THE LAMONT COOPERATIVE SEISMOGRAPHIC NETWORK AND THE ADVANCED NATIONAL SEISMIC SYSTEM: EARTHQUAKE HAZARD STUDIES IN THE NORTHEASTERN UNITED STATES.

Final Technical Report

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External Grant Award Number: 01HQAG-0137

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1 Abstract

The operation of the Lamont Cooperative Seismographic Network (LCSN) to monitor earthquakes in the northeastern United States is supported under this award. The goal is to compile a complete earthquake catalog for this region (ANSS-NorthEast) to assess the earthquake hazards correctly, and to understand the causes of the earthquakes in the region. The LCSN now operates 16 modern, broadband seismographic stations and 24 short-period analog stations in seven states: Connecticut, Delaware, Maryland, New Jersey, New York, Pennsylvania and Vermont. Four accelerographic stations are also deployed around metropolitan New York City as part of the ANSS urban ground motion network. During July 2001 through June 2004, scientists and staff at the Lamont-Doherty Earth Observatory of Columbia University (LDEO) satisfactorily carried out three main objectives of the project: 1) continued seismic monitoring for improved delineation and evaluation of hazards associated with earthquakes in the Northeastern United States, 2) improved real-time data exchange between regional networks and the USNSN for development of an Advanced National Seismic System (ANSS) and expanded earthquake reporting capabilities, and 3) promoted effective dissemination of earthquake data and information products.

A significant amount of associated research effort was related to rapid determination of seismic moment tensor and focal depth of small to moderate-sized earthquakes in the eastern United States by using three-component, broadband seismic waveform data. For real-time data exchange, integration and archive, LCSN exceeds the "ANSS Performance Standard (APS)". For rapid generation of earthquake parameters, LCSN performs slightly under the target outlined in the category, Mod-High Hazard Area. In particular, hypocenter and magnitude are usually posted in 15–30 minutes. We are working towards $\sim$5 minutes latency for accurate hypocenter and magnitude information. Moment tensor and ShakeMap have similar latency than the ANSS performance standard, and LCSN is trying to meet the APS target, that is, $\sim$10–15 minutes posting time.

The LCSN is unusual in using a variety of station operators (college & university faculty, secondary school teachers, public places etc.) to engage a wide variety of audiences and to reach out to large numbers of the general public. It also provides professional development and improved awareness among station operators who are not professional seismologists. About half of the broadband station operators and stations belong to each participating organization. Hence, a large portion of the operation and maintenance cost are born by over 20 participating organizations.

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2 Operation of the Lamont Cooperative Seismographic Network (LCSN)

2.1 Operation of the Network

Continued seismic monitoring for improved delineation of seismogenic faults and evaluation of hazards associated with earthquakes are the main operational objectives of the Lamont Cooperative Seismographic Network (LCSN). In conjunction with installation of the Earthworm data acquisition systems, 16 broadband seismographic stations have been deployed since October 1999 in the northeastern United States by LCSN and have become backbone stations (see Figure 1 & Table A1). Two broadband stations – NCB (Newcomb, NY) and LSCT (Lakeside, CT), are deployed and operated by LCSN, but the data acquisition is directly incorporated into USNSN as cooperating stations. These broadband seismographic stations record the data continuously at a nominal sampling rate of 40 samples/sec and send the digital seismogram data to the data collection and processing facility at the Lamont-Doherty Earth Observatory (LDEO) via the Internet. Short-period stations around more seismically active areas are recording 100 samples/s continuously.

At remote data acquisition sites (DA), broadband seismometers are installed in the modified ANSS standard McMillan type (McMillan, 2002) concrete vault and digitized with 24 bit A/D dataloggers. Timing is provided by GPS clock and digital data are telemetered to a data processing (DP) site usually at schools with Internet access. Telemetry is through digital spread-spectrum radio. Remote DA sites are usually powered by solar panels and backup batteries.

The LCSN promotes active participation of about 20 organizations in the northeastern U.S. and relies upon their support in station maintenance and operation in the region. The organizations who operate LCSN stations consist of a secondary school, an environmental research and education center, 3 state geological surveys, a public place (Central Park, NYC), 3 two-year colleges and 12 four-year universities (see Section 5 for a full list). We installed the Earthworm system at these organizations providing them with an ability to utilize the acquired data. These sites collect seismic data from short-period sub-networks or from a single 3-component broadband seismograph and send the data in real time to the central processing facility at LDEO via Earthworm and Internet. These cooperative efforts provide cost-effective earthquake monitoring capability in the region and facilitate data acquisition efforts of LCSN, and serve as an education and outreach program.

The configuration of the LCSN has evolved continuously for the past few years, and now consists of four sub-networks with a total of 24 short-period stations (see Table A2), and 16 three-component broadband stations, and four ANSS urban ground motion monitoring stations, covering NY, NJ, DE, MD, PA and District of Columbia, and portions of western CT and VT (see Figure 1). The short-period stations with mostly 1 sec natural period sensors and analog FM radio telemetry are "legacy stations" that have existed since the 1970's. These short-period stations are increasingly difficult to maintain these days, moreover their limited dynamic range and uncertain instrument response make them unfit for LCSN to meet ANSS performance standards. Hence, much of DME (development, modernization and expansion) for the next few years will be devoted to convert many of these legacy stations into modern broadband or short-period digital seismographic stations.

ANSS-NE, LCSN, NESN, CNSN & Other Seismographic Stations

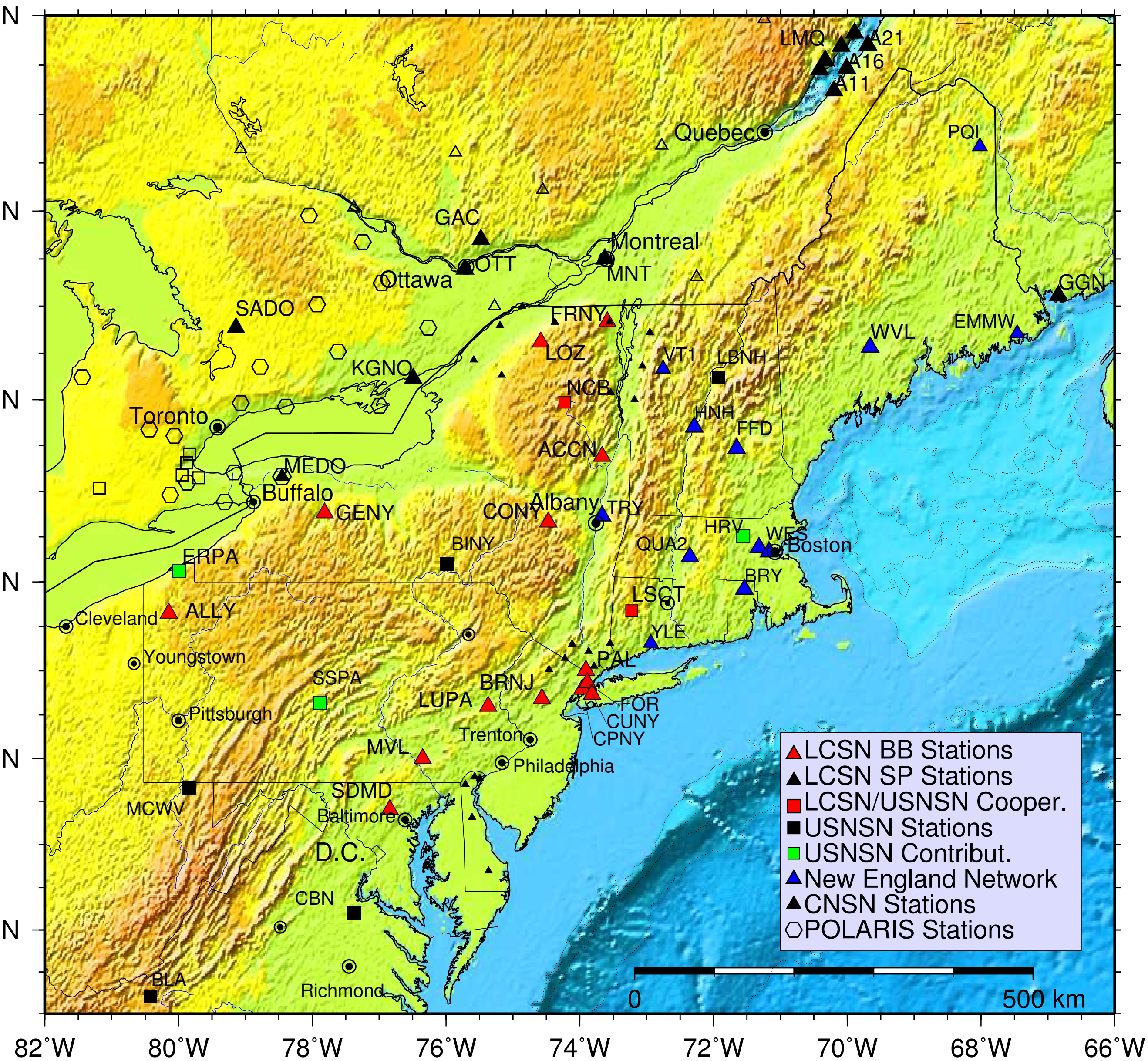


Figure 1: Map showing the overview of the broadband and short-period seismographic stations of Lamont Cooperative Seismographic Network (LCSN), USNSN, NESN (New England Seismic Network) in northeastern United States and stations in southeastern Canada (CNSN and POLARIS) as of June 2004. 14 LCSN Broadband stations are plotted with *red triangles*, USNSN stations are plotted with *filled squares* and LCSN short-period stations are plotted with *small filled triangles*. Two LCSN stations, NCB & LSCT, are called USNSN cooperating stations.

