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: 04HQAG-0115

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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 21 modern, broadband seismographic stations and 22 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 2004 through November 2006, 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. We implemented rapid generation of instrumental ground motion and intensity maps – ShakeMaps. For real-time data exchange, integration and archive, LCSN exceeds the "ANSS Performance Standard (APS) v2.4". 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 ∼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, ∼10–15 minutes posting time.

The 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 about 25 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, 21 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). 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. Some broadband stations around more seismically active areas are recording 100 samples/s continuously since 2006.

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 25 organizations in the northeastern US and relies upon their support in station maintenance and operation in the region. The organizations who operate LCSN stations consist of 2 secondary schools, 2 environmental research and education centers, 3 state geological surveys, a museum dedicated to Earth system history, 2 public places (Central Park, NYC & Howe Caverns), 3 two year colleges and 15 four-year universities (see Section 4 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 22 short-period stations (see Table A2), and 21 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.

Figure 2 shows broadband station uptime and data recovery percentage during 2006. Target is over 90% uptime across the network and over 95% data recovery rate. BRNY, HCNY and

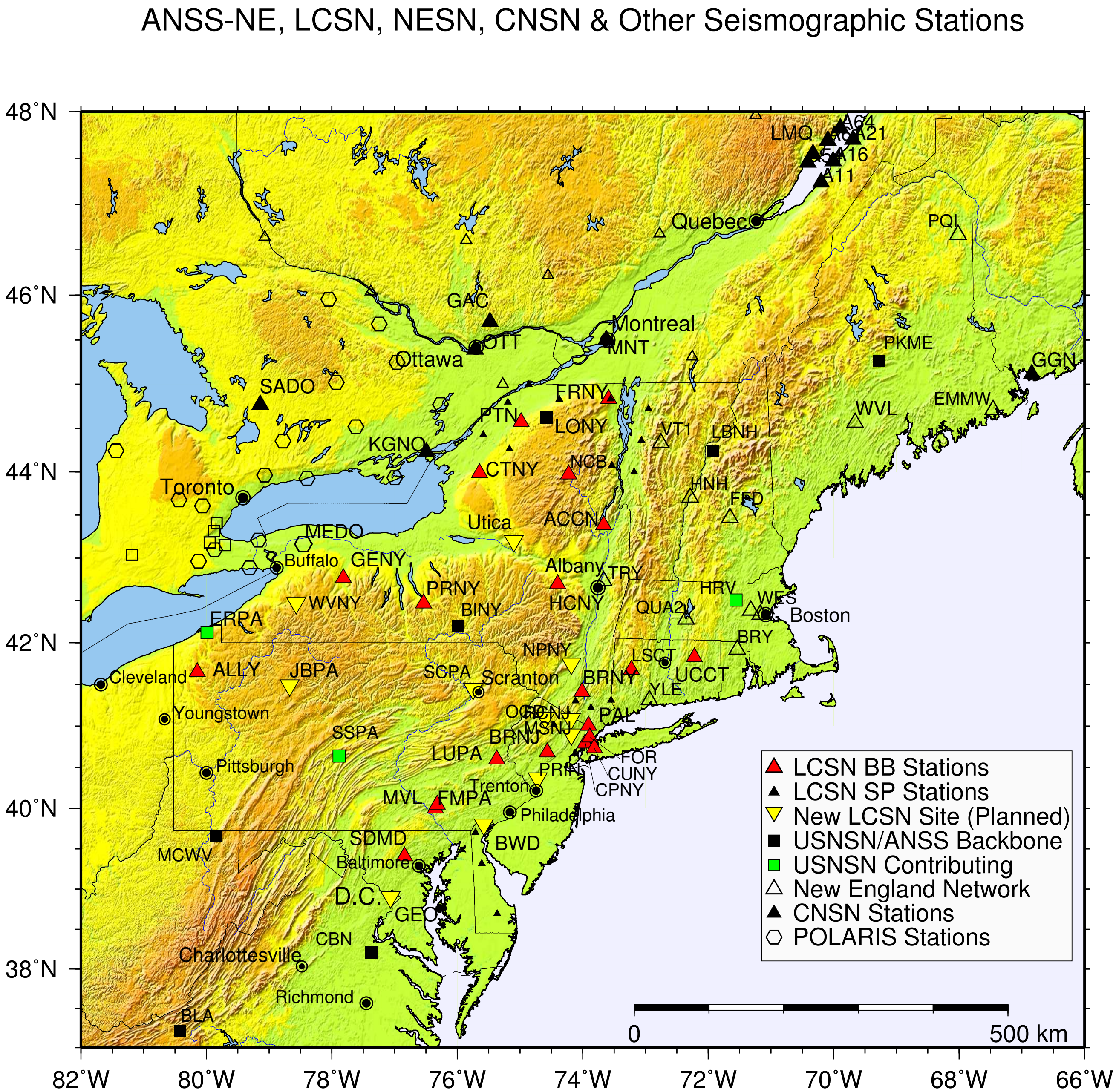

Figure 1: Map showing the overview of the broadband and short-period seismographic stations of Lamont Cooperative Seismographic Network (LCSN), USNSN, NESN (New England Seismic Network) in northeastern United States and stations in southeastern Canada (CNSN and POLARIS) as of December 2006. 21 LCSN Broadband stations are plotted with *red triangles*, USNSN stations are plotted with *filled squares*, *inverted yellow triangles* indicate 11 sites that are considered for future BB and short-period station deployment. These are Johnsonburg, PA. (JBPA), West Valley, NY (WVNY), Georgetown University, DC (GEO), Princeton, NJ (PRIN) among others.

