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SOURCE CHARACTERISTICS AND HAZARD IMPLICATIONS OF THE APRIL 20, 2002, MW 5, PLATTSBURGH, NY, EARTHQUAKE SEQUENCE

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Technical Abstract

The Mw 5.0 Au Sable Forks earthquake and its largest aftershock (M_L 3.7) 14 minutes later were extremely well recorded in eastern North America. Over 50 broad-band 3-component records are available for the mainshock from regional stations over distance ranges from 70 to 2000 km. Focal mechanism and source depth of the mainshock were determined from broad-band waveforms recorded at distances between 144 and 1250 km. The results of a regional waveform inversion for double-couple source indicate that two nodal planes strike N-S, dip at intermediate angles (43°E and 47°W), and have predominantly thrust motion. The *P*-axis is nearly horizontal (plunge = 2°) and trends E-W (274°), which is similar to nearly E-W trending *P*-axis reported for the October 1983 Goodnow earthquake that occurred about 70 km SW from the Au Sable Forks shock. This orientation differs slightly from the ENE trending regional average *P*-axes orientation in the region. The best-fit regional waveform modeling yields a mainshock source depth of 11 km. This depth is consistent with aftershock hypocenter distribution. It is also generally consistent with previous hypocenters in the northern and eastern Adirondacks. The April 2002 Au Sable Forks earthquake sequence includes several strong early aftershocks, mostly prior to the initiation of local recordings. Differences in waveforms and *P* wave first motion polarities at common regional stations for these aftershocks suggest a range of focal depths and source mechanisms.

Data from the local network yielded 63 accurately located aftershocks during April – November, 2002. Small RMS residuals (≤ 0.03sec) and differences in locations were obtained due to high-quality digital data with a high sample rate (200 samples/s). We estimate relative location uncertainty of ± 0.5 km. These 63 hypocenters outline an aftershock volume much larger than location uncertainties. Most Au Sable Forks aftershocks are clustered at the western and deep (10 – 13 km) portion of the volume. They occupy a tabular space about 1 km thick, 2 km wide along a N-S strike, and 2.5 km along an intermediate dip to the west. This cluster is about the size of the mainshock rupture as derived from spectral analysis. There are several aftershocks that are shallower and east of the inferred mainshock rupture. These off-rupture aftershocks may illuminate the up-dip extension of the source fault. Accurate aftershock hypocenter distribution provides constraints on mainshock rupture and critical information for investigating tectonic processes and for assessing hazard from future earthquakes in the region.

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Non-Technical Abstract

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 $10 million US dollars and on May 16, 2002, Presidential disaster declaration was issued for Clinton and Essex Counties, NY (Disaster No.: FEMA-1415-DR-NY). The mainshock and its aftershocks were extremely well recorded by modern digtial, 3-component seismographic stations in eastern North America. Over 50 broad-band 3-component records are available for the mainshock from regional stations over distance ranges from 70 to 2000 km. Focal mechanism determined from the waveform data is predominantly thrust faulting along north-south striking fault plane dipping to the west at 47°. Focal depth of the mainshock is about 11 km and distribution of over 60 aftershocks is also consistent with this depth. Accurate aftershock hypocenter distribution provides constraints on mainshock rupture and critical information for assessing hazard from future earthquakes in the region.

Introduction

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 (see Figure 2). 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 (see Figure 2). The earthquake caused substantial damage and on May 16, 2002, Presidential disaster declaration was issued for Clinton and Essex Counties, NY (Disaster No.: FEMA-1415-DR-NY).

There were damages 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. This is the seventh damaging earthquake in the area of the northeastern US west of New England (NY, PA, NJ, MD, DE, OH) and the third one in the Adirondacks during the last 60 years. Three decades of epicenters from a regional seismic network confirm that Adirondack seismicity is relatively high (Figure 1). This seismicity was concentrated in well-defined zones, but was not particularly high near the Au Sable Forks source. No prior known earthquake is likely to stem from the source of the Au Sable Forks sequence.

This report includes results on the April 2002 Au Sable Fork mainshock from regional stations, and characterization of the source zone by aftershocks, and some general observations about the macroseismic effects of the mainshock.

Damage and Felt Reports

The Au Sable Forks earthquake caused light, but widespread damage. Newspaper accounts and direct unsystematic observations suggest that most of the damage is limited to the content of buildings (MMI VI), but it also includes many fallen or damaged chimneys and some structurally damaged buildings (MMI VII). The epicenter is in the middle of a 5-10 km wide uninhabited mountainous area and the maximum intensity might have been higher if more structures had been exposed to near-field ground motion. Slope failure along the north bank of the Au Sable River southeast of the epicenter severely damaged a section of Rt. 9N about 10 km east of the epicenter. Ground failure may also be the cause of damage to a bridge near Jay, about 15 km south of the epicenter. The USGS Community Intensity Map shows areas of MMI VII and MMI VI about 20 and 70 km across (Figure 2).

Site response characteristics in the Au Sable Forks area may play a key role in the damage distribution. Site conditions in the epicentral region are markedly differentiated into three categories: hard (≈ 6 km/s) glacially polished rock; glacially consolidated sediment (mostly till); and post-glacial unconsolidated sediment, which is notoriously weak. Most of the older buildings