2.2 Deployment of ANSS Urban Ground Motion Network in the Metropolitan New York City Region

LCSN deployed four digital accelerographs in NYC area as part of the ANSS Urban Strong Motion Network during FY01-04. They are at Central Park, NYC; Fordham University, the Bronx; Columbia University Faculty House, Uptown Manhattan, and Palisades, NY (Figure 1 & Figure 2). The data are continuously recorded with 100 samples/s and the event waveform data are sent to NSMP (National Strong Motion Program).

2.3 Data Processing Center Operation

2.3.1 Real-time data acquisition and processing

Since the fall of 1999, the LCSN began using the Earthworm data acquisition system to transfer data from seismic stations in real-time to a Master Earthworm system at Lamont-Doherty Earth Observatory (LDEO) where the seismic traces are run through various Earthworm modules for event detection, triggering, and location of seismic events. The real-time data exchange and integration at LCSN is shown schematically in Figure 3.

The performance target for the real-time earthquake monitoring in the northeast is based on "ANSS Performance Standard (APS)" under the category, Mod-High Hazard Area. The current LCSN monitoring capacity meets APS target for Mod-High Hazard Area throughout the region covered by the network. However, we plan to upgrade to High-Risk Urban Areas for 31 Counties of the Metropolitan New York City Region. For this, we need higher seismographic station density than the current one (target station spacing of $\sim$100 km or less), which is the basis of our future DME plan (see Figure 1). For rapid earthquake information product generation, LCSN is not meeting the performance standard target outlined in APS for Mod-High Hazard Area, in particular, hypocenter and magnitude are usually posted in 15–30 minutes. This is not acceptable and we are working towards 5 minutes latency for hypocenter and magnitude information. Moment tensor and ShakeMap have similar latency, that is, about a factor of three longer posting time than APS performance standards, that is, 10–15 minutes on APS vs 30–45 minutes for LCSN.

2.3.2 Real-time data exchange and integration

The real-time waveform data exchange and integration are achieved using the Earthworm system. Data exchange with neighboring networks and national networks are: exporting 10 sites and importing 6 sites to and from USNSN/NEIC; exporting two sites data to CERI (Center for Earthquake Research and Information, University of Memphis), and exporting 7 and importing 7 stations from NESN (New England Seismic Network). We plan to establish real-time waveform data export/import with Canadian National Seismic Network (CNCN) operated by the Geological Survey of Canada, in Ottawa, Canada, and the Puerto Rico Seismic Network (PRSN) in FY2005, to improve earthquake detection and location in the region. All waveform data are exported to the IRIS-DMC for permanent archiving and dissemination. LCSN is meeting, and exceeding the APS Performance Standards on real-time data exchange and integration.

Figure 2: Initial seven strong-motion instrument sites in New York City as urban monitoring network under the ANSS-Northeast implementation plan of FY2003.

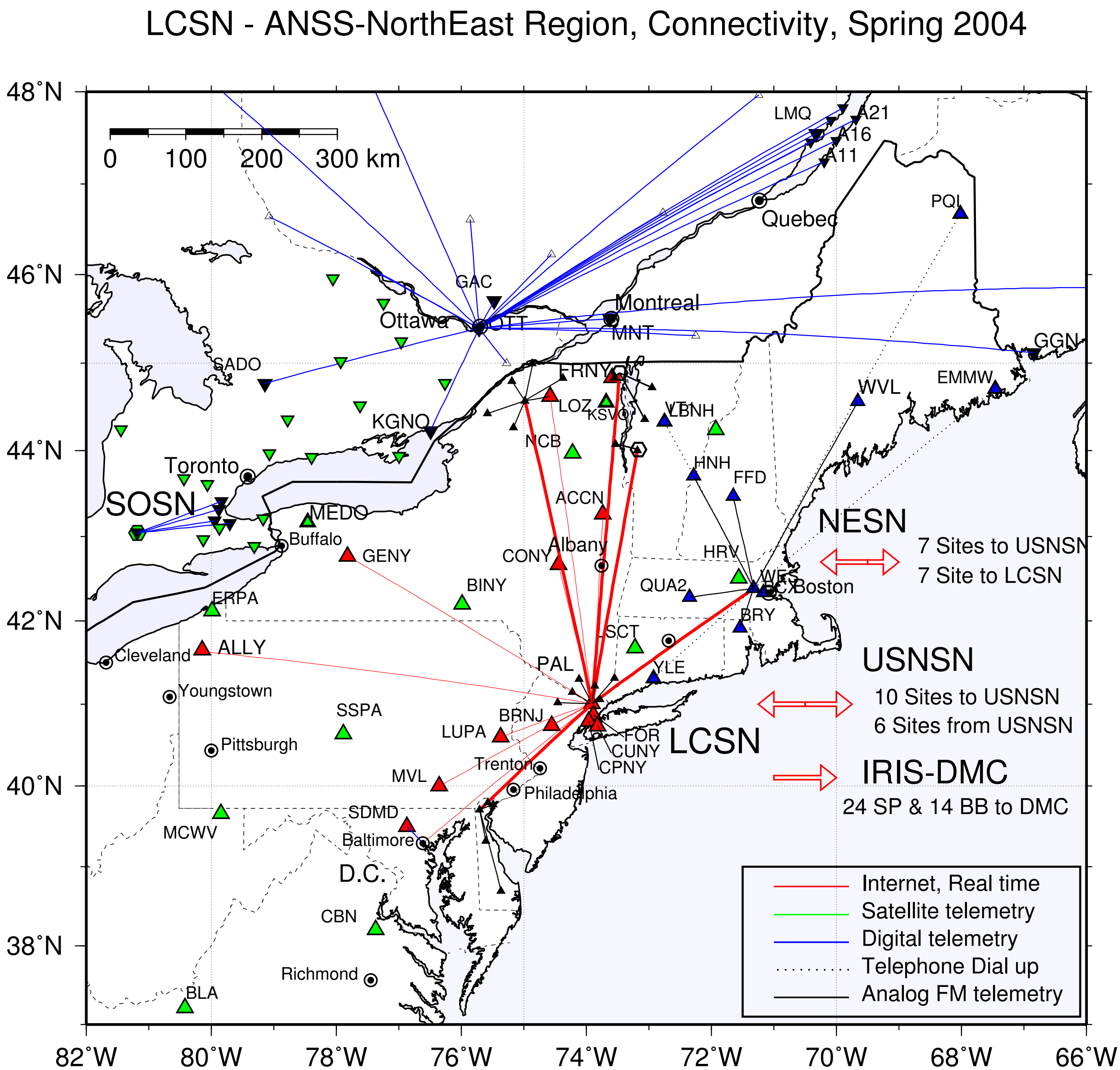


Figure 3: LCSN real time waveform data exchange and integration scheme. Data exchange with neighboring networks: exporting 10 sites and importing 6 sites to and from USNSN/NEIC, exporting 7 and importing 7 from New England Seismic Network. All waveform data are exported to the IRIS-DMC in real time for permanent archiving and dissemination.

2.3.3 Real-time submission of seismic phase data to NEIC and catalog data to ANSS composite catalog

Earthquake catalog data has been submitted to ANSS composite catalog through QDDS. Since January of 2001, LCSN sends all waveform data to IRIS-DMC in real-time for archiving at the data center. Waveform data from all stations of the LCSN (network code: LD) are available at the IRIS-DMC in near real-time as Buffer of Uniform Data (BUD) via worldwide web, the URL is, <http://www.iris.washington.edu/bud_stuff/dmc/>. All archived data at the DMC are available at <http://www.iris.edu/SeismiQuery/> and users can query waveform data using network code "LD". About 2 months of waveform data are currently available through *AutoDRM* on LCSN web site <http://www.almaty.ldgo.columbia.edu:8080/data.request.htm>.

For waveform data archiving at IRIS-DMC, instrument response and other metadata are available on-line as well as on LCSN web site with URL:
<http://www.ldeo.columbia.edu/LCSN/Metadata/DATALESS_SEED_LD_20040203.bin>.