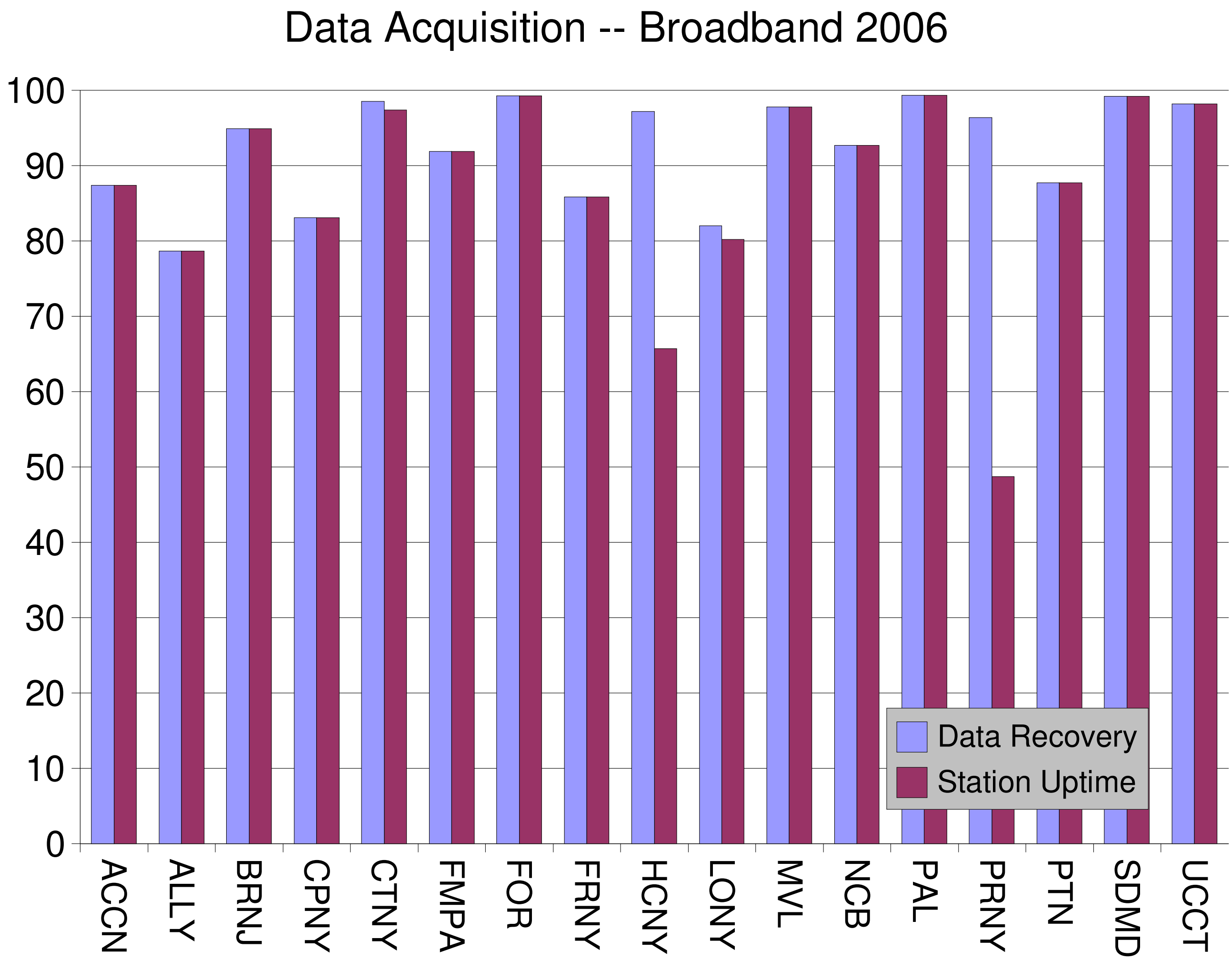

Figure 2: Diagram showing broadband station uptime and data recovery percentage during 2006. Target is over 90% uptime across the network and over 95% data recovery rate. BRNY, HCNY and PRNY were deployed 2006, whereas PTN and UCCT are below target operation. CUNY, GENY, LUPA and LSCT are down and are not shown in the diagram.

PRNY were deployed 2006, whereas PTN and UCCT are below target operation. CUNY, GENY, LUPA and LSCT were down through the summer of 2006 and are not shown in the diagram. Two broadband stations, LUPA and CUNY, were resuscitated during the fall of 2006. We are working on the two stations (LSCT & GENY) which are down due to various reasons, chiefly broadband sensor problems during FY2006.

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 FY04-06. They are at Central Park, NYC; Fordham University, the Bronx; Westchester Community College, Valhalla, NY; and Palisades, NY (Figure 1 & Figure 3).

The data are continuously recorded with 100 samples/s and are sent to NSMP for event waveform data.

We plan to deploy additional stations in NYC for ground motion studies during FY07-09 in collaboration with the Earthquake Hazards Team at USGS, led by Dr. Art Frankel. The plan is to deploy K2 digital instruments in about 6 locations in New York City. The sensors on these instruments and the recorders have sufficient dynamic range to record weak motions from M $>$ 2.5 earthquakes within about 30 km of the station and larger events to a greater distance.

Initially these instruments will be deployed as pairs, with each instrument located on a different surficial geology to quantify the site amplification of these different units. For example, we will have one site on artificial fill and one on nearby stiff soil or rock. We will also use these instruments to do studies of seismic noise that will reveal the site response and path effects in the area. For example, by correlating the seismic noise at adjacent stations we can determine the Green's function between the sites. We plan on deploying these instruments for a period of at least 3 years. It is likely that some of these stations will be replaced by permanent installations. Additional sites that can be considered are: Columbia University in uptown Manhattan; Downtown Washington Square Park, NYU; City Hall, Downtown, Manhattan; Long Island City (42 Ave, 11 St; ConEdison, off Queensboro Bridge); Queens College, Flushing, Queens, NYC; a site in Brooklyn and Staten Island, NYC (see Figure 3).

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 4.

The performance target for the real-time earthquake monitoring in the northeast is based on "ANSS Performance Standard v2.4 (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$50 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.

Figure 3: Initial seven strong-motion instrument sites in New York City as urban monitoring network under the ANSS-Northeast implementation plan of FY2003.

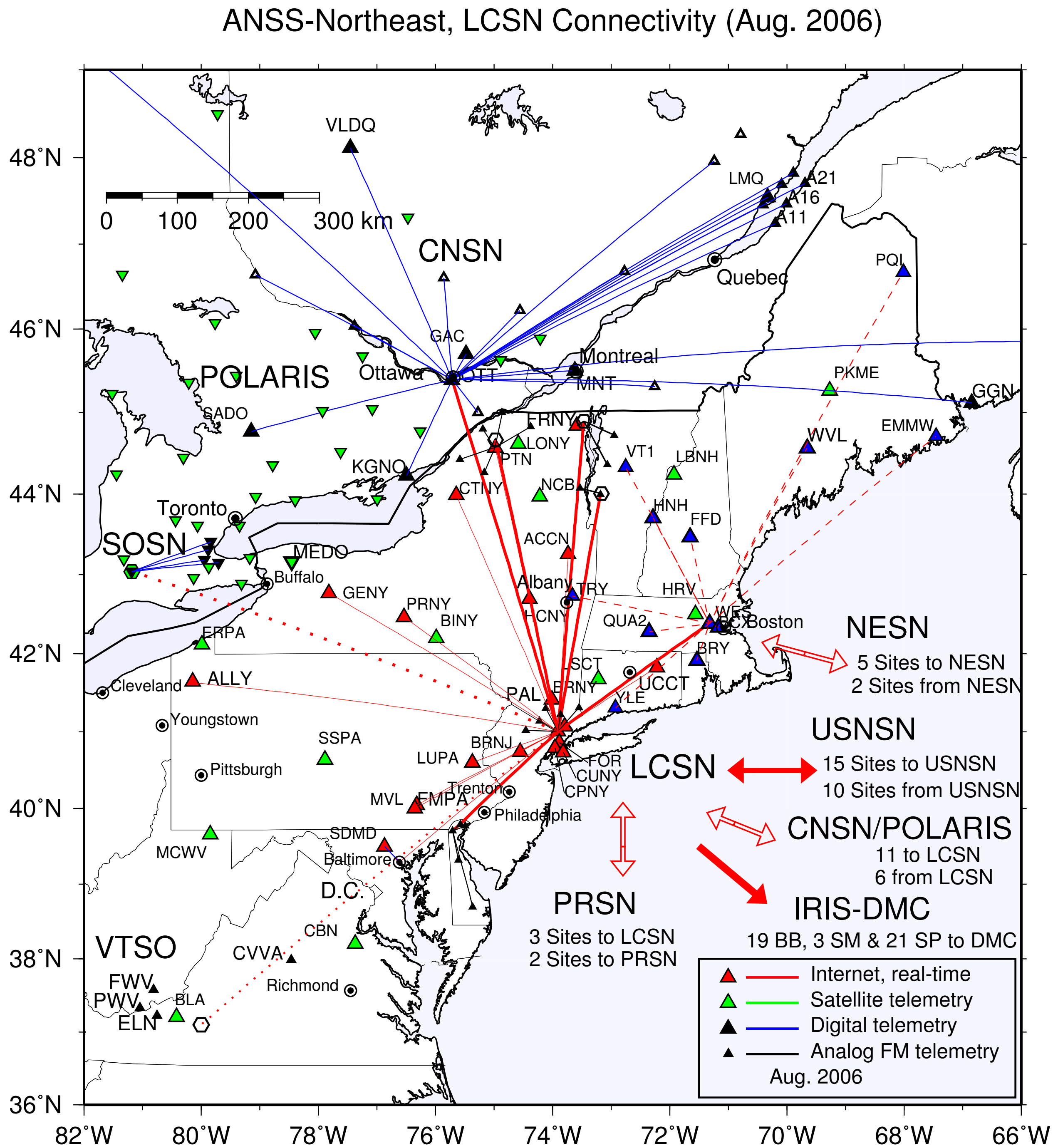

Figure 4: LCSN real time waveform data exchange and integration scheme. Data exchange with neighboring networks: exporting 15 sites and importing 10 sites to and from USNSN/NEIC; exporting 6 and importing 11 from CNSN/POLARIS of Canada, and exporting 5 and importing 2 from New England Seismic Network. All waveform data are exported to the IRIS-DMC for permanent archiving and dissemination.