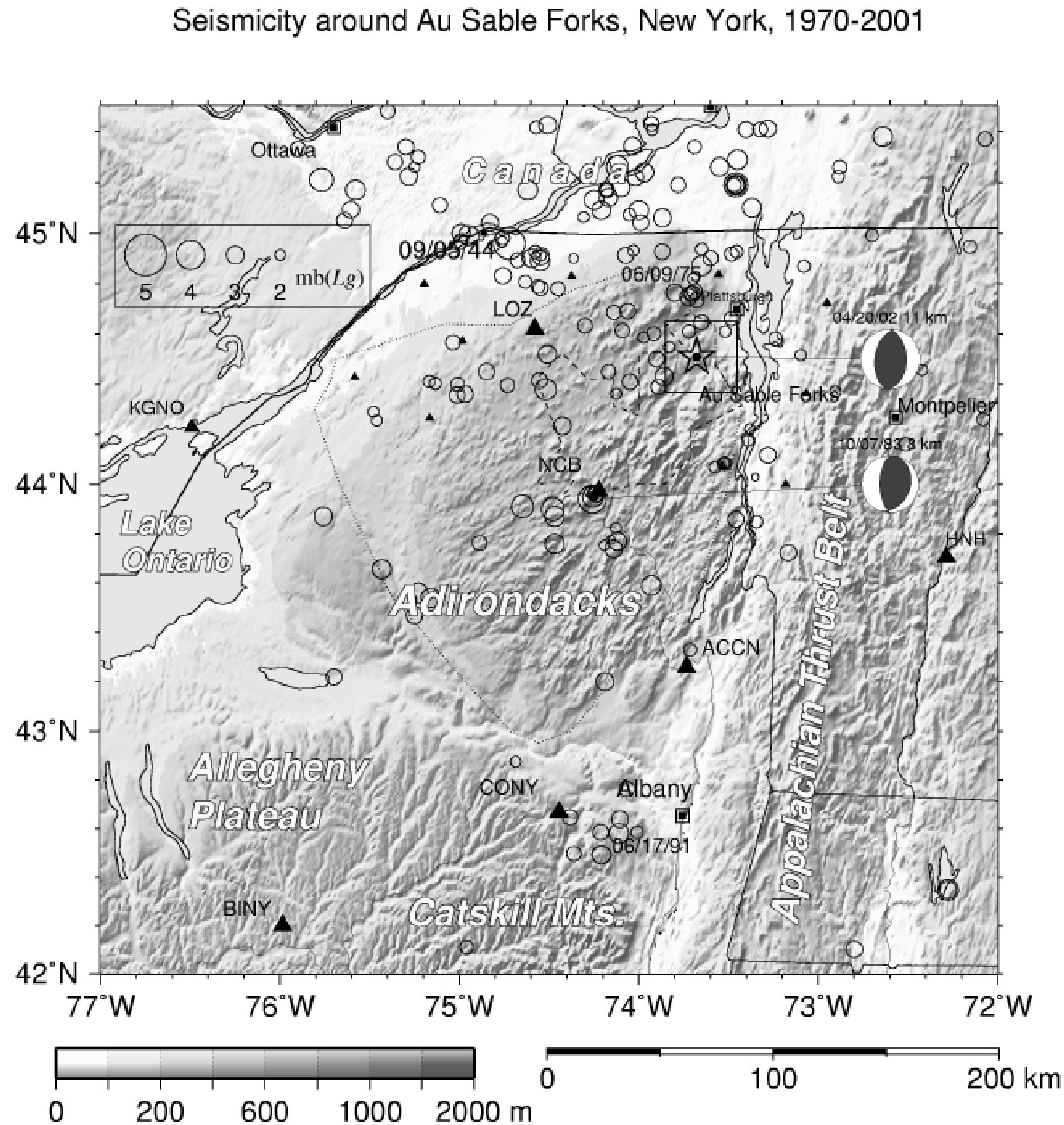

Figure 1. Shaded topographic map of New York and adjacent states with the epicenters of earthquakes that occurred during 1970-2001. The 2002 Au Sable Forks epicenter is marked by a *star*. Other important earthquakes are marked by dates (Conwall-Massena, 09/05/1944, Ms 5.4; Altona, 06/09/1975 M4.1 and Goodnow 10/07/1983 mb(Lg) 5.1). Broadband stations in the region are also plotted with *triangles* (Lamont Cooperative Seismographic Network, New England Seismic Network and US National Seismic Network). 2002 Au Sable Forks epicentral area is indicated by square box.

are on alluvial sediment near rivers, which offer the best farmland; recently built homes tend to be on consolidated sediment and higher ground; bedrock outcrops tend to be uninhabited. Most of the structural damage seems to be in alluvial valleys. Financial losses above 10 million dollars have been announced and Federal Disaster Area status was granted to the affected Clinton and Essex Counties.

The felt area extends as far as Buffalo New York, Philadelphia PA, Bangor Maine and into Canada. This far-field intensity distribution is symptomatic of low attenuation (Frankel et al., 1990) and resembles the intensity field for the Goodnow event and other regional earthquakes of similar size. The Au Sable Forks mainshock is the latest in series of damaging earthquakes in the area (Table 1) monitored with either fixed or temporary stations by the Lamont Cooperative Seismographic Network (LCSN). Source depth is known to affect maximum intensity and the fall-off with distance. For example, the very shallow 1994 mb(Lg)4.7 Cacoosing Valley PA earthquake caused significant damage while the 4 - 5 km deep 1986 mb(Lg) 4.0 Lancaster PA event in a similar cultural environment caused no damage but was felt at greater distance (Seeber et al., 1998). Depth may be a factor in the more rapid fall-off with distance of intensities in the 1983 mesoseismal area than in the 2002 one (Figure 2).

The 1944 Massena event is the first damaging earthquake in the Adirondacks. Two more have occurred since. Lack of known earlier damaging earthquakes is probably symptomatic of very sparse population. Previous $M \geq 5$ events in the Adirondacks may have been misinterpreted as smaller events originating near population centers surrounding the Adirondacks. Except for the relatively small 2001 Ashtabula mainshock, most of the earthquakes with precisely determined source characteristics occurred in non-urban areas, while New York City, which comprises by far the greatest exposure, experienced earthquake damage at least twice historically, but not since the 19th century. An important task is to systematically compare source parameters, site-response characteristics, felt and damage reports, and built-asset exposure for damaging earthquakes in the northeastern US.

Table 1. Damaging Earthquakes in Northeastern United States.

Year	Magnitude	Location	Intensity (MMI)	Depth (km)
1737	M5	New York City region	MMI VII	
1783	Mfa5.0	New York City region	MMI VI(?)	
1884	Mfa5.2	New York City	MMI VII	
1929	Mb5.2	Attica, NY	MMI VIII	
1944	Ms5.4	Massena, NY	MMI VIII	depth 10-20 km
1983	M_L 5.1	Goodnow, NY	MMI VII	depth 7-8 km
1986	mb(Lg) 5.0	Leroy OH,	VI-VII	depth 4-5km
1994	mb(Lg) 4.7	Cacoosing Valley PA	VI-VII	depth 0.5-2.5 km
1998	mb(Lg) 5.2	Pymatuning PA	VI-VII	depth 4-5 km
2001	mb(Lg) 4.5	Ashtabula OH	MMI VI	depth 2-3 km
2002	Mw5.0	Au Sable Forks NY	MMI VII	depth 10-13 km