2.4 Rapid Generation of Earthquake Information

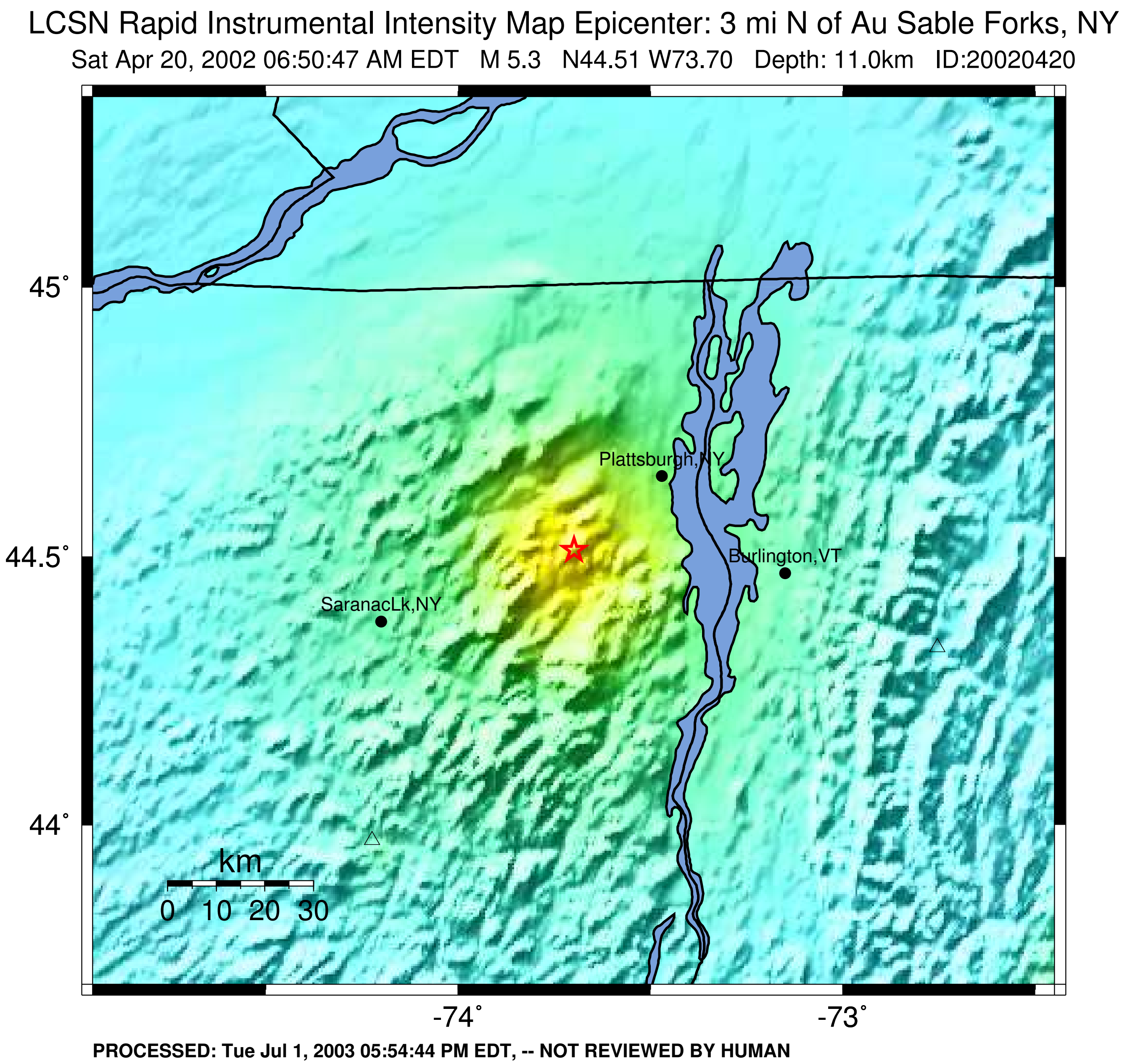
In this section, we will briefly describe near real-time generation of earthquake information such as, ShakeMap, focal mechanisms and focal depth.

2.4.1 Rapid generation of instrumental ground motion (ShakeMaps)

ShakeMap represents a significant step forward in the development of real-time seismic information relevant to post-earthquake emergency management. ShakeMap can be used by emergency managers to: 1) assess the geographic scope of an earthquake, 2) identify areas in which damage is likely, or unlikely, to have occurred, and 3) provide decision support for resource mobilization and prioritization of reconnaissance efforts. We developed preliminary Instrumental Intensity Map, ShakeMaps, for northeastern U.S. using the LCSN real-time data, which are on the LCSN web site at: <http://www.ldeo.columbia.edu/LCSN/ShakeMap>.

Four types of ShakeMaps are generated (see Wald et al., 1999a, 1999b); 1) Instrumental Intensity; 2) Peak Ground Acceleration (PGA); 3) Peak Ground Velocity (PGV), and 4) Peak response spectral amplitudes at various periods (e.g., 0.3, 1 and 3 sec). This preliminary Instrumental Intensity Map is generated for the Mw 5.0 April 20, 2002 Au Sable Forks, NY earthquake (Figure 4) and can be compared with the Community Internet Intensity Map (CIIM; <http://pasadena.wr.usgs.gov/shake/ne/STORE/Xdeam/zoomin.gif>).

The ShakeMap generated utilized ground motion values, but no attempt was made to correct for site conditions. Even peak ground motion attenuation curves for California given by Boore et al. (1997) and Joyner & Boore (1988) are used. Although the earthquake is the best recorded M 5 event in the NEUS, only 50 stations in the distance ranges from 73 to 1,000 km were available for generating the ShakeMap. Obviously, suitable ground motion attenuation relations must be used to fill the data gaps. Although it is a very preliminary test to examine the feasibility of generating the ShakeMaps in the NEUS, nonetheless the Instrumental Intensity Map produced Modified Mercalli Intensity (Imm) V to VII area quite well when compared with the CIIM. This example illustrates that we should be able to generate more useful ShakeMaps for the earthquakes in the NEUS.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	*16-31*	*31-60*	*60-116*	*>116*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 4: Instrumental intensity map – ShakeMap, for Mw 5.1 Au Sable Fork, NY earthquake on 20 April 2002.

2.4.2 Timely determination of seismic moment tensor and focal depth

Since the fall of 2000, seismic moment tensors for earthquakes with magnitude $M_L \geq 3.8$ that occurred in the northeastern U.S. and southeastern Canada have been determined by using three-component, broadband seismic waveform data. Results are reported by Du, Kim & Sykes (2003) and Kim (2003). The most significant results were a distribution of deep and shallow earthquakes in the central and northeastern U.S. and their implications on the thickness of the seismogenic layer. This in turn, yields information on the seismic potential of a seismic zone in the region.

An example moment tensor inversion using intermediate-period (passband 0.05 to 0.5 Hz) part of the broadband records are shown in Figure 5. In addition to the seismic moment tensor, we also obtain accurate focal depth with an uncertainty usually less than 2 km. The focal depth is very important for assessing the ground motion excitation from the earthquakes and for evaluating earthquake hazards in the northeastern US. This is not an ideal case of regional seismic moment tensor inversion. Although the event (Mw 4.3, December 9, 2003, Goochland, central Virginia) was one of the largest earthquakes to have occurred in the region, the quake is not very well recorded by seismographic stations, mainly due to poor station coverage in central Virginia.

Even though the synthetic seismogram calculations and moment tensor inversion can be done in reasonable time, it still takes about an hour to determine a reliable solution. It does not meet the ANSS recommended latency of 15 minutes for an automatic solution for $M \geq 4.5$.

Another issue is magnitude threshold for which such moment tensor analysis can be carried out. The current threshold is about magnitude 4, due to sparse broadband station coverage of earthquakes in the NEUS. In order to make the moment tensor determination for smaller sized, more numerous events (magnitude around 3.5 or greater), as well as to reduce the latency of the solution, we need to improve broadband station coverage in the region, so that at least one or two stations would be at a reasonable epicentral distance range (about 100 km or less) with high signal to noise ratio at longer period, say 1 to 10 seconds period. Obviously, signals at a higher frequency band have to be utilized to determine the seismic moment tensor for such small events. For higher frequency data, waveform modeling must allow path dependent Green's functions in the inversion and we must fine tune for generating relevant Green's functions (Dreger & Helmberger, 1993). We are working to reduce existing latency and to lower the magnitude threshold for determining the seismic moment tensor and focal depth.

2.5 Earthquake Contingency Plans

2.5.1 Continuity of network operations

We coordinate earthquake response and reporting by adhering to system-wide rules for authoritative reporting of earthquake location and magnitude with NEIC and neighboring networks. We include appropriate attribution and identification of earthquake data and information providers. For all significant earthquakes (either felt or magnitude larger than 3.5), we continue to work to provide our automatic solutions as well as revised source parameters to the NEIC as quickly as possible.