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 15 sites and importing 10 sites to and from USNSN/NEIC; exporting 6 and importing 11 from CNSN/POLARIS of Canada; exporting two sites data to CERI (SDMD, MVL); exporting 5 and importing 2 stations from NESN (New England Seismic Network); exporting 2 and importing 3 stations from PRSN (Puerto Rico). We plan to establish real-time waveform data export/import with VTSO (Virginia Tech Seismic Observatory) and OhioSeis (Ohio) in FY2007 to improve event detection and location. 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.

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. We are working to disseminate earthquake parameters in EQ XML (Extensible Markup Language) messages under the new Earthquake Information Distribution System (EIDS). We will implement EQ XML handling software and EIDS as soon as they are available. 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>. This will be increased to 6 months of local archive without additional support.

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/archive/LCSN/DATALESS_SEED>.

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 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 is 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.

However, it is a preliminary work and we need to implement:

1. Regression relationships between intensity and peak ground motions (e.g., Wald et al. (1999a),

2. Ground motion attenuation relations: evaluate available attenuation relations for the EUS, e.g., Atkinson & Boore (1995); Toro et al. (1997); Somerville et al. (2002) and Campbell (2003) and select the best one for the ShakeMap,

3. Geology and site corrections: When performing interpolations between stations, a uniformly spaced grid of site conditions is required to generate the ShakeMaps. NEHRP Classification (types A through E, given as an associated average 30 m shear velocity) and corresponding amplification factors. A=Hard rock site, V30m $>$ 1,500 m/s through E=Soft clays, V30m $<$ 180 m/s (Borcherdt, 1994). Compiled soil database in NY (1:250,000 geologic map), NJ (1:10,000 agricultural map) and part of CT and are available from the database, for example, <http://www.nycswcd.net/files/RSSw_photo.jpg>,

4. A lack of near field (distance less than 100 km) peak ground motion data due to sparse station distribution in the ENA has been known as a serious problem on studies of the ground motion attenuation in the northeastern U.S. (Kim, 1998). Hence, we will work continuously to improve the station coverage with station spacing of ∼50 to 100 km in the northeastern U.S.

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 US 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 3.1 August 4, 2004, Lake Ontario, NY) was one of the largest earthquakes to have occurred in the region, it is too small in general to have good data. The quake is fairly well recorded by over 10 broadband stations around Lake Ontario only due to recent high density deployment by POLARIS Consortium, Canada.

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. Hence, we plan to reduce the latency by making an automated process.

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.

We will establish plans to ensure the continuity of earthquake reporting in the event of a significant network disruption (fire, natural disaster, long-term power disruption, etc.) with NEIC and neighboring regional networks by January 31, 2008.

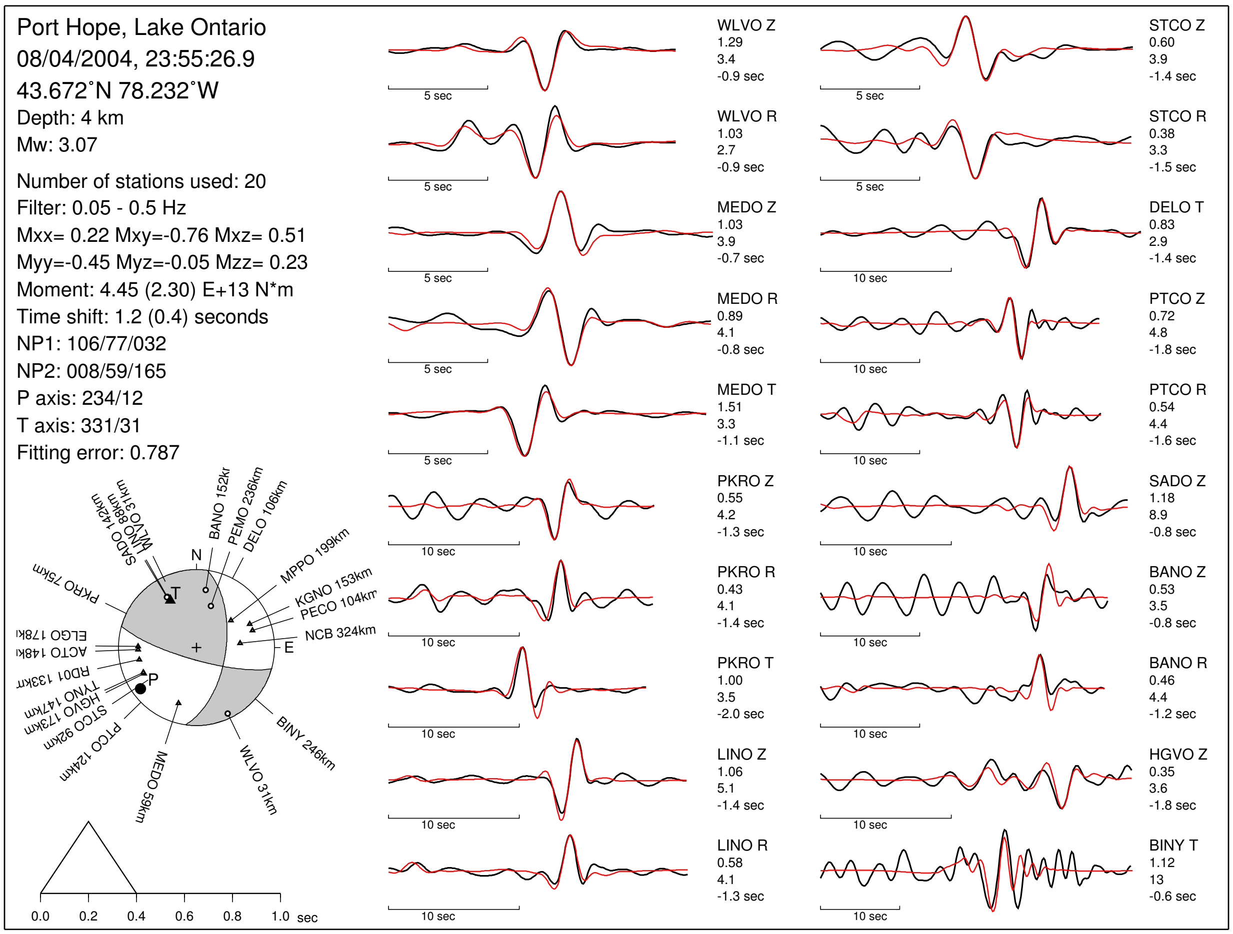

Figure 5: An example seismic moment tensor determination using regional waveform modeling and inversion. 3-component, broadband records at about 11 stations from August 4, 2004 Lake Ontario, NY shock are used for the analysis. A beach-ball at lower left represents source mechanism (strike-slip faulting) and stations used. Station code and distance from the source are indicated along their azimuth. Waveform fits for a focal depth of 4 km are plotted with observed displacement record in solid line and corresponding synthetics in red 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. We will make this system available for rapid deployment as part of the earthquake contingency plan for ANSS-NE.