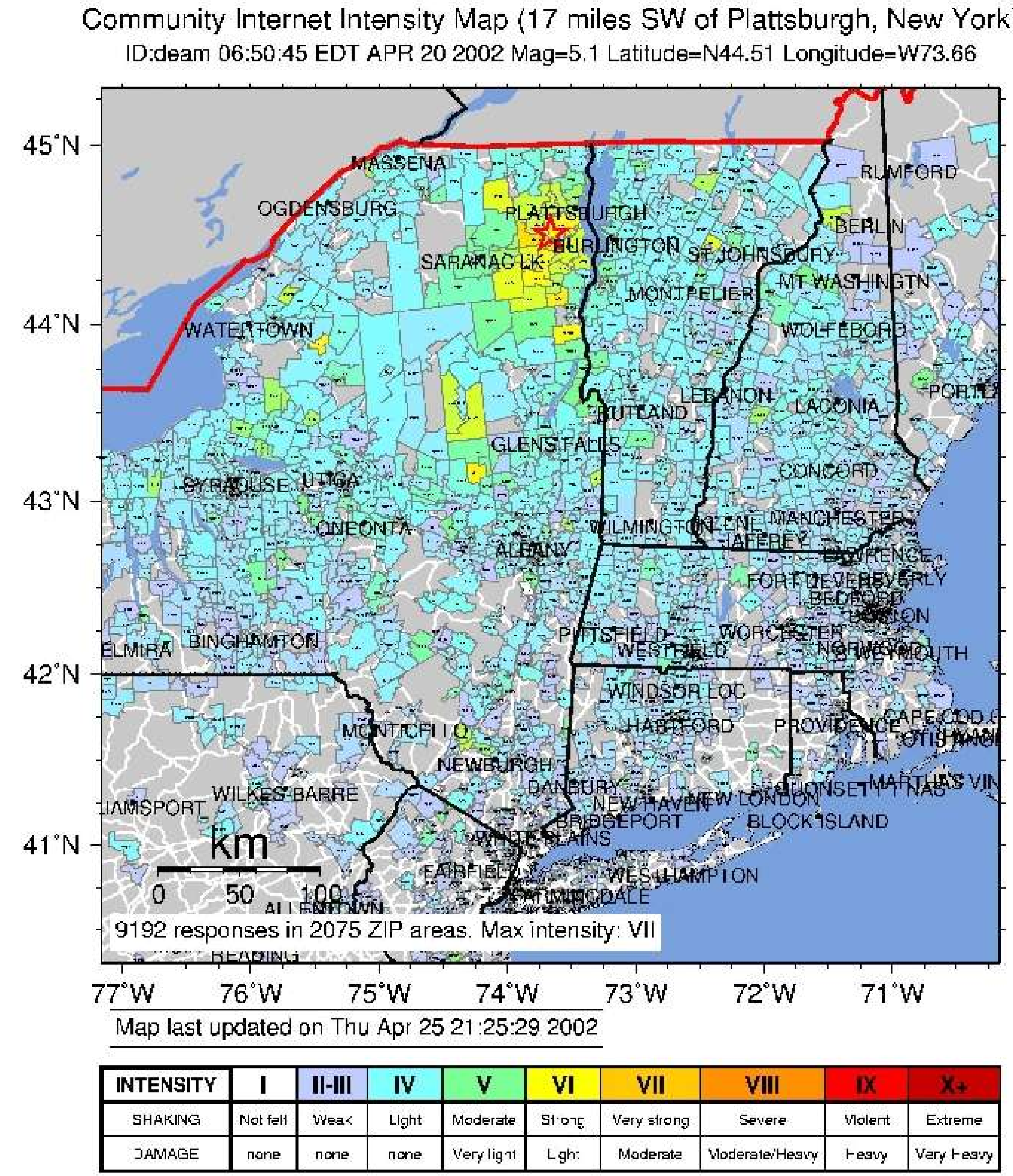

Figure 2. Community Internet Intensity Map (CIIM) for the 20 April 2002 Au Sable Forks, NY earthquake using data collected between April 20 – 25, 2002. 9,192 responses at 2,075 postal ZIP code areas were used. Fill corresponds to the Modified Mercalli (MM) intensity values given in the legend. The epicenter is shown with a *star*. The shock attained a maximum intensity of VII (MM) near the epicenter (Clinton and Essex Counties, NY) with reports of minor damages at these Counties. (Courtesy Wald et al., U.S. Geological Survey).

Instrument Deployment and Aftershocks

Following the mainshock, LDEO (Lamont-Doherty Earth Observatory) deployed digital portable seismographs to monitor aftershocks. The first station was installed about 1/2 day after the mainshock and four more stations were installed the next day (see Figure 3). Additional portable digital seismographs were deployed through collaborative efforts with colleagues in the US and in Canada. Hence, CERI (Center for Earthquake Research and Information, University of Memphis) dispatched two of their technical staff to the epicentral area with four accelerometers and a broadband seismograph; the PASSCAL Instrument Center of IRIS (Incorporated Research Institutions for Seismology) Consortium shipped three digital seismographs and ancillary equipment within one day of the request; personnel of ISTI (Instrumental Software Technologies, Inc., Saratoga Springs, NY) joined LDEO staff and deployed the first portable station in the epicentral area; and the POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity) Consortium, Canada sent a field crew of three with a near real-time, satellite telemetry based earthquake monitoring system. The POLARIS station, KSVO (Keeseville, NY), powered by a solar panel and batteries, was already transmitting data to the central Hub in London, Ontario, Canada within a day after the field crew arrived in the Au Sable Forks area. These collaborations allowed us to maximize the scarce resources available for monitoring this damaging earthquake and its aftershocks in the Northeastern U.S. By April 27, 2002, a week after the mainshock, 15 portable, digital seismographic stations were deployed at 13 sites for monitoring the aftershocks in the epicentral area (Table 2; Figure 3). 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 69 small aftershocks. The preliminary mainshock hypocenter from regional stations was only about 3 km NW and within the depth range of the aftershock hypocenters. Thus we were able to capture early aftershocks with a network that spans a 20 km-wide area (see Figure 3), centered above a 10 km deep source.

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 & 4 and are listed in Table 3.

The aftershock hypocenters from the Au Sable Forks local network covering the period April – November, 2002 are plotted in Figure 3 & 4. 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 2. Aftershock monitoring local seismic network for April 2002 Au Sable Forks, New York earthquake sequence*.

Station (code)	**Latitude (N)**	**Longitude (W)**	**Elev (m)**	**Datalogger (type)**	**Sensor**	**Operation (start date)**	**Affiliation**
FORD	44.510	73.770	365	DM24	CMG-40T	2006-04-21	ISTI
JEEP	44.480	73.630	144	262	L22	2006-04-21	LDEO
SCRF	44.560	73.630	333	526	L22	2006-04-21	LDEO
LAKE	44.495	73.716	354	524	L28	2006-04-21	LDEO
MESS	44.571	73.715	283	232	L22	2006-04-21	LDEO
BARN	44.593	73.629	256	240	L28	2006-04-22	LDEO
				DM24	CMG-40T	2006-04-25	CERI
BILL	44.482	73.806	408	6115	L22	2006-04-23	LDEO
				K2/1365	L28	2006-04-25	CERI
SKUN	44.535	73.594	180	K2/1368	L28	2006-04-25	CERI
GREE	44.425	73.629	238	479	L22	2006-04-25	PASSCAL
				K2/1361	L28	2006-04-25	CERI
OREB	44.586	73.781	280	K2	L4C	2006-04-25	CERI
BROK	44.462	73.749	300	393	L22	2006-04-25	PASSCAL
KSVO	44.552	73.686	381	Trident	CMG-3ESP	2006-04-26	POLARIS
HALL	44.519	73.521	210	117	L22	2006-04-27	PASSCAL

*) Affiliation: PASSCAL= 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).