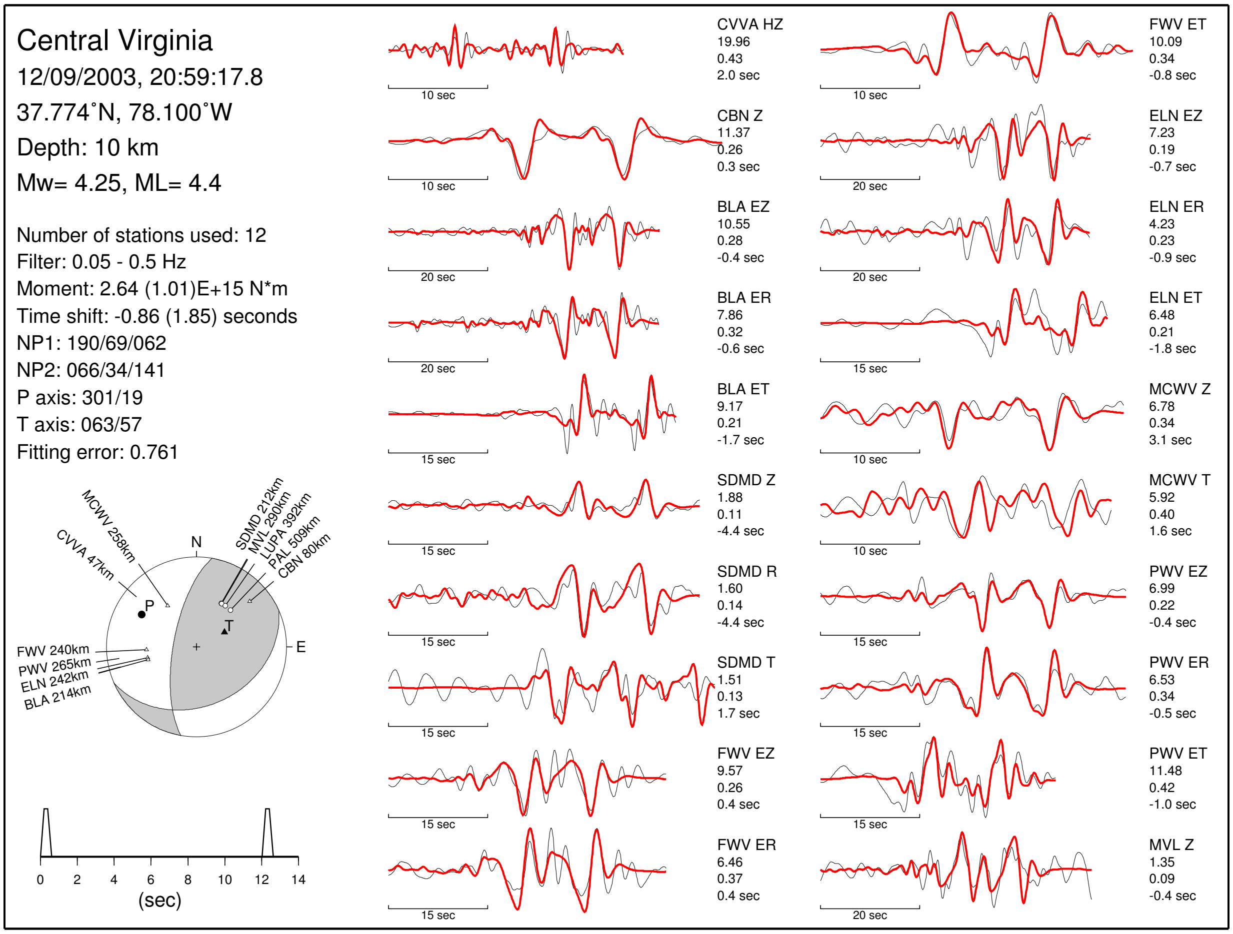


Figure 5: An example seismic moment tensor determination using regional waveform modeling and inversion. 3-component, broadband records at four stations and five short-period stations from the December 9, 2003 Goochland, Virginia shock are used for the analysis. A beach-ball at lower left represents source mechanism (strike-slip faulting) and stations used. Station code and distance from the source are indicated along their azimuth. Waveform fits for the synthetics (*red line*) calculated with two sources separated by 12 s at a focal depth of 10 km are plotted with observed displacement record (*solid line*) for each station.

2.5.2 Rapid deployment of portable instrument for aftershock survey

Portable instruments have permitted high-resolution studies of earthquake sources for almost half a century in the Eastern North America (ENA). 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.

Abundant small earthquakes can be used to monitor mechanical changes associated with earthquake triggering and with sequences of related earthquakes. Some of the seismological field studies of earthquake sources that significantly expanded our view of seismogenesis in the northeastern North America are listed below. By deploying portable seismographs around the mainshock epicenter, we can learn about the fault plane. This is a very effective way to improve the observational basis for regional hazard estimates and for understanding fundamental processes responsible for ENA seismogenesis.

LCSN prepared four portable seismographs that can be rapidly deployed around the epicentral area following the large earthquakes ($M \geq 4$) in the northeastern U.S.

Selected earthquake sequences in Eastern North America with salient characteristics revealed by field studies using portable seismographs.

- 1983 Goodnow, NY, M_w 4.9 aftershocks confined in a relatively small volume and clustered in a ring around the rupture (Seeber and Armbruster, 1996; Nabelek and Suarez, 1989);
- 1994 Cacoosing, PA, M_w 4.6 a very shallow rupture triggered by quarry unloading after quarry is flooded (Seeber et al., 1998);
- 2001 Ashtabula, OH, M_w 3.9, long-lasting sequence triggered by deep fluid injection; largest event 7 years after injection ceased (Seeber et al, 2002);
- 2002 Au Sable Fork, NY, M_w 5.0 damaging mainshock, thrust-faulting with west dipping fault plane.

3 Earthquake Information and Data Product

3.1 Earthquake Bulletin and Catalogs for Earthquake Hazard Evaluation

Over 80 local and regional earthquakes with magnitude greater than about 1.0 that have occurred in the northeastern United States and southern Canada were detected and located by the LCSN during July 1, 2001 through June 30, 2004 (see Figure 6). These earthquakes range from magnitude 0.8 (Mc) to 5.3 (M_L) and are listed in Table A3.

A general seismicity pattern during this period is similar to the previous years. A relatively higher level of seismicity is in Adirondacks and in Western Quebc seismic zone in southern Canada. Notable earthquakes during the period are:

- October 27, 2001, M_L 2.6 earthquake in Manhattan, New York City;
- April 20, 2002, M_L 5.3 Au Sable Forks, New York earthquake sequence;

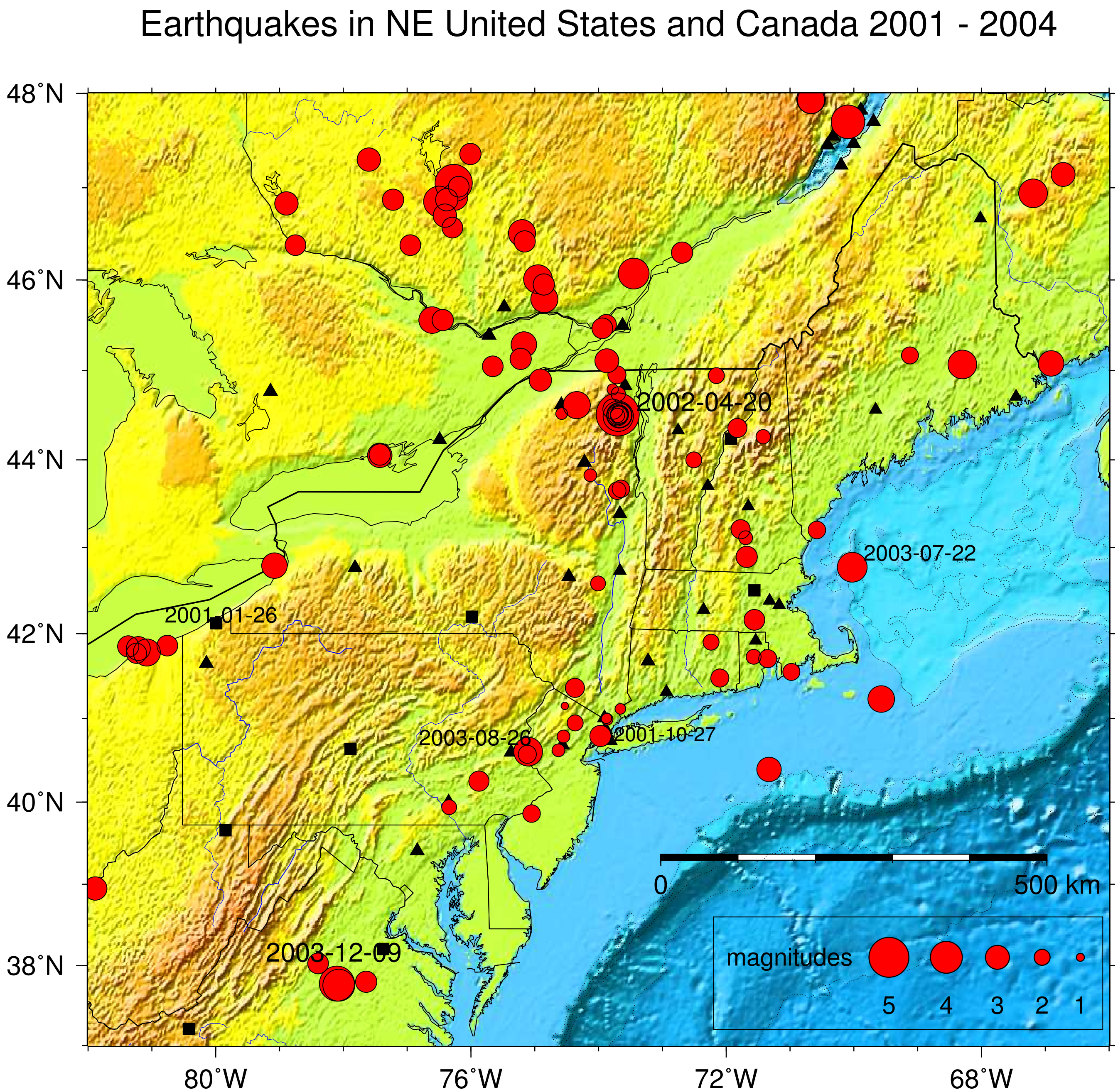


Figure 6: Earthquakes which have occurred in the northeastern United States and southeastern Canada in the time period of July 1, 2001 through June 30, 2004 recorded by the LCSN. Symbol size is proportional to magnitude. Broadband stations of the LCSN, USNSN, NESN, and CNSN are plotted for reference *triangles*.