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

- 1982 Miramichi, NB, Canada, M_w 5.5 & 5.0; a complex and long-lasting sequence involving a relatively large volume of crust (Wetmiller et al, 1984)
- 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),
- 1987 Saguenay, Quebec; M_w 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)
- 1990 Ungava, Quebec; M_w 6.0 a very shallow rupture breaching the surface on a new brittle fault (Adams et al., 1991)
- 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 160 local and regional earthquakes with magnitude greater than about 1.5 that have occurred in the northeastern United States and southern Canada were detected and located by the LCSN during July 1, 2004 through December 1, 2006 (see Figure 6). These earthquakes range from magnitude 0.3 (Mc) to 4.7 (M_w) and are listed in Table A3.

Notable earthquakes during the period are:

- four very small earthquakes that occurred on Dec. 12-15, 2004 in Lower East Side of Manhattan, New York City just around the East River. These were small events with magnitude ranging from Mc 0.3 to 0.8, but many residents in Long Island City, Queens felt the events;
- Five earthquakes with magnitude between 1.1 to 2.9 occurred near the town of Chateaugay about 20 km east of Malone, NY during March 3-June 12, 2005;
- Two events occurred around Au Sable Forks and Plattsburgh, NY on April 17 (Mc 2.5) and July 1, 2005 (Mc 2.2);
- The largest earthquake that occurred in the region was M_w 4.7 (Mn 5.4) Riviere-du-Loup, Quebec event in the Charlevoix seismic zone.
- September 22 - October 22, 2006 Bar Harbor, Maine earthquake sequence. The Bar Harbor earthquake sequence started with a magnitude 3.4 event on September 22, 2006 which was preceeded by four earthquakes with magnitude ranges of 1.8 to 2.4. Many aftershocks of magnitude $\approx$ 2 followed the September 22 shock, then a magnitude 4.2 earthquake occurred in the same epicentral area on October 3, 2006 (see Table A4 & Figure 7).

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

The recent Bar Harbor, Maine earthquake sequence has been fairly well recorded by regional and national seismographic networks. The list of earthquakes of the sequence located by Weston Observatory (WES) of Boston College or by the Geological Survey of Canada (GSC) is listed in Table A4. A preliminary analysis of the largest earthquake in the sequence, a magnitude 4.2 event on 10/03/2006, suggests that the shock was a reverse faulting along moderately dipping nodal planes striking north-south. The fault plane is either a nodal plane dipping 55° to the east or a plane dipping 35° to the west.

In order to detect and locate very small aftershocks that may occur in the epicentral area, LCSN (Lamont Cooperative Seismographic Network) deployed portable seismographic stations in the epicentral area. The main objective is to locate accurately those small aftershocks and identify causative fault(s) in the area. Such information is very important for correctly evaluating the hazards associated with earthquakes in the region.

The field crew from Lamont-Doherty deployed six portable seismographic stations in and around Mount Desert Island during 10/04-10/05, 2006 through timely help from staff at the Maine Geological Survey, the Acadia National Park, Weston Observatory of Boston College, and many others in the area. Under the auspices of the ANSS (Advanced National Seismic System), NEIC in Golden, Colorado promptly provided two portable digital seismographs. These stations are indicated by triangles on the map (Figure 7). Some basic information about the earthquake sequence is available via the WWW at URL:

<http://www.ldeo.columbia.edu/LCSN/Eq/20060922_Maine>.

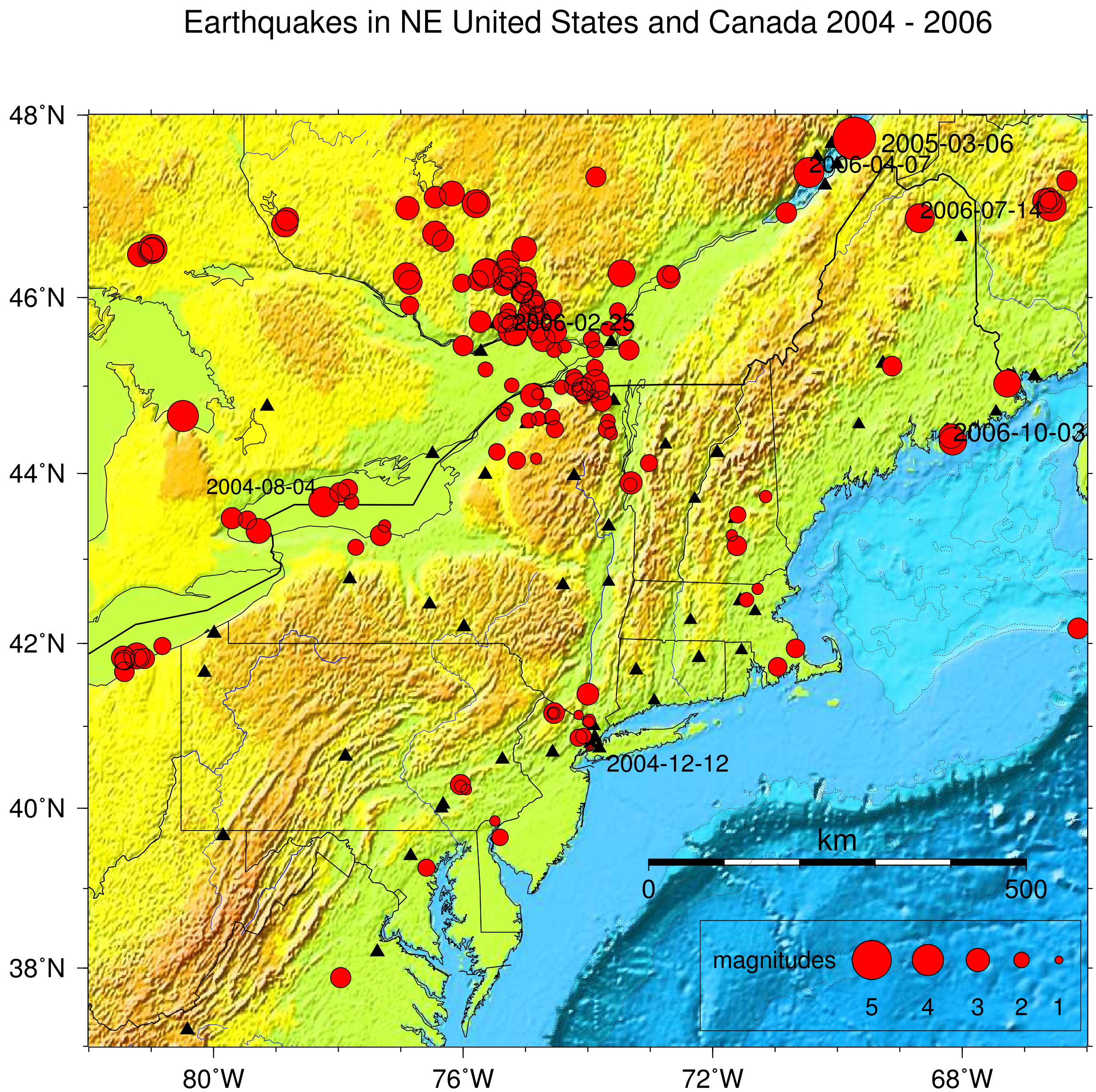

Figure 6: Earthquakes which have occurred in the northeastern United States and southeastern Canada in the time period of July 1, 2004 through December 1, 2006 recorded by the LCSN. Symbol size is proportional to magnitude. Broadband stations of the LCSN, USNSN, NESN, and CNSN are plotted for reference.