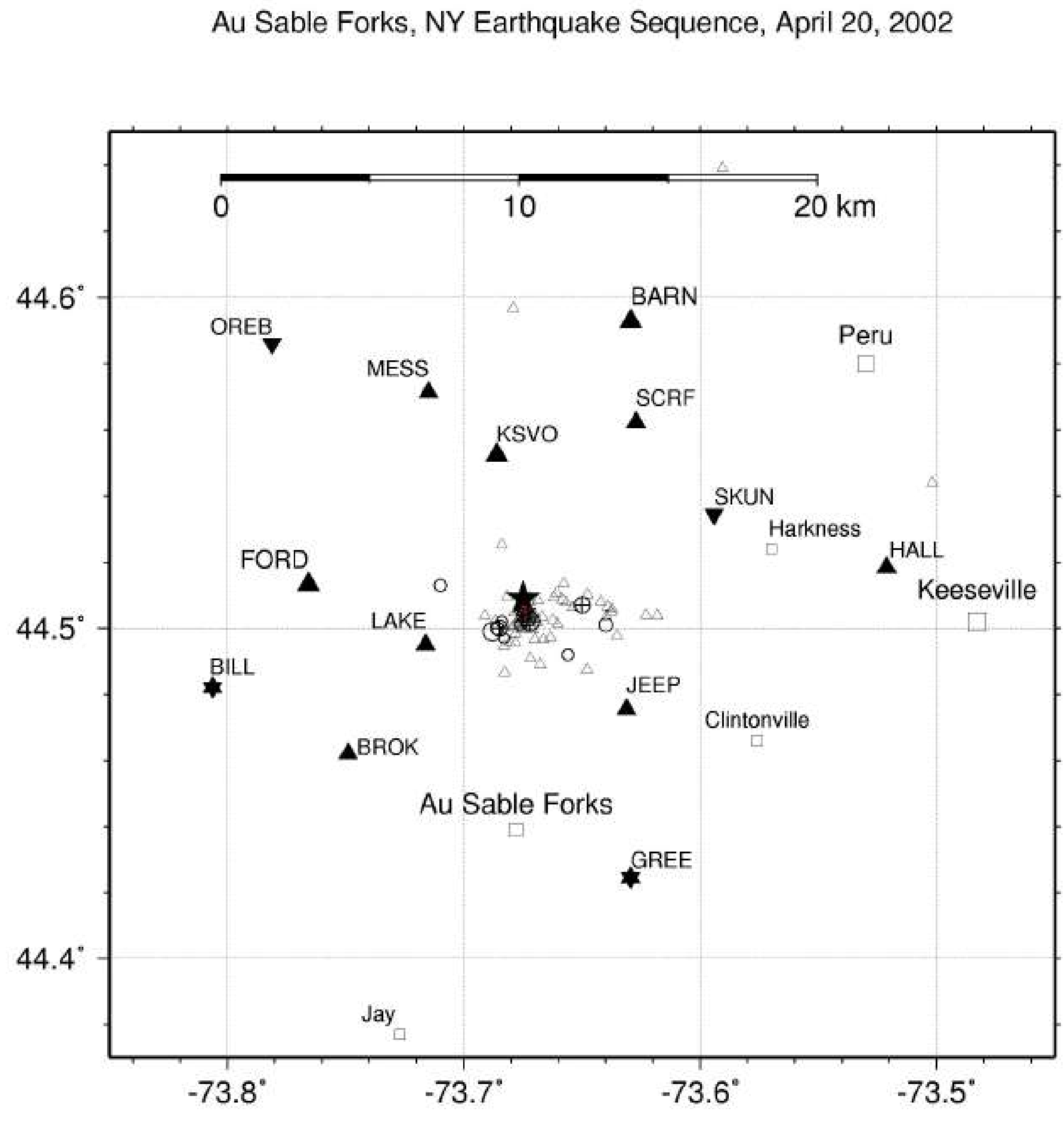

Figure 3. Map of the Au Sable Forks epicentral area in northeastern Adirondacks showing the temporary monitoring stations and aftershock epicenters. The epicentral area is indicated in Figure 1. A *large solid star* indicates the mainshock, *small open circles* are epicenters of aftershocks located by 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 (contributed by CERI, University of Memphis; some are co-located with velocity sensors). *Open squares* indicate towns in the area (e.g., Keeseville, Au Sable Forks etc.).