- May 5, 2003, m_b(Lg) 3.9 Central Virginia earthquake near Richmond, VA;
- July 22, 2003, M_L 3.6 Offshore Cape Ann, MA close to the 1755 M 6 Cape Ann earthquake;
- August 26, 2003, M_L 3.5 earthquake in Milford, NJ-Upper Black Eddy, PA;
- October 1, 2003, M_L 2.4 aftershock of the August 26, 2003 earthquake in Milford, NJ;
- December 9, 2003, m_b(Lg) 4.5 Central Virginia earthquake near Goochland west of Richmond, VA;
- June 30, 2004, Mc 3.3 earthquake that occurred in Ashtabula, Ohio.

Manhattan, New York City earthquake on Oct. 27, 2001

A small earthquake of M_L =2.6 occurred on 10/27/2001 at 12:34 in Upper West Side of Manhattan, New York City. Residents in the Upper West Side of Manhattan felt the event, but the response from the public were less than M_L 2.3 event that occurred on Jan. 17 in the Upper East Side of Manhattan. Probably due to the fact that it occurred in early morning hour (local time 00:42) on Saturday. LCSN deployed four portable seismographs around the epicenter in New York City to capture aftershocks which can provide accurate locations of the earthquakes that occurred in 2001. No clear aftershocks were detected.

Au Sable Forks, New York, Earthquake on April 20, 2002

On April 20, 2002 at 06h 50m 47.5s (EDT), a moderate earthquake of magnitude M_L 5.3 occurred about 29 km SW of Plattsburgh, New York (Figure 7). The epicenter of the mainshock is about 5 miles north of town of Au Sable Forks and the focal depth of the mainshock is about 11 km from the surface. 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. Residents in the two counties – Clinton and Essex Counties, around the epicenter felt intensity VI (MMI) and up to VII 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 (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. The photo shows one of the roads damage due to slumping on Route 9N near Clintonville (see Figure 8).

The main shock is followed by aftershock of magnitude M_L 3.7 at 11:04:42 and smaller aftershock with M_L 2.6 at 11:45:31 (see Table 1). 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.

Plattsburgh, New York Earthquake on April 20, 2002

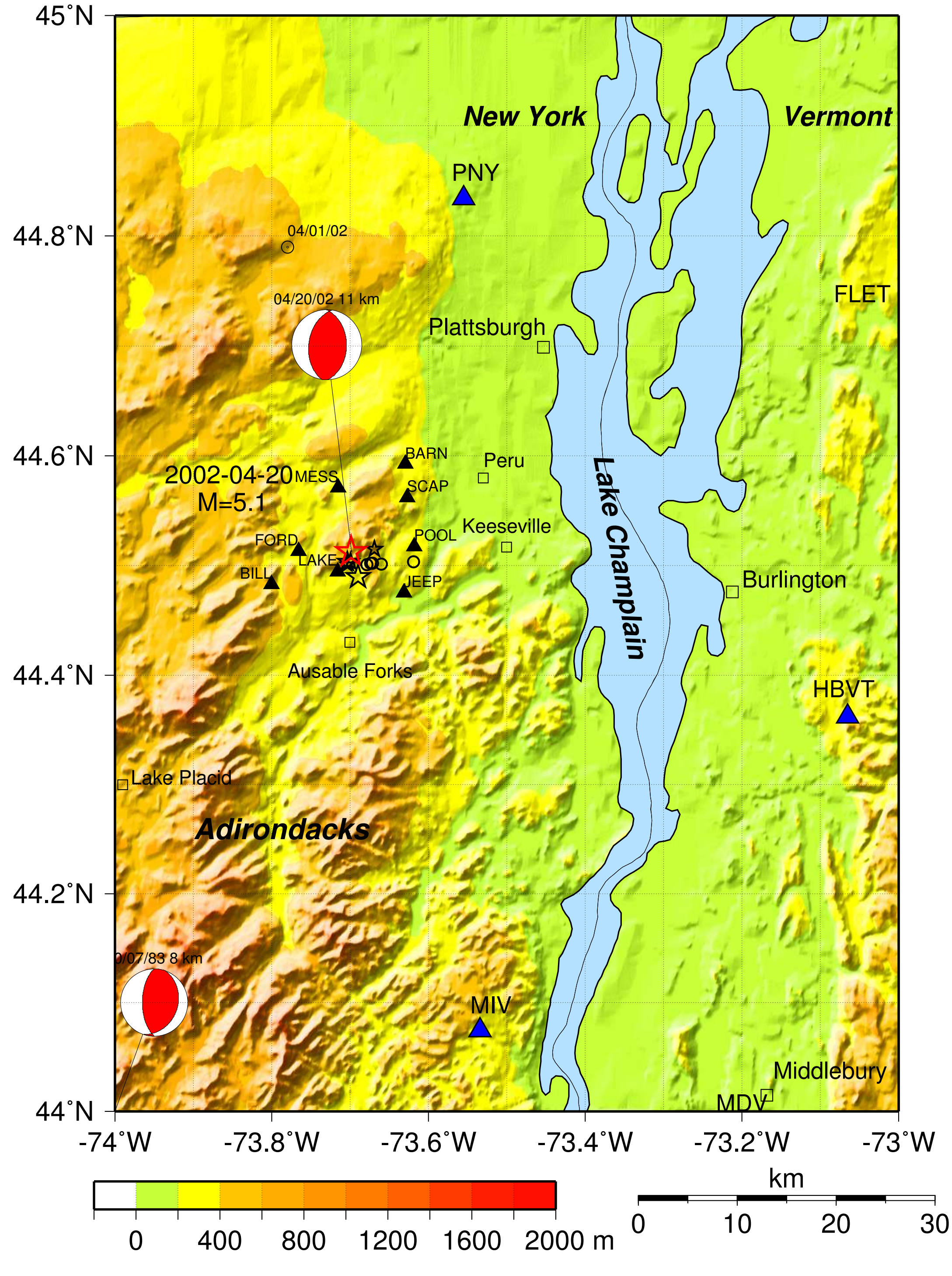


Figure 7: Topographic relief map around Lake Champlain–Adirondacks, NY. Epicenter of the April 2002 Au Sable Forks mainshock is marked by a *red star* and its source mechanism is indicated by a beach–ball which suggests predominant thrust faulting. Large and small aftershocks are plotted with *black stars* and *circles*, respectively. A beach–ball in the lower left corner indicates the Goodnow earthquake on 10/07/1983 (mb(Lg) 5.1). Seismographic stations in the region are plotted with *blue triangles*. Temporary stations deployed to monitor aftershocks are plotted with *small solid triangles*.

Figure 8: Road damage due to slumping on Route 9N near Clintonville, Clinton County, NY.

Table 1: April 20, 2002, Au Sable Forks, New York Earthquake Sequence

Date Year/Mo/Dy	Time (hr:mn:sec)	Latitude (°N)	Longitude (°W)	Depth (km)	Magnitude M_L
2002/04/20	10:50:47.5	44.513	73.699	11	5.3
2002/04/20	11:04:42.4	44.490	73.690	10	3.7
2002/04/20	11:08:26.0	44.501	73.704	10	1.7
2002/04/20	11:45:28.7	44.504	73.703	10	2.6
2002/04/21	11:47:09.9	44.515	73.669	10	2.2
2002/04/21	12:39:10.7	44.504	73.700	10	2.3
2002/04/25	13:39:56.0	44.503	73.674	11	2.2
2002/05/24	23:46:00.1	44.505	73.675	12	3.1
2002/06/25	13:40:28.0	44.503	73.675	11	3.0

The mainshock and its largest aftershock (M_L =3.7) on 04/20/2002, 11:04 are well recorded by broadband, 3-component stations in the Eastern North America. For the mainshock, we obtained over 50 broadband, 3-component records from regional stations in the distance ranges from 70 to 2000 km. Waveform data are used to determine focal depth and source mechanism parameters using moment tensor inversion method. Source mechanism indicates predominantly thrust faulting along 45 degree dipping fault plane striking due South (aftershock distribution indicates that fault plane dips due West). The seismsic moment is M_0= $3.5 \cdot 10^{16}$ Nm (Mw = 5.0) and a rupture radius is about 1.3 km.