1. Otter Creek (OTC), Mount Desert Island, 4 km South of Bar Harbor, Mr. Kevin Le Clair's back yard, AC power with CMG-40T broadband seismometer,
2. Long Pond Fire Road (LPF), Pretty Marsh, western Mount Desert Island, Mr. Charles Jacobi of the park office led us to the site, solar panel - battery with CMG-40T broadband seismometer,
3. Schoodic Point (SCH), east of the Mount Desert Island, Mr. Edward Pontbriand of the park service helped us at the site (old naval base), AC power with CMG-40T broadband seismometer,
4. Lamoine State Park (LAM), north of Mount Desert Island, Mr. Jay MacIntosh of the state park service helped us locating and installing a station at the shore front of the park, solar panel - battery with L-22 short-period seismometer.
5. McFarland Mt. (MFL), near the Acadia National Park headquarters, it is co-located with the weather station, solar panel - battery with L-22 short-period seismometer,
6. Baldpeak Mt. (BALD), along the carriage trail, solar panel - battery with L-22 short-period seismometer.

3.2.1 Preliminary results of 10/03/2006 Bar Harbor, Maine earthquake sequence

Three large aftershocks on 10/22/2006 are located using the local network data from four stations. The locations of these events are around Champlain Mountain close to the east coast of Mount Desert Island (see Figure 7) about 3 km south of Bar Harbor. The focal depths of these shocks are about 1.5 km. Hence, the epicenters of the 2006 Bar Harbor, Maine earthquake sequence appear to be along a north-south trending feature near Champlain Mountain. The Shatter Zone in the area surrounding the Cadillac Mountain granite seems to be an interesting geologic feature that may provide some clues on causative fault(s) in the area (Gilman & Chapman, 1988).

3.2.2 Participants for the aftershock monitoring

Acadia National Park
Charles Jacobi (Resource Specialist/Visitor Use), David Manski (Chief of Resource Mangement), Bill Gawley (Biologist- Air/Water/Data Mgt.), Edward Pontbriand (Schoodic District Ranger), Pete Berquist (Geologist & Acadia National Park Ranger)

Maine Geological Survey
Robert G. Marvinney (State Geologist and Director), Henry N. Berry IV (Geologist)

University of Maine at Machias
Gerard Zegers (Assistant Research Professor)

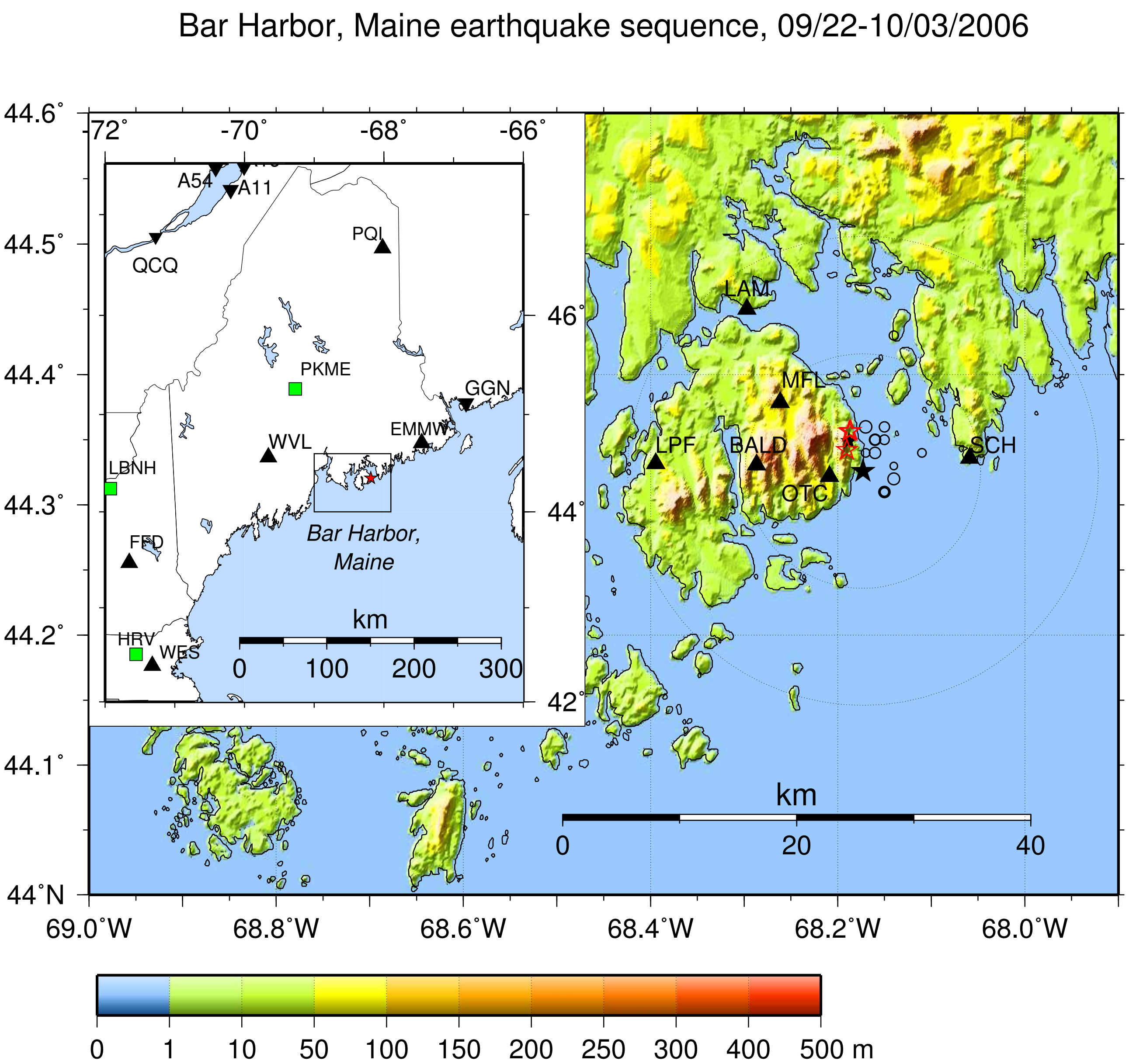

Figure 7: Portable seismographic stations in the Acadia National Park region deployed for monitoring aftershocks of the Bar Harbor, Maine earthquake sequence of September 22 - October 22, 2006 are plotted with *triangles*. The largest event (M 4.2) that occurred on 10/03/2006 and the second largest event on 09/22/2006 are plotted with *filled stars*, aftershocks during September 22 - September 28, 2006 are plotted with *circles*, and three aftershocks on October 22, 2006 accurately located by using the local network data are plotted with small *red stars*. (*inset*) map showing seismographic stations in and around Maine. US National Seismographic Network stations are plotted with *green squares*, Canadian National Network stations are plotted with *inverted triangles*, and New England Seismic Network stations are plotted with *filled triangles*.

Lamoine State Park
Jay MacIntosh (park manager)

Weston Observatory, Boston College
John Ebel (director of Weston Observatory), Anastasia Macherides-Moulis (Analyst)

Lamont-Doherty Earth Observatory of Columbia University
Won-Young Kim (director of Lamont Cooperative Seismographic Network), Mitchell Gold (Analyst/network managing), John Contino (Sr. Electronic Technician).

U.S. Geological Survey/ANSS/NEIC
Harley M Benz (Regional network coordinator), Mark E Meremonte (Geophysicist).

4 Reports and Dissemination of Information and Data

4.1 Continuous Waveform Data

Continuous, broadband (40 samples/sec and 100 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.