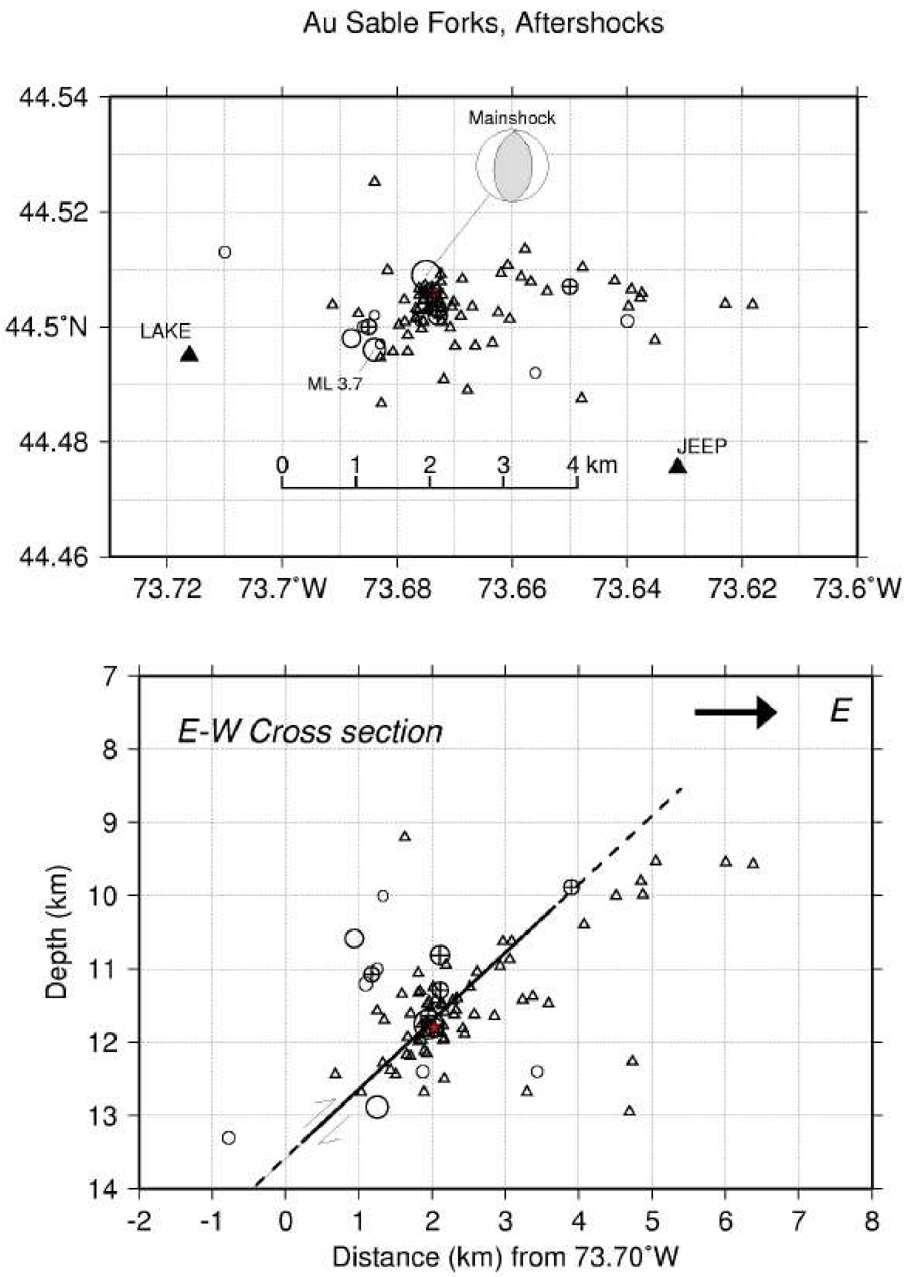

Figure 4. (*top panel*) Epicenters of the Au Sable Forks earthquake sequence during April – November, 2002. The mainshock and its first day aftershocks as well as other large aftershocks that are recorded both by the local and regional network stations are plotted by *circles*, whereas small aftershocks 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. Some aftershocks, however, are located a significant distance from the rupture suggesting a large aftershock volume and the activation of secondary faults.

Table 3. List of regionally recorded earthquakes in the 2002 Au Sable Forks sequence

Date (year-mo-dy)	Time (hh:mm:sec)	Lat. (°N)	Long. (°W)	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	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	

Seismological View of the Source

The Au Sable Forks mainshock (M_L 5.3; 10:50) and the largest aftershock (M_L 3.7; 11:04) 14 minutes later were extremely well recorded in eastern North America. Over 50 broad-band 3-component records are available for the mainshock from regional stations over distance ranges from 70 to 2000 km. Focal mechanism and source depth of the mainshock were determined from broad-band waveforms recorded at distances between 144 and 1250 km. The results of a regional moment tensor inversion (Dreger & Helmberger, 1993; Zhao & Helmberger, 1994; Du et. al., 2004) are shown in Figure 5. The nodal planes strike N-S, dip at intermediate angles (43° and 47°), and have predominantly thrust motion. The *P*-axis is nearly horizontal and strikes E-W (274°). Nearly E-W trending *P*-axis was also reported for the Goodnow mainshock (Nabelek and Suarez, 1989, Figure 1). This orientation differs slightly from the ENE trending regional average *P*-axes orientation (Yang and Aggarwal, 1981) and the inferred maximum horizontal stress direction (Zoback and Zoback, 1989). The best-fit regional waveform inversion yields a mainshock source depth of 11 km. This depth is consistent with aftershock hypocenters (Figure 4). It is also generally consistent with previous hypocenters in the northern and eastern Adirondacks (e.g., Yang and Aggarwal, 1981). Earthquakes in the western and southern Adirondacks tend to be shallower.

The Au Sable Forks sequence includes several strong early aftershocks, mostly prior to the initiation of local recordings (Table 3). Differences in waveforms at regional stations for the aftershocks in Table 3 (e.g., Figure 6) suggest a range of focal depths and source mechanisms. This hypothesis is consistent with hypocenters and first-motions for subsequent smaller aftershocks recorded by local stations.

Data from the local network yielded 63 accurate hypocenters. Small RMS residuals (≤0.03sec) and differences in locations were obtained with two different *P*-wave velocity models: 6.1 km/sec, 0 - 4 km and 6.6 km/sec, 4 - 35 km (Yang and Aggarwal, 1981); versus 6.4 km/sec, 0 - 18km and 6.8 km/sec, 18 - 35km. Vp/Vs = 1.73 was assumed in both cases. High sampling rates (200sps) and similar waveforms allow for very consistent *P*-phase picks. In addition, the nearly ideal station distribution (Figure 3) contributes to the accuracy of these hypocenters. We conservatively estimate relative location uncertainty of ±0.5 km. These 63 hypocenters outline an aftershock volume much larger than location uncertainties. Most Au Sable Forks aftershocks are clustered at the western and deep (10 – 13 km) portion of the volume. They occupy a tabular space about 1 km thick, 2 km wide along a N-S strike, and 2.5 km along an intermediate dip to the west. This cluster is about the size of the mainshock rupture as derived from spectral analysis and is proposed to "illuminate" this rupture. The remaining 7 hypocenters are shallower and east of the inferred mainshock rupture (see Figure 4). These off-rupture aftershocks may illuminate the up-dip extension of the source fault. One reliable hypocenter is only 6 km deep.

Moment-tensor inversion and spectral analysis of regional mainshock waveforms and early aftershock hypocenters from local stations delineate a source about 7 km north of this town, at 44.50N, 73.68W, and a depth of 10-13 km. The mainshock rupture strikes N-S, has an intermediate dip to the west, a reverse slip, a moment $M_0 = 3.5 \times 10^{16}$ Nm (Mw 5.0) and a rupture radius of 1.2-1.4 km. Most of the aftershocks are within a 1 x 2 x 3 km zone inferred to illuminate the mainshock rupture; the others are significantly shallower and to the east, possibly illuminating the causative fault up-dip from the rupture.