The waveform modeling technique also suggests that the synthetic seismograms calculated for a source depth of about 11 km fit the observed records best. This focal depth is quite consistent with the early aftershock locations discussed in a later section.

Milford, NJ–Upper Black Eddy, PA earthquake on August 26, 2003

A small earthquake of M_L =3.5 occurred on 08/26/2003 at 18:24 (14:24 EDT) close to the town of Milford, NJ along the Delaware River. The shock was felt by residents with high intensity and residents around the Milford reported hearing explosion like sound associated with the shock. However, the isoseismic maps and felt areas during the shock is much smaller than other earthquakes of similar size in the eastern US. Aftershocks recorded by local network deployed in October 2003 indicated that main- and after-shocks must have been at very shallow depths. Focal depth of about 40 aftershocks are clustered at around 1.5 to 2 km depth. The earthquake occurred close to the boundary fault between Precambrian Reading prong and Mesozoic Newark basin, but the lineation of the aftershocks seems nearly perpendicular to the orientation of the boundary fault. It is a significant event, for its implication on seismic hazards in the region and on seismo tectonic setting.

3.2 Aftershock Study Using Portable Instrument to Delineate Active Faults and Seismogenic Zones: A Case Study

Following the M_L 5.3 Au Sable Fork, NY mainshock on April 20, 2002, scientists and staff at the Lamont-Doherty Earth Observatory of Columbia University in Palisades, NY immediately went to the epicentral region with six digital portable seismographs to monitor aftershocks. The first station was installed about 1/2 day after the mainshock. Six more stations were installed the next day (see Figure 9).

We achieved an important milestone in monitoring earthquakes and evaluating their hazards through rapid cross-border (Canada-US) and cross-regional (Central US-Northeastern US; Southwestern US-NE US) collaborative efforts. Hence, ISTI staff – Paul Friberg & Sid Helman, who live in Upstate New York joined LDEO staff and deployed the first portable station in the epicentral area; CERI dispatched two of their technical staff to the epicentral area with four accelerometers and a broadband seismograph; the IRIS/PASSCAL facility shipped three digital seismographs and ancillary equipment within one day of the request; the POLARIS Consortium, Canada sent a field crew of three with a near real-time, satellite telemetry based earthquake monitoring system. This collaboration allowed us to maximize the scarce resources available for monitoring this damaging earthquake and its aftershocks in the Northeastern U.S.

By June 1, 2002, 12 seismographic stations were monitoring the aftershocks in the region. The following people have participated in the field work; CERI - field crew & support; Jim Bollwerk, Chris Watson, Arch Johnston, Mitch Withers; ISTI - Paul Friberg, Sid Hellman; POLARIS Consortium, Canada - field crew; Calvin Andrews, Mike Patten and Isa Asudeh; other personnel, John Adams, David Eaton and Gail Atkinson; PASSCAL/IRIS - Mark Alvarez, Noel Barstow, Jim Fowler; LDEO - John Grenville, Jian Zhang, John Contino, Golam Sarker, Jeremiah Armitage, John Armbruster, Nano Seeber and Won-Young Kim.

4 Reports and Dissemination of Information and Data

4.1 Continuous Waveform Data

Continuous, broadband (40 samples/sec) and short-period (100 samples/sec) waveform data are acquired in real time via Earthworm and Antelope system and are submitted to IRIS-DMC for public dissemination in real time and archiving. Waveform data from all stations of the LCSN (network code: LD) are available at the IRIS-DMC in near real-time as Buffer of Uniform Data (BUD) via worldwide web, the URL is, <http://www.iris.washington.edu/bud_stuff/dmc/>.

All archived data are available at <http://www.iris.edu/SeismiQuery/> and users can query waveform data using network code "LD". Approximately 60 days of data are also available at LCSN via *AutoDRM* at <http://www.ldeo.columbia.edu/LCSN/>.

A complete instrument response and other information for the waveform data are available as "DATALESS SEED volume for LCSN Data" at the LCSN web site or from the IRIS-DMC as well as it is downloadable on LCSN main web page.

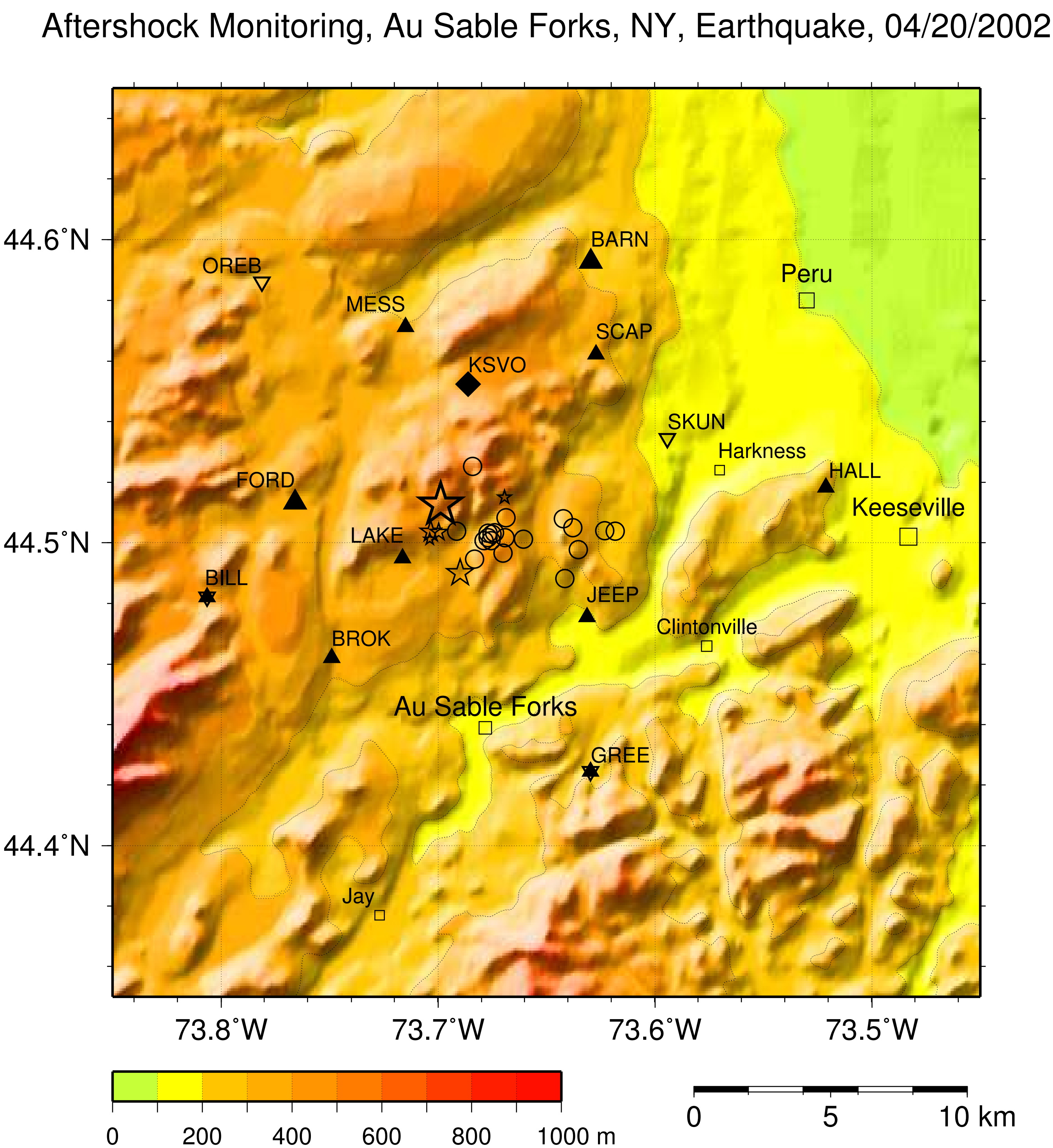


Figure 9: Topographic map of the Au Sable Forks source area in the northeastern Adirondacks showing the temporary monitoring stations and preliminary aftershock epicenters. Key to symbols: small and large triangles indicate short period and broadband sensors (GREE and HALL are contributed by IRIS-PASSCAL); inverted triangles are strong motion sensors (contributed by CERI, University of Memphis; some are co-located with velocity sensors); Diamond is a broadband sensor relayed near-real-time via satellite telemetry (contributed by the POLARIS project, Canada); stars are epicenters from the regional stations; circles are aftershocks located by the local stations.

4.2 Event Waveform Data

Waveform data of all regional events located by LCSN are available through entry on "finger quake" list with URL <http://www.ldeo.columbia.edu/cgi-bin/quake.cgi>. The data are in full SEED volumes and users do not need additional metadata. The phase data for the earthquakes in recent years are available also from the LCSN web site as "Finger Quake for Recent Seismic Events in the Northeastern U.S.". Part or all of the waveform data are also sent to NEIC, CERI and New England Seismic Network (NESN) in real time.