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. In the summer of 2006, we increased the data availability to most users by using event oriented waveform database via WWW. The phase data as well as full waveform data for the earthquakes in recent years are available from the LCSN web site as "LCSN Database/waveform archive"

<http://almaty.ldeo.columbia.edu:8080/eventwfdb.html>. Part or all of the waveform data are also sent to NEIC, CERI and Geological Survey of Canada in real time. Event database for selected regional events are also available at LCSN web site.

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 EDIS) 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 Earthquake Catalog Archive

We developed a standard earthquake catalog search tool with the ability to plot the results on a postscript map using GMT (Generic Mapping Tools). The LCSN earthquake catalog search tool is at URL: <http://almaty.ldeo.columbia.edu:8080/data.search.html>. We will make available some related databases such as the NCEER earthquake catalog.

4.5 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.

4.6 LCSN Earthquake Information on Google Map with Error Ellipses

As map images of various resolution become available in the Internet, the general public has an opportunity to have earthquake information with a more detailed picture. However, we find it hard to explain to non-scientist about the uncertainties of epicenters determined by seismic methods. Hence, we are developing a tool that can plot hypocentral data onto map images with error

Figure 8: Epicenters of two small earthquakes that occurred near Orangeburg, NY are plotted with Error ellipses with 95% confidence level, which indicate 95% chance that the "true" epicenters will be included within the ellipses.

ellipses. An example is presented in Figure 8 in which epicenters are plotted with appropriate location uncertainties through error ellipses, which indicate 95% chance of containing the *true* epicenter. This can reduce unnecessary questions among people.

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 ∼25 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 2 secondary schools, 2 environmental research and education centers, 3 state geological surveys, a museum dedicated to Earth system history, 2 public places (Central Park, NYC & Howe Caverns), 3 two year colleges and 15 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)
Black Rock Forest Consortium, Cornwall, NY (BRNY)
Central Park Conservancy, Manhattan, NYC (CPNY)
Carthage Central High School, NY (CTNY)
Queens College, City University of New York (CUNY)
Delaware Geological Survey, Newark, DE (DGS subnet)
Franklin and Marshall College, PA (FMPA)
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)
Howe Caverns, Cobleskill, New York (HCNY)
SUNY Cobleskill (HCNY)
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)
Paleontological Research Institution, Museum of the Earth, Ithaca, NY (PRNY)
Cornell University, Ithaca, New York (PRNY)
Potsdam College of Art & Science, SUNY – Potsdam, NY (PTN)
Maryland Geological Survey, Baltimore, MD (SDMD)
University of Connecticut, Storrs, CT (UCCT)
Westchester Community College, SUNY (WCCN)
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. Examples include research seismometers installed and used for education in a high school in Carthage, NY, at the Black Rock Forest Consortium for environmental research and education in the Hudson Highlands, and at a museum dedicated to Earth system history in Ithaca, NY.

In the fall of 2006, LCSN tryed to promote analysis of seismic data acquired by each of the 25 partners. One of the topics is, "Mapping the Moho beneath your station", and the other is "Ambient Noise and Site Response of Your Station". About 6-8 people volunteered for each of these topics. This exercise is still progressing. It motivates the LCSN partners to utilize seismic data collected by the network and achieve its goal of using the seismic data for evaluating the earthquake hazards in the region.

6.1 Mapping the Moho Beneath Your Station

Preliminary receiver function analysis of several stations along New York City to Lehigh Valley, PA suggest that Moho depth is about 34 km beneath the Bronx, Manhattan, and Palisades, and it gradually increases to about 42 km beneath Basking Ridge, NJ and Lehigh, Pennsylvania going westward (see Figure 9). This suggests an $\sim$8 km increase of the Moho depth along 130 km distance from the east to the west (from the Bronx to Lehigh), which corresponds to $\sim 3.5^{\circ}$slope for a flat Moho. Back-azimuth gathers of receiver functions at Basking Ridge, NJ suggest that the Moho might locally dip to the southeast by as much as 20°. The Ps phase, P to S converted phase at the Moho, samples very close to the station ($\sim$6 to 10 km), and is the most prominent phase sampling the lateral structure (Figure 9). Since the LCSN broadband stations cover a region with a diverse geological environment – Newark basin, Appalachian, Adirondacks and Avalonian from the south to the north, we expect that the receiver function analysis will provide very interesting results. This is an example that we would like to continue during FY07-09.

6.2 Ambient Noise and Site Response of Your Station

The participants of the LCSN are past its deployment stage, and are starting to analyze data for education and scientific research. It is imperative to have a good understanding of the ambient noise characteristics and site response of each station, in order to correctly utilize the data. Hence, we began to analyze the data using a software tool, QUACK (QUality Analysis Control Kit) developed by NEIC and available on the IRIS-DMC web site for waveform data archived there with corresponding instrument response in DATALESS SEED as for all LCSN data.

Preliminary analysis of the ambient noise suggests that the microseism noise spectral peak at PRNY (Ithaca, NY) is about 0.2 Hz (5 second-period), which is slightly shorter period than at PAL and HCNY (Howe Caverns, Cobleskill, NY; 7-8 second-period), probably due to lower microseisms at PRNY, as the site is a farther distance from the Atlantic Ocean than PAL or HCNY (see Figure 10).

The broadband stations of LCSN are distributed in diverse environments such as a 45 m deep natural cave (HCNY), middle of the most dynamic city in the world (CPNY in Manhattan), and relatively quiet mountain sites (NCB, FRNY; Flat Rock, Altona, NY). For site characteristics, we take horizontal versus vertical component amplitude spectral ratio of regional signals to constrain the empirical site response.