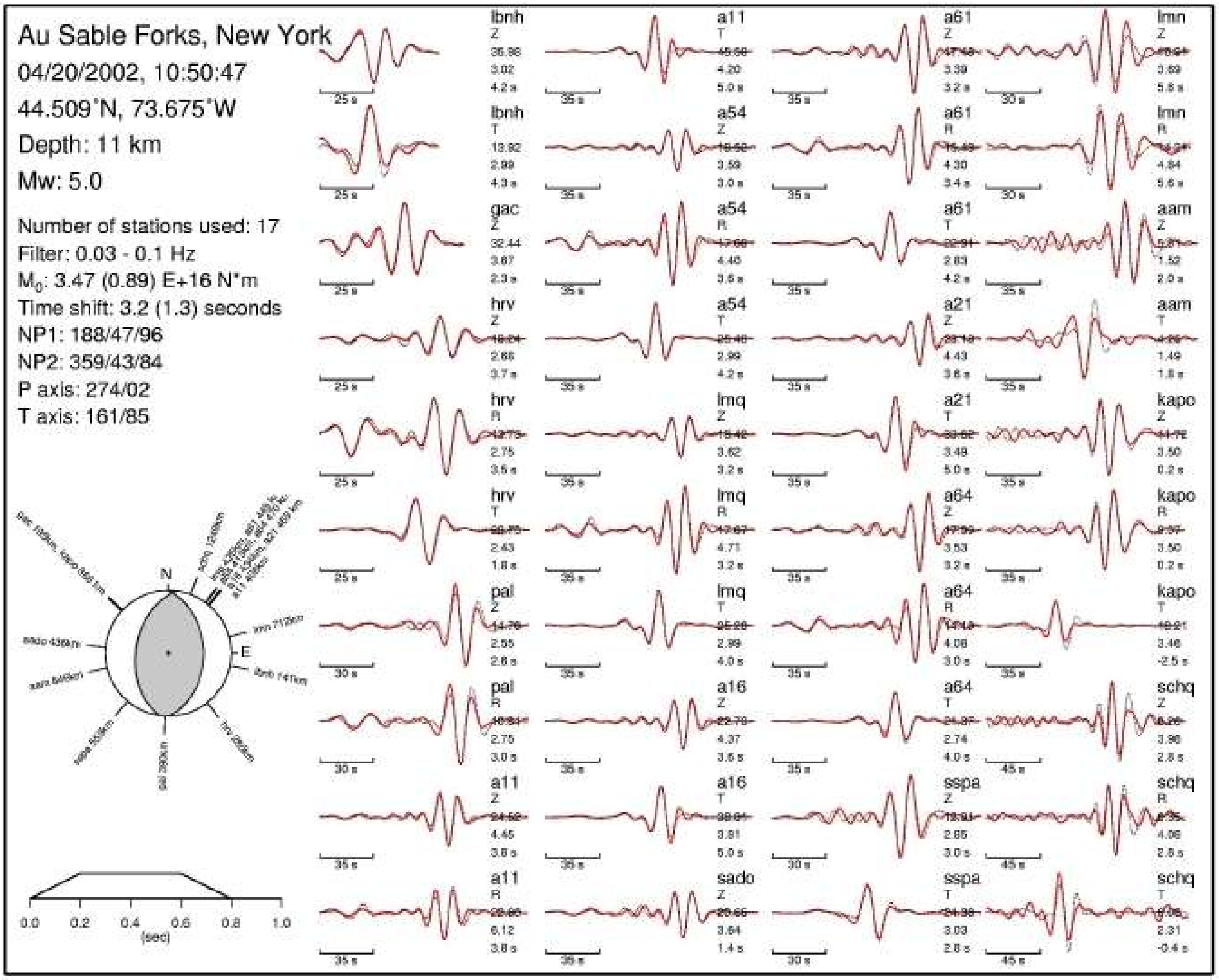

Figure 5. Comparison between observed (*solid lines*) and synthetic (*dotted red lines*) waveforms of the 20 April 2002 earthquake. Synthetic seismograms are calculated for a focal depth of 11 km. Station code and component (Z=vertical, R=radial, T=transverse components), peak amplitude of the observed signal in micrometers, seismic moment in 10^{15} N m and time shift δt in seconds are indicated at the end of each trace. Focal mechanism of the event is represented by the typical beach ball representation of lower-hemisphere projection. Shaded quadrants denote compression for *P* waves. The epicentral distance of each station is marked around the beach ball according to azimuth. Two nodal planes (NP1 and NP2), as well as azimuth and plunge angle in degrees of the *P* and *T* axes are indicated. The simple trapezoidal source time function used is shown.