Contact person for additional inquiries and assistance:
Name: Mr. Mitchell Gold
Phone: 845-365-8583
E-mail: goldm@ldeo.columbia.edu
Data format: SEED, AH, ASCII

4.3 Processed Parametric Data

Epicenter, origin time and magnitude of local and regional events are sent out as earthquake alert messages to Emergency Management Offices at counties and states, local and regional authorities who are responding to earthquake inquiries. Earthquake locations and magnitudes are promptly contributed to ANSS composite earthquake catalog via QDDS (Quick Data Distribution System) and are available through "Recent Earthquakes" with URL:
<http://www.ldeo.columbia.edu/LCSN/recenteqs/>.

Earthquake information is also routinely disseminated to news media, and to the general public in the form of press releases using FAX, phone, e-mails and WWW. We will coordinate for rapid earthquake reporting among regional seismic networks and the USNSN/NEIC as recommended by ANSS TG - v1.0. A timely coordination with neighboring networks such as Weston Observatory and Geological Survey of Canada is important, and we will maintain near real-time communication capability among these networks. Earthquake parameters are sent via QDDS for compiling an ANSS composite earthquake catalog as recommended by the ANSS. The results of various scientific studies such as detailed distribution of micro-earthquakes and possible seismogenic faults revealed by the aftershock monitoring surveys can be disseminated to various customers using the LCSN web page.

4.4 Did-You-Feel-It and ShakeMap

Earthquake response activities and useful electronic interfaces are provided to the public, for instance "Did You Feel It" (a community internet intensity map) is at URL:

<http://pasadena.wr.usgs.gov/shake/ne/> and at <http://www.ldeo.columbia.edu/LCSN>.

Though infrequent, felt earthquakes in the metropolitan New York City region draw a large number of inquiries mainly due to high population density in the region. ShakeMap generation is still in progress.

5 Partnerships

The Lamont Cooperative Seismographic Network (LCSN) is unusual in using a variety of station operators (college & university faculty, secondary school teachers, museums, etc.) to engage a wide variety of audiences and to reach out to large numbers of the general public. It also provides professional development and improved awareness among station operators who are not professional seismologists. About half of the broadband station operators and stations belong to each participating organization. Hence, a large portion of the operation and maintenance cost are born by the participating organizations. A complete list of 21 partners are listed below. The LCSN relies upon their support in station maintenance and operation in the region. The organizations who operate LCSN stations consist of a secondary school, an environmental research and education center, 3 state geological surveys, a public place (Central Park, NYC), three two-year colleges and 12 four-year universities.

Partners of LCSN are (ordered by station code):

Adirondack Community College, SUNY, Glens Falls, NY (ACCN)
Allegheny College, PA (ALLY)
William Annin Middle School, Basking Ridge, NJ (BRNJ)
SUNY Cobleskill (CONY)
Central Park Conservancy, Manhattan, NYC (CPNY)
Queens College, City University of New York (CUNY)
Delaware Geological Survey, Newark, DE (DGS subnet)
Fordham University, the Bronx (FOR)
Miner Agricultural Research Institute, West Chazy, NY (FRNY, PNZ)
Plattsburgh State, SUNY (FRNY)
Geneseo College, SUNY (GENY)
University of Vermont, Burlington (HBVT)
Potsdam College of Art & Science, SUNY – Potsdam, NY (LOZ)
Lehigh University, PA (LUPA)
Middlebury College, VT (MDV, MIV)
POLARIS Consortium, Canada (MEDO)
Millersville University, PA (MVL)
College of Environmental Science and Forestry, Syracuse, SUNY (NCB)
Maryland Geological Survey, Baltimore, MD (SDMD)
Westchester Community College, SUNY (WCC)
Department of Environmental Protection, State of Connecticut (LSCT)

6 Education and Outreach

The Lamont Cooperative Seismographic Network contributes to outreach in ways that are unique to its structure. It is unusual in using a variety of station keepers (college & university faculty, secondary school teachers, museums, etc.) to engage a wide variety of audiences and to reach out to large numbers of the general public. It also provides professional development and improved awareness among station operators who are not professional seismologists. All of this is an example of involving the community to extend observations and thereby make science accessible to the public.

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9 Appendix/Tables

Table A1: List of LCSN Broadband Stations Supported with USGS/ANSS Funds*

Station code	Lat. (°N)	Long. (°W)	Elev (m)	Type	Open (year-mo-da)	Network	Location (state)
ACCN	43.380	73.670	340	bb	1999-11-09	LD	NY
ALLY	41.650	80.140	390	bb	2002-05-30	LD	PA
BRNJ	40.680	74.570	50	bb	1999-11-21	LD	NJ
CONY	42.666	74.469	468	bb	2001-07-13	LD	NY
CPNY	40.790	73.960	27	bb/sm	2002-02-21	LD	NY
CUNY	40.730	73.820	20	bb	2002-05-23	LD	NY
FOR	40.860	73.890	24	bb/sm	2002-04-18	LD	NY
FRNY	44.840	73.590	223	bb	2003-11-13	LD	NY
GENY	42.770	77.820	195	bb	2001-10-27	LD	NY
LOZ	44.620	74.583	440	bb	1999-11-19	LD	NY
LSCT	41.680	73.220	318	bb	1993-08-06	US	CT
LUPA	40.600	75.370	236	bb	2001-01-01	LD	PA
MVL	40.000	76.350	91	bb	2001-02-15	LD	PA
NCB	43.970	74.220	575	bb	1992-01-01	US	NY
PAL	41.010	73.910	66	bb/sm	1999-11-04	LD	NY
SDMD	39.410	76.840	213	bb	2001-11-01	LD	MD

* Type: bb= 3-component broadband, sm= strong-motion instrument; Open= Station opening date; Network: LD= Lamont Cooperative Seismographic Network, US= US National Seismic Network.

Table A2: List of LCSN Short-period Stations Supported with USGS/ANSS Funds*

Station code	Lat. (°N)	Long. (°W)	Elev (m)	Type	Open (year-mo-da)	Network	Location (state)
ARNY	41.303	74.115	430	EHZ	1993-12-16	LD	NY
BGR	44.829	74.374	297	EHZ	1976-11-01	LD	NY
BRCN	44.428	75.583	83	EHZ	1976-11-01	LD	NY
BVD	39.775	75.499	58	EHZ	1985-02-01	LD	DE
BWD	39.800	75.577	63	EHZ	1985-02-01	LD	DE
CHIP	44.798	75.195	97	EHZ	1994-07-01	LD	NY
CRNY	41.312	73.548	293	EHZ	1981-12-01	LD	NY
DEMA	39.319	75.610	12	EHZ	1999-10-01	LD	DE
FINE	44.265	75.167	354	EHZ	1997-10-01	LD	NY
FLET	44.723	72.952	366	EHZ	1977-08-01	LD	VT
GPD	41.018	74.461	360	EH3	1976-08-01	LD	NJ
HBVT	44.362	73.065	342	EHZ	1980-09-01	LD	VT
MANY	41.222	73.869	133	EHZ	1993-12-08	LD	NY
LOZ	44.620	74.580	440	EHZ	1984-11-01	LD	NY
MDV	43.999	73.181	134	EHZ	1970-03-01	LD	VT
MIV	44.075	73.534	317	EHZ	1984-10-01	LD	NY
MSNY	44.998	74.862	55	EHZ	1976-11-01	LD	NY
NED	39.704	75.705	47	EHZ	1972-11-01	LD	DE
PAL	41.010	73.910	66	EH3	1949-01-01	LD	NY
PNZ	44.835	73.577	215	EHZ	1996-10-22	LD	NY
PTN	44.570	74.982	197	EHZ	1971-10-01	LD	NY
SCOM	38.696	75.363	12	EHZ	1999-10-01	LD	DE
TBR	41.142	74.222	261	EHZ	1975-01-01	LD	NY
WCC	41.059	73.792	100	EHZ	1987-06-01	LD	NY

* Type: EHZ= short-period vertical-component; EH3= 3-component, short-period station; Open= Station opening date; Network: LD= Lamont Cooperative Seismographic Network.