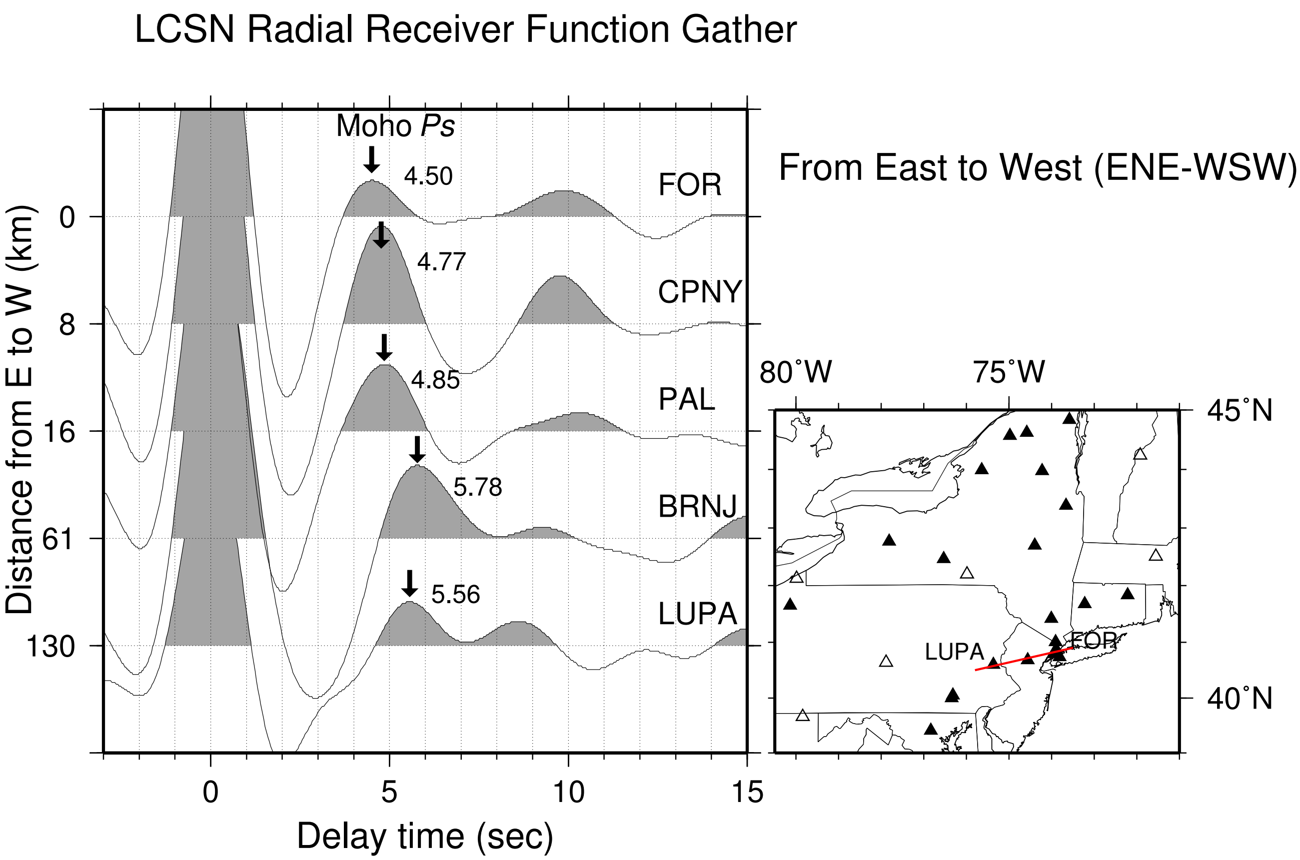

Figure 9: Radial receiver functions that show Ps phase (P to S converted at the Moho) at five stations of LCSN along ENE to WSW direction (azimuth ∼250°). The RF at each station is plotted with the positive amplitude shaded to help clear display of the Ps phase and other converted phases. P wave arrival is at time zero (0) and Ps phase arrival is marked by an arrow and its time is indicated next to the phase arrival. The vertical axis shows distance from a reference point, in this case, Fordham (FOR) in the Bronx, NYC, to each station along WSW direction. Hence, LUPA (Lehigh) is about 130 km from the FOR. Moho depth is about 34 km beneath the Bronx, Manhattan, and Palisades, and it gradually increases to about 42 km beneath Basking Ridge, NJ and Lehigh, PA going westward, assuming (*Ps* - *P*) time × 8 km/s. Eight kilometer difference along 130 km distance corresponds to ∼3.5°slope for a flat Moho.

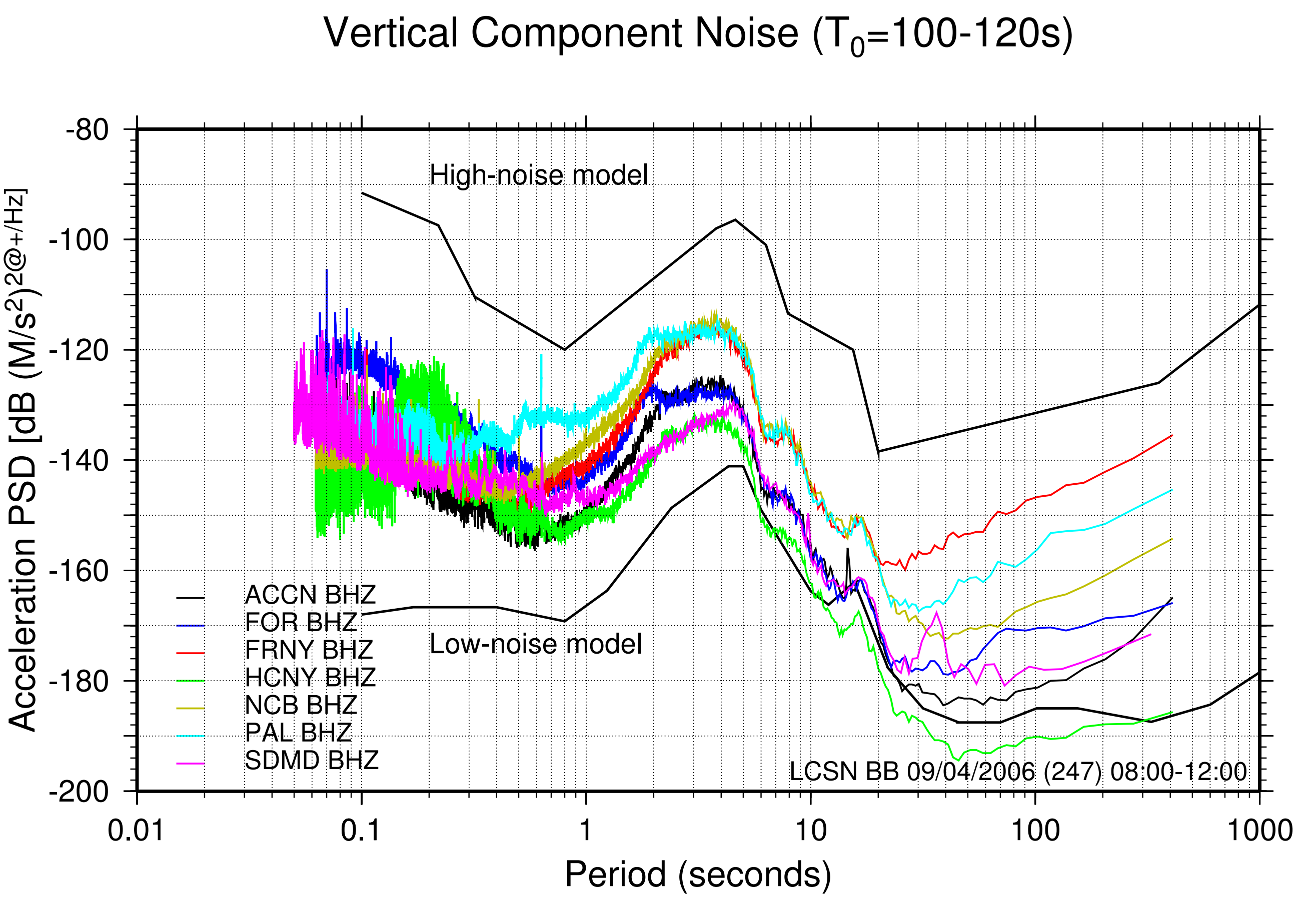

Figure 10: Ambient noise power spectral density of the vertical-component records at LCSN stations with broadband seismometers with natural period greater than 100s. The noise PSD at long-period ($\geq$ 30s) band indicates that the ambient noise varies by as much as 30dB between the quiet (e.g., HCNY & ACCN) and noisy sites (e.g., FRNY, PAL & NCB).

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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 (yearmoda)	Network	Location (state)
ACCN	43.380	73.670	340	bb	19991109	LD	NY
ALLY	41.650	80.140	390	bb	20020530	LD	PA
BRNJ	40.680	74.570	50	bb	19991121	LD	NJ
BRNY	41.414	74.012	282	bb	20060622	LD	NY
CPNY	40.790	73.960	27	bb/sm	20020221	LD	NY
CTNY	43.988	75.645	187	bb	20051108	LD	NY
CUNY	40.730	73.820	20	bb	20020523	LD	NY
FMPA	40.048	76.321	121	bb	20050222	LD	PA
FOR	40.860	73.890	24	bb/sm	20020418	LD	NY
FRNY	44.840	73.590	223	bb	20031113	LD	NY
GENY	42.770	77.820	195	bb	20011027	LD	NY
HCNY	42.697	74.398	273	bb	20060228	LD	NY
LSCT	41.680	73.220	318	bb	19930806	US	CT
LUPA	40.600	75.370	236	bb	20010101	LD	PA
MVL	40.000	76.350	91	bb	20010215	LD	PA
NCB	43.970	74.220	575	bb	19920101	US	NY
PAL	41.010	73.910	66	bb/sm	19991104	LD	NY
PRNY	42.467	76.536	205	bb	20060330	LD	NY
PTN	44.570	74.982	197	bb	20051028	LD	NY
SDMD	39.410	76.840	213	bb	20011101	LD	MD
UCCT	41.794	72.226	223	bb	20050113	LD	CT
WCCN	41.068	73.791	144	sm	20060518	LD	NY