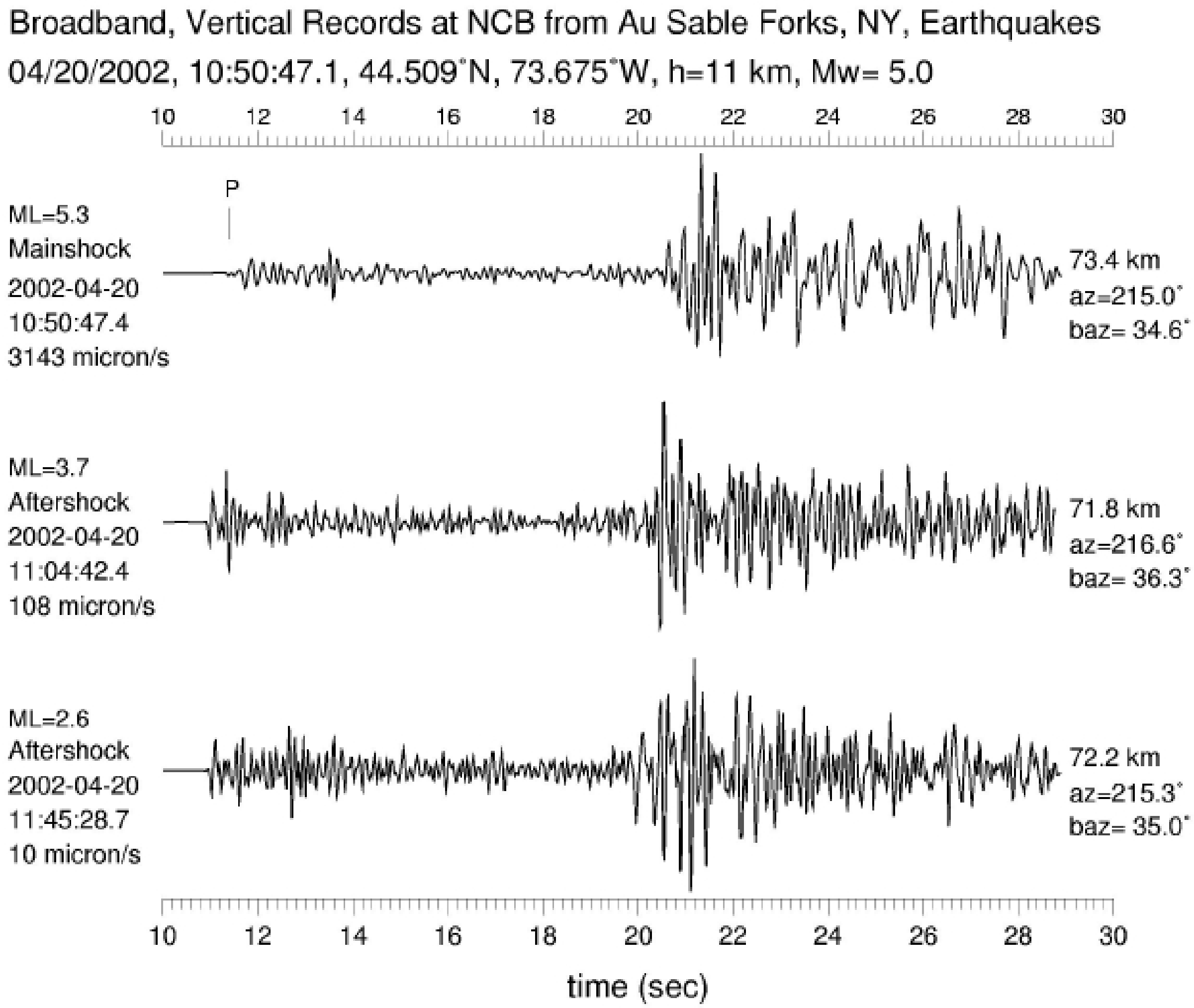

Figure 6. Waveforms from the three largest events in the Au Sable Forks sequence. These vertical component broad-band waveforms were recorded at station NCB (Newcomb, NY), about 75km SW of Au Sable Forks epicenter (Figure1). Notice that *P* wave arrivals from three events are all different from each other, suggesting diverse focal mechanisms of these events.

Regional Seismicity and Geologic Setting in a Stable Continental Regions (SCR)

The Au Sable Forks sequence is centered in the northeastern flank of the Adirondack massif (Figure 1). This dome exposes high-grade Grenville age (≈ 1,000 Ma) rocks of the North American craton. The epicentral area is within the Lake Champlain boundary zone between this craton and the Paleozoic age Appalachian thrust belt to the east. This boundary zone is characterized by NS-striking brittle faults associated with post-Grenville opening of the Iapetus ocean and subsequent lower Paleozoic (Ordovician Period) closing of this ocean in the Taconic collision (~460 Ma). These faults, therefore, include both normal faults, typically high angle, and thrust/reverse faults (Isachsen and McKendree, 1977; Isachsen et al., 1983). Evidence of fault reactivation abounds in eastern North America and shows that some faults persist as weaknesses over long geologic time (e.g., Ratcliffe et al., 1996; Adams et al, 1991; Bollinger and Wheeler, 1982). After Iapetus extension and Taconic compression, the same faults in the Champlain Valley may have again accommodated extension in the upper Ordovician (e.g., Rogers et al, 1990). Focal mechanism of the Au Sable Forks mainshock show reverse faulting on a NS-striking fault (Figure 5). This geometry is consistent with reactivation of brittle faults in the Champlain Valley zone.

While ductile Grenville-age structure is dominantly east-west striking and generally quite complex, brittle structure in the Adirondacks is dominated by regional sub-vertical fracture zones trending NNE (Isachsen and McKendree, 1977; Isachsen et al., 1983). Some of these fractures are traced for hundreds of kilometers across the entire Adirondacks massif and they have a clear expression in the morphology (e.g., Figure 1). Yet they cannot generally be classified as ***faults*** because they tend to exhibit surprisingly little accumulated displacement. Evidence so far is negative about these structures being involved in current seismogenesis. Finally, the Au Sable Forks source is in a belt of leucogranitic gneiss near the northeastern boundary of the Marcy anorthosite province. This boundary is remarkably straight and could be tectonic. However, it has a northwesterly trend and is unlikely to be directly involved with the 2002 Au Sable Forks source.

The October 1983 Goodnow, NY earthquake source was associated with a local north-northeast to north-south trending brittle structure system that was expressed at the surface by mesoscopic-scale features and by the Catlin Lake lineament (Dawers and Seeber, 1991). Although often recognizable in the pre-existing structure, many of the seismogenic faults in stable continental regions (SCR) are minor elements in this structure, and show very small displacements accumulated in the current regime. For example, all clearly resolved seismogenic faults flanking the Newark Basin, including the source of the January 1994 earthquake sequence in Cacoosing Valley, Pennsylvania, strike at high angle with the Ramapo border fault and the main Appalachian structure (Seeber et al., 1998). These major structures are sub-parallel to the axis of maximum horizontal compression and thus may not be favorably oriented for shear failure. In contrast, the maximum compressive stress axis crosses the structural front along the Champlain Valley at high angle (Sbar and Sykes, 1973; Yang and Aggarwal, 1981; Zoback and Zoback, 1989). A detailed comparison of geologic and seismogenic structure in the Au Sable Forks area offers an opportunity to test whether the geometry of the faults relative to the stress orientation is the sole factor in determining reactivation, or whether reactivation is intrinsically more likely for small SCR faults than for master faults.

Damaging earthquakes provide critical information for investigating tectonic processes and for assessing hazard from future earthquakes. In the eastern US and other stable continental regions (SCR), seismicity is much lower than in active regions and tends to receive less seismological attention. Partly for this reason, SCR seismogenesis is poorly understood and the related hazard is still subject to large uncertainties. Nevertheless, SCR earthquake disasters worldwide demonstrate that this hazard is significant. Furthermore, exposure and fragility are generally high in large urban areas of the eastern US and thus risk is disproportionally high (USGS, 2002).

Available data on earthquakes in eastern North America span a wide range of magnitudes, observational techniques, and geologic environments. Constraints on older earthquakes can be improved and fundamental characteristics of the seismicity can be revealed by combining available data with new case studies. Portable instruments have permitted high-resolution studies of earthquake sources for almost half century. Accurate aftershock hypocenters provide independent constraints on mainshock parameters, particularly on the location and geometry of the mainshock rupture. They may also illuminate other faults and provide structural data that can be directly compared with surface geologic observations. Finally, abundant small earthquakes can be used to monitor mechanical changes associated with earthquake triggering and with sequences of related earthquakes. Some of the seismological and/or geological field studies of northeastern North American earthquake sources that significantly expanded our view of seismogenesis in northeastern North America are listed in Table 4. New earthquakes offer opportunities to capture additional aspects of the seismogenic process and to apply improved instrumental and analytical techniques for yet higher resolution. This is a very effective way to improve the observational basis for regional hazard estimates and for understanding fundamental processes responsible for SCR seismogenesis.

Table 4: Selected NE North American Earthquake Sequences and Salient Characteristics Revealed by Field Studies

Year Location Magnitude	**Comments**
1982 Miramichi NB, Mb5. 7; 5.2; 5.4; 5.0	a complex and long-lasting sequence involving a relatively large volume of crust (Wetmiller et al, 1984)
1983 Goodnow NY, M_L5.1	aftershocks confined in a relatively small volume and clustered in a ring around the rupture (Seeber and Armbruster, 1996; Nabelek and Suarez, 1989)
1987 Saguenay, Quebec, Mw 5.9	a source in the deep crust producing widespread liquefaction and surprisingly large ground motion at regional distances (North et al, 1989; Tuttle et al., 1990; Hough et al., 1989)
1989 Ungava, Quebec, Mw 6.0	a very shallow rupture breaching the surface on a new brittle fault (Adams et al, 1991)
1994 Cacoosing PA M_L 4.6	a very shallow rupture triggered by quarry unloading after quarry is flooded (Seeber et al., 1998)
2001 Ashtabula OH M_L 4.2	long-lasting sequence triggered by deep fluid injection; largest event 7 years after injection ceased (Seeber et al, 2002)

Conclusions

The 20 April 2002 Au Sable Forks mainshock is the latest in a series of damaging northeast US earthquakes, three of which occurred in the Adirondacks during the last 60 years. MMI VII damage is reported from a 10 by 20 km area. The total damage was several millions of dollars, despite the low population density in the epicentral area.