Table A3: Earthquakes recorded by LCSN for period July 1, 2001 through June 30, 2004[a]

Date Year-Mo-Da	Time (hr:mn:ss)	Lat. (°N)	Long. (°W)	h (km)	Mag (Mn)	Location
			2001			
2001-07-14	20:08:29.4	40.946	74.366	7	1.9c	7 km NE of Boonton,NJ
2001-07-17	14:41:20.2	39.937	76.340	1	1.8c	6 km S of Millersville, PA
2001-08-05	04:12:10.2	43.824	74.129	9	1.5c	51 km S of Saranac Lake, NY
2001-08-15	14:44:35.4	41.899	72.236	15	1.9c	Hazardville, CT
2001-08-19	22:47:21.4	42.584	74.010	6	1.8c	27 km W of Delmar, NY
2001-09-16	21:24:54.4	44.945	72.155	9	1.9c	61 km SW of Sherbrooke, QUE
2001-09-22	16:01:20.5	38.026	78.396	2	2.5c	7 km E of Charlottesville, VA
2001-10-02	23:40:19.0	44.360	71.824	8	2.3c	52 km W of Berlin, NH
2001-10-25	00:24:28.0	45.07	68.30	8	3.5c	31 km NE of Old Town, ME
2001-10-27	05:42:21.0	40.793	73.970	5	2.6c	Manhattan, NY
2001-12-24	16:58:21.0	46.850	76.500	18	3.8n	67 km NW of Maniwaki, QUE
			2002			
2002-01-20	14:11:55.0	49.490	66.950	30	4.1n	280 km N of Miramichi, N.B.
2002-01-21	08:25:55.0	44.520	74.580	5	1.4c	36 km SE of Potsdam, NY
2002-02-11	11:41:37.0	46.070	73.450	18	3.8n	4 km N of Joliette, QUE
2002-02-24	21:38:33.0	45.290	75.170	18	3.1n	44 km E of Ottawa, ONT
2002-03-05	01:33:52.2	41.115	73.657	6	1.2c	12 km NW of Stamford, CT
2002-03-06	11:09:45.5	41.707	71.349	17	2.2n	3 km NE of Warwick, RI (WES)
2002-03-12	07:13:23.0	41.23	69.57	4	3.2c	71 km SE of South Yarmouth, MA
2002-03-18	02:56:41.0	41.15	74.53	5	0.8c	21 km NE of Newton, NJ
2002-04-01	12:31:18.0	44.79	73.78	10	1.3c	28 km W of Plattsburgh, NY
2002-04-04	02:48:41.0	43.112	71.695	4	1.6c	17 km SW of Concord, NH
2002-04-20	10:50:47.5	44.513	73.699	11	5.3L	Au Sable Fork, NY, Mainshock
2002-04-20	11:04:42.3	44.490	73.690	10	3.7L	Au Sable Fork, NY, Aftershock
2002-04-20	11:08:26.0	44.501	73.704	10	1.7c	Au Sable Fork, NY, Aftershock
2002-04-20	11:45:28.7	44.504	73.703	10	2.6L	Au Sable Fork, NY, Aftershock
2002-04-21	11:47:09.9	44.515	73.670	10	2.2c	Au Sable Fork, NY, Aftershock
2002-04-21	12:39:10.7	44.504	73.700	10	2.3c	Au Sable Fork, NY, Aftershock
2002-04-25	13:39:56.0	44.503	73.674	10	2.2c	Au Sable Fork, NY, Aftershock
2002-04-28	00:07:20.8	41.850	81.370	5	2.6c	18 km NW of Painesville, OH
2002-05-06	22:26:51.5	38.948	81.889	5	2.8c	46 km SE of Athens, OH
2002-05-16	07:06:18.0	44.74	73.69	3	1.7c	20 km W of Plattsburgh, NY
2002-05-24	23:46:00.1	44.504	73.675	10	3.1L	Au Sable Fork, NY, Aftershock
2002-05-28	09:15:37.0	45.56	76.61	3	3.2n	73 km W of Ottawa, ONT
2002-06-01	11:35:29.0	45.51	73.88	15	2.4n	22 km W of Montreal, QUE
2002-06-07	10:16:04.0	42.160	71.560	5	2.5c	4 km NW of Milford, MA

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Date Year-Mo-Da	Time (hr:mn:ss)	Lat. (°N)	Long. (°W)	h (km)	Mag (Mn)	Location
2002-06-25	13:40:28.0	44.503	73.675	9	3.0L	Au Sable Fork, NY, Aftershock
2002-07-11	21:53:45.0	40.39	71.33	0	3.0c	114 km SE of Hampton Bays, NY
2002-07-23	02:08:59.0	49.59	66.95	18	4.0n	291 km N of Miramichi, N.B.
2002-08-09	14:59:56.0	40.62	74.63	4	1.5c	5 km N of Somerville, NJ
2002-08-11	03:06:00.0	43.65	73.71	5	2.1c	38 km N of Glens Falls, NY
2002-08-11	03:06:49.0	43.67	73.65	5	2.1c	40 km N of Glens Falls, NY
2002-08-22	18:58:38.2	41.479	72.101	8	2.2c	2 km W of Norwich, CT
2002-09-07	21:27:46.0	46.90	76.26	16	3.2n	64 km N of Maniwaki, QUE
2002-09-16	06:09:26.5	44.260	71.420	1	1.7c	45 km SW of Berlin, NH
2002-09-28	23:47:25.0	42.89	71.68	1	2.6c	6 km NW of Milford, NH
2002-11-07	16:55:06.0	44.05	77.43	18	3.0c	93 km N of Webster, NY
2002-11-08	17:14:47.0	44.00	72.51	5	1.9c	22 km S of Barre, VT
2002-12-25	18:25:20.5	44.572	73.776	6	2.4c	Au Sable Forks, NY, Aftershock
2003						
2003-01-11	02:24:09.8	41.004	73.879	3	1.2c	Hastings-On-Hudson, NY
2003-01-15	00:58:18.3	40.990	73.866	3	1.4c	Hastings-On-Hudson, NY
2003-02-09	16:18:03.0	46.51	75.20	18	3.3n	24 km E Mont-Laurier, Que (OTT)
2003-04-08	15:06:14.3	44.615	74.340	10	3.3c	27 km S of Malone, NY
2003-04-20	12:24:43.8	41.361	74.370	7	2.3c	8 km SW of West Point, NY
2003-05-05	16:32:32.7	37.755	78.072	5	3.9g	Central Virginia (PDE)
2003-06-13	11:34:40.0	47.70	70.09	11	4.1n	Charlevoix, Que (OTT)
2003-06-30	19:21:19.1	41.826	81.214	5	2.9c	21 km NE of Painesville, OH
2003-07-17	00:44:10.0	41.86	80.76	2	2.5n	Ashtabula, Ohio (OGS)
2003-07-22	11:41:15.6	42.772	70.023	11	3.6n	76 km E of Gloucester, MA
2003-08-20	01:58:17.0	46.01	74.95	18	3.5n	32 km NE of Ripon, QUE
2003-08-24	09:21:37.1	40.784	74.548	6	1.5c	18 km W of Millburn, NJ
2003-08-26	18:24:18.4	40.606	75.106	3	3.5L	Milford, NJ-Upper Black Eddy, PA
2003-08-27	19:55:39.1	44.955	73.711	10	2.2c	30 km NW of Plattsburgh, NY
2003-09-19	17:22:34.0	45.79	74.85	18	3.3n	50 km NE of Buckingham, Que
2003-10-01	08:07:57.4	40.572	75.116	3	2.2c	Milford, NJ-Upper Black Eddy, PA
2003-10-07	01:32:03.2	41.73	71.57	6	1.8n	SW of Providence, RI (WES)
2003-10-12	08:26:06.0	47.05	76.27	18	4.6n	76 km NW Maniwaki, Que (OTT)
2003-10-15	04:13:14.0	45.08	66.91	18	3.1n	21 km E St.Stephen,NB(OTT)
2003-10-18	16:25:07.0	46.94	67.19	18	3.5n	99 km SE Edmundston,NB(OTT)
2003-11-04	13:37:31.8	40.251	75.877	1	2.4c	10 km SE of Reading, PA
2003-12-09	20:59:18.7	37.774	78.100	10	4.3w	Goochland, central Virginia
2004						
2004-01-20	17:11:55.3	43.208	71.777	3	2.3n	19 km W of Concord, NH
2004-02-24	01:54:42.4	41.55	70.98	5	2.0n	S of New Bedford, MA (WES)

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Date Year-Mo-Da	Time (hr:mn:ss)	Lat. (°N)	Long. (°W)	h (km)	Mag (Mn)	Location
2004-03-14	05:05:10.3	41.77	81.24	5	2.4n	NE of Cleveland, OH
2004-03-17	01:44:44.4	43.20	70.58	5	2.1n	SSW of Biddeford, ME (WES)
2004-03-17	12:38:15.0	45.05	75.66	18	2.5n	41 km S of Ottawa, ONT (OTT)
2004-03-17	22:01:58.1	44.896	74.912	8	2.7c	4 km S of Massena, NY
2004-03-22	15:21:39.9	39.860	75.048	7	2.1c	12 km SW of Ramblewood, NJ
2004-06-16	06:31:27.0	42.79	79.08	18	3.1n	18 km SE of Port Colborne, ON
2004-06-22	10:17:53.0	45.17	69.12	9	2.0n	NW of Bangor, ME (WES)
2004-06-30	04:03:14.6	41.78	81.08	5	3.3n	NE of Cleveland, OH

* Mag=Magnitude: g = mb(Lg) Nuttli's 1-sec period Lg-wave magnitude reported by NEIC; c = Mc, coda duration magnitude determined by LDEO; L = M_L , local Richter magnitude determined and reported by Lamont-Doherty Earth Observatory of Columbia University; w = M_w , moment magnitude from waveform moment tensor inversion; n = Mn, Nuttli's mb(Lg) reported by Geological Survey of Canada, Ottawa or by the Weston Observatory, Boston College, MA.
Reporting agency: OTT=Geological Survey of Canada, Ottawa; WES=Weston Observatory, Boston College; PDE= Preliminary Determination of Epicenters, NEIC/USGS; OGS= Ohio Geological Survey.