125	03.0	b
29	2002-05-07	06:38:16.28	44.5032	73.6723	11.95	15	098	03.6	b
30	2002-05-10	02:41:21.15	44.5003	73.6797	11.34	8	134	04.7	b
31	2002-05-10	02:42:10.03	44.4985	73.6782	11.61	14	136	03.0	b
32	2002-05-10	04:57:25.58	44.9555	73.2710	09.00	9	343	49.3	d
33	2002-05-10	12:04:47.42	44.4908	73.6720	10.94	16	125	03.5	b
34	2002-05-14	20:27:13.61	44.5078	73.6568	11.37	8	178	04.1	b
35	2002-05-15	03:36:01.64	44.5078	73.6725	11.97	6	198	04.8	c
36	2002-05-15	09:23:50.77	44.5035	73.6398	12.95	6	196	03.2	d
37	2002-05-16	07:06:17.81	44.7817	73.6742	11.25	14	319	21.3	c
38	2002-05-17	05:51:21.94	44.5093	73.6620	10.62	9	182	04.5	c

39	2002-05-18	07:02:26.43	44.5072	73.6752	11.48	10	121	04.9	b
40	2002-05-20	03:37:27.47	44.5028	73.6765	11.30	8	128	04.7	b
41	2002-05-20	16:32:28.46	44.5062	73.6757	12.12	10	122	04.9	b
42	2002-05-23	17:51:30.46	44.5013	73.6768	11.99	14	103	04.6	b
43	2002-05-24	13:50:55.02	44.5040	73.6725	11.77	10	202	07.4	c
44	2002-05-24	23:46:00.12	44.5048	73.6753	12.15	14	097	04.7	b
45	2002-05-25	04:48:56.89	44.5055	73.6762	11.75	14	096	04.8	b
46	2002-05-26	03:29:21.80	44.5065	73.6393	12.26	6	195	03.5	d
47	2002-05-31	18:52:55.42	44.5968	73.6792	09.20	8	231	03.9	c
48	2002-06-03	08:34:02.21	44.5062	73.6752	11.87	9	122	04.8	b
49	2002-06-03	11:50:03.47	44.4957	73.6808	12.44	10	143	04.5	b
50	2002-06-05	10:05:11.40	44.5067	73.6762	11.97	12	122	04.9	b
51	2002-06-05	16:53:56.40	44.5057	73.6753	11.75	9	124	04.8	b
52	2002-06-18	17:04:10.72	44.3067	73.4825	08.86	7	335	23.7	d
53	2002-06-20	23:37:53.30	44.5098	73.6817	12.38	14	087	03.2	a
54	2002-06-21	06:12:29.79	44.5025	73.6625	10.96	6	119	03.9	b
55	2002-06-24	07:29:36.46	44.5058	73.6375	09.99	5	191	03.4	d
56	2002-06-25	13:40:27.95	44.5030	73.6747	11.53	12	080	04.6	a
57	2002-06-25	13:57:23.05	44.4967	73.6665	11.04	7	239	07.9	c
58	2002-06-25	14:03:00.87	44.5020	73.6728	11.48	10	178	07.6	b
59	2002-07-02	04:21:38.04	44.5008	73.6723	12.50	11	179	04.3	b
60	2002-07-03	19:05:11.19	44.5043	73.6702	11.56	8	199	04.4	c
61	2002-07-08	02:56:44.82	44.5055	73.6722	11.59	12	177	04.6	b
62	2002-07-12	04:52:15.12	44.5103	73.6478	10.39	7	156	06.0	b
63	2002-07-13	10:08:25.46	44.4998	73.6708	11.43	8	132	07.2	b
64	2002-07-14	06:45:20.41	44.5035	73.6670	11.62	6	309	07.2	c
65	2002-07-20	08:36:07.06	44.4890	73.6678	11.24	5	253	09.9	c
66	2002-07-25	18:01:49.22	44.2912	73.5465	04.40x	9	327	16.3	d
67	2002-08-29	04:27:59.59	45.0742	73.1930	26.57x	8	349	63.7	d
68	2002-09-01	09:00:06.29	44.4997	73.6758	12.68	6	183	08.5	c
69	2002-09-09	16:54:11.63	44.5047	73.6728	11.47	6	175	07.3	b
70	2002-09-19	16:59:09.95	44.2997	73.5260	04.09x	8	330	16.2	d
71	2002-09-25	18:52:45.09	44.6390	73.5907	13.00	6	326	06.0	c
72	2002-09-28	18:15:13.68	44.5035	73.6705	11.62	6	309	07.4	c
73	2002-11-09	14:47:53.63	44.5440	73.5020	11.67	5	342	10.1	c
74	2002-11-12	20:41:46.63	44.5135	73.6578	12.68	5	238	05.9	c

*) Phase = number of *P* or *S* arrival picks used for location; Gap = maximum gap in the azimuthal coverage in degree; Dmin= epicentral distance to the nearest station; Q = quality of location solution indicator. Events #32, #37, #52, #66, #67 and #70 are located outside of Au Sable Forks epicentral area.