No prior event from 30 years of network data or from historic reports can be confidently associated with the inferred source of the 2002 Au Sable Forks earthquake.

Regional moment-tensor inversion of regional recordings of the mainshock plus hypocenters of locally recorded aftershocks delineate a rupture 10 - 13 km deep, dipping westward at intermediate dip and with reverse slip. Some of the aftershocks are located significantly above and to the east of the rupture.

The subhorizontal *P*-axis trends due East-West (274°), which is slightly different from the ENE trending regional average *P*-axes orientation (~65°) and the inferred maximum horizontal compression axis.

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References

Adams, J., R.J. Wetmiller, H.S. Hasegawa, and J. Drysdale, The first surface faulting from an intraplate earthquake in North America, *Nature,* **352**, 617-619, 1991.

Bollinger, G.A., and R.L. Wheeler, The Giles County, Virginia, seismic zone-Seismological results and geological interpretation, *U.S. Geological Survey Professional Paper* **1355**, 85p, 1988.

Dawers, N.H., and L. Seeber, Intraplate faults revealed in crystalline bedrock in the 1983 Goodnow and 1985 Ardsley epicentral areas, New York, *Tectonophys.* **186**, 115-131, 1991.

Du, Wen-xuan, Won-Young Kim, and Lynn R. Sykes. Earthquake source parameters and state of stress for northeastern United States and southeastern Canada from analysis of regional seismograms, *Bull. Seism. Soc. Am.*, **93**, 1633-1648, 2003.

Frankel, A., A. McGarr, J. Bicknell, J. Mori, L. Seeber and E. Cranswick, Attenuation of high-frequency shear waves in the crust: Measurements from New York State, South Africa and Southern California, *J. Geophys. Res.* **95**, 17,441-17,457, 1990.

Hough, S.E., K.H. Jacob, and P.A. Friberg, The 11/26/88 M=6 Saguenay earthquake near Chicoutimi, Quebec: Evidence for anisotropic wave propagation in northeastern North America, *Geophys. Res. Lett.* **16**, 645-648, 1989.

Isachsen, Y.W. and W.G. McKendree, Preliminary brittle structure map of New York, scale 1:250,000, N.Y. State Museum Science Service Map Chart Series 31, 1977.

Isachsen, Y.W., E.P. Geraghty and R.W. Wiener, Fracture domains associated with a neotectonic basement-cored dome -- the Adirondack Mountains, New York, in R.H. Gabrielsen, I.B. Ramberg, D. Roberts, and O.A Steinlein (*editors*), *Proceedings of the 4th International Conference on Basement Tectonics*, International Basement Tectonics Association, Salt Lake City, Utah, 287-305, 1983.

Nabelek, J., and G. Suarez, The 1983 Goodnow earthquake in the central Adirondacks, New York: Rupture of a simple circular crack, *Bull. Seism. Soc. Am.* **79**, 1762-1777, 1989.

North, R.G., R.B. Wetmiller, J. Adams, F.M. Anglin, H.S. Hasegawa, M. Lamontagne, R. Du Berger, L. Seeber, and J. G. Armbruster, Preliminary results from the November 25, 1988 Sagueney (Quebec) earthquake, *Seism. Res. Lett.* **60**, 89-93.

Ratcliffe, N.M., W.C. Burton, R.M. D'Angelo, and J.K. Costain, Low-angle extensional faulting, reactivated milonites, and seismic reflection geometry of the Newark basin margin eastern Pennsylvania, *Geology* **14**, 766-770, 1986.

Rogers, W.B., Y.W. Isachsen, T.D. Mock, and R.E. Nyahay, Educational Leaflet 33: Plate 2 Geologic Map and Cross Sections, New York State Museum Cultural education Center, Albany, NY, 1990.

Sbar, M.L., and L. R. Sykes, Contemporary compressive stress and seismicity in eastern North America: An example of intra-plate tectonics, *Geol. Soc. Amer. Bull.*, **84**, 1861-1882, 1973.

Seeber, L. and J.G. Armbruster, A study of earthquake hazard in New York State, and Adjacent areas, report to the U.S. Nuclear Regulatory Commission, NUREG CR-4750, 98pp, 1986.

Seeber, L., J.G. Armbruster, and W.-Y. Kim, A fluid-injection-triggered earthquake sequence in Ashtabula, Ohio: Implications for seismogenesis in stable continental regions, *Bull. Seism. Soc. Am.*, **94**, 76-87, 2004.

Seeber, L., J. G. Armbruster, W. -Y. Kim, C. Scharnberger, and Noel Barstow, The 1994 Cacoosing earthquakes near Reading, PA: A shallow rupture triggered by quarry unloading, *J. Geophys. Res.* **103**, 24,505-24,521, 1998.

Tuttle, M.P., Law, K.T., L. Seeber and J. Jacob, Liquefaction and ground failure induced by the 1988 Saguenay, Quebec, earthquake, *Can. Geotech. J.* **27**, 580-589, 1990.

USGS, Requirement for and Advanced National Seismic System, US Geological survey Circular 1188, 59pp., 2002.

Wetmiller, R.J., J. Adams, F.M. Anglin, H.S. Hasegawa, and A.E. Stevens, Aftershock sequences of the 1982 Miramichi, New Brunswick earthquakes. *Bull Seism Soc. Am.* **74**, 621-653. 1984.

Yang, J.P., and Y. Aggarwal, Seismotectonics of northeastern United States and adjacent Canada, *J. Geophys. Res.* **86**, 4981-4998, 1981.

Zoback M.L. and M.D. Zoback, Tectonic stress field of the continental United states, in *Geophysical Framework of the continental United States*, L. Parkiser and W. Mooney (*editors*), *Geol. Soc. Am. Memoir* **172**, 523-539, 1989.

Bibliography (publications resulting from this award include)

Seeber, L., W.-Y. Kim, J. G. Armbruster, W.-X. Du, A. Lerner-Lam, and P. Friberg, The 20 April 2002 Mw 5.0 earthquake near Au Sable Forks, Adirondacks, New York: A first glance at a new sequence, *Seism. Res. Lett.* **73**, 480-489, 2002.