* 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 (yearmoda)	Network	Location (state)
ARNY	41.303	74.115	430	EHZ	19931216	LD	NY
BGR	44.829	74.374	297	EHZ	19761101	LD	NY
BRCN	44.428	75.583	83	EHZ	19761101	LD	NY
BVD	39.775	75.499	58	EHZ	19850201	LD	DE
BWD	39.800	75.577	63	EHZ	19850201	LD	DE
CHIP	44.798	75.195	97	EHZ	19940701	LD	NY
CRNY	41.312	73.548	293	EHZ	19811201	LD	NY
DEMA	39.319	75.610	12	EHZ	19991001	LD	DE
FINE	44.265	75.167	354	EHZ	19971001	LD	NY
FLET	44.723	72.952	366	EHZ	19770801	LD	VT
GPD	41.018	74.461	360	EH3	19760801	LD	NJ
HBVT	44.362	73.065	342	EHZ	19800901	LD	VT
MANY	41.222	73.869	133	EHZ	19931208	LD	NY
LOZ	44.620	74.580	440	EHZ	19991119	LD	NY
MDV	43.999	73.181	134	EHZ	19700301	LD	VT
MIV	44.075	73.534	317	EHZ	19841001	LD	NY
MSNY	44.998	74.862	55	EHZ	19761101	LD	NY
NED	39.704	75.705	47	EHZ	19721101	LD	DE
PNZ	44.835	73.577	215	EHZ	19961022	LD	NY
POTS	41.41	74.01	248	EH3	20060616	LD	NY
SCOM	38.696	75.363	12	EHZ	19991001	LD	DE
TBR	41.142	74.222	261	EHZ	19750101	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, 2004 through December 1, 2006(c)

Date Year-Mo-Da	Time (hr:mn:ss)	Lat. (°N)	Long. (°W)	h (km)	Mag (Mn)	Location
2004						
2004-07-20	09:13:14.4	32.972	80.248	10	3.1b	32 km NW of Charleston, NC
2004-07-22	13:10:22.0	46.54	75.02	18	3.1n	Felt in Sainte Veronique, QC
2004-07-26	23:11:47.0	49.07	67.48	18	2.7n	25 km N from Matane, QC
2004-08-04	23:55:26.9	43.672	78.232	4	3.8c	30 km S from Port Hope, ON. (PAL)
2004-08-05	00:22:10.0	49.09	67.35	17	3.2n	30 km NE from Matane, QC
2004-08-10	16:24:22.0	49.19	67.11	18	2.5n	33 km W from Cap-Chat, QC
2004-08-17	05:10:52.0	46.99	76.89	16	2.9n	98 km NW from Maniwaki, QC
2004-08-20	14:21:13.0	49.64	66.57	18	2.7n	47 km SE from Port-Cartier, QC
2004-08-28	12:38:37.9	43.157	71.612	5	2.4n	16 km W of Concord, NH (WES)
2004-09-04	02:05:32.0	44.899	74.893	4	2.9c	3 km S of Massena, NY (PAL)
2004-10-08	02:25:46.0	42.52	71.46	1	1.8n	17 km SW of Lowell, MA (WES)
2004-10-14	09:36:02.4	41.394	73.986	8	2.5c	6 km SE of Cornwall, NY (PAL)
2004-11-06	22:44:21.0	42.18	66.14	18	2.6n	Offshore Nova Scotia
2004-12-01	10:55:19.0	47.29	66.32	5	2.5n	65 km SW from Bathurst, NB
2004-12-03	00:06:29.0	45.94	74.88	18	2.8n	29 km NE Saint-Andre-Avellin, QC
2004-12-03	01:27:13.9	37.878	77.963	10	2.5b	48 km E Charlottesville, VA (BLA)
2004-12-05	16:09:55.0	46.94	70.82	18	2.6n	14 km SE from Beaupre, QC
2004-12-12	01:25:38.0	40.746	73.973	5	0.8c	Lower East Side of Manhattan, NYC
2004-12-12	01:26:42.0	40.753	73.961	5	0.6c	Long Island City, Queens, NYC
2004-12-12	01:43:45.0	40.761	73.957	6	0.3c	Long Island City, Queens, NYC
2004-12-15	02:34:50.0	40.754	73.962	4	0.7c	Long Island City, Queens, NYC
2004-12-17	05:30:26.0	39.639	75.414	7	2.0c	17 km SE of Wilmington, DE
2004-12-24	19:30:23.0	46.87	78.82	9	2.8n	30 km NE from Temiscaming, QC
2005						
2005-01-02	15:05:15.0	45.73	75.73	18	2.7n	18 km NE from Wakefield, QC
2005-01-05	15:32:42.0	47.01	66.57	5	3.7n	Miramichi region, NB (OTT)
2005-01-08	20:30:00.0	43.28	71.69	0	1.4n	19 km NW of Concord, NH
2005-01-08	21:11:21.0	47.07	66.68	5	3.0n	Miramichi region, N.B. Aftershock
2005-01-09	13:22:33.0	47.06	66.58	5	2.7n	Miramichi region, N.B. Aftershock
2005-01-13	12:00:58.0	45.58	75.16	18	2.7n	19 km S of Ripon, QUE
2005-02-01	13:01:14.0	41.82	81.11	5	2.5n	Southern Lake Erie
2005-02-14	09:07:25.0	47.10	66.61	5	2.6n	Miramichi region, NB
2005-02-23	14:22:44.1	39.260	76.588	9	2.1c	7 km E of Baltimore, MD (PAL)
2005-02-26	11:12:14.0	46.53	80.99	1	2.9n	Sudbury, ON
2005-03-03	02:22:01.0	45.022	74.190	8	2.9c	21 km NE of Malone, NY
2005-03-06	06:17:49.0	47.75	69.73	15	4.7w	Riviere-du-Loup, QC

continue on next page

Date Year-Mo-Da	Time (hr:mn:ss)	Lat. (°N)	Long. (°W)	h (km)	Mag (Mn)	Location
2005-03-13	17:08:14.0	46.54	80.98	18	3.6n	5 km N of Sudbury, ONT (GSC)
2005-03-28	16:39:38.0	43.33	79.28	5	3.1n	19 km N from St. Catharines, ON
2005-03-31	15:13:08.0	46.28	75.64	18	3.4n	27 km SE from Maniwaki, QC
2005-04-05	22:01:02.0	41.72	70.96	9	2.3n	19 km E of Fall River, MA (WES)
2005-04-08	04:32:38.0	46.27	73.46	18	3.4n	7 km SW Saint-Gabriel, QC
2005-04-10	00:27:06.0	39.84	75.49	5	1.2c	8 km N of Wilmington, DE
2005-04-10	03:06:50.0	43.73	71.15	10	1.5n	35 km NE of Laconia, NH (WES)
2005-04-10	17:37:17.0	49.49	66.59	18	2.9n	40 km N Sainte-Anne-des-Monts, QC
2005-04-15	23:58:42.0	47.33	73.87	18	2.5n	72 km N Saint-Michel-des-Saints,QC
2005-04-17	00:18:38.0	44.83	73.78	18	2.5n	30 km NW of Plattsburgh, NY
2005-04-23	14:24:51.0	40.885	74.069	6	1.9c	1 km E of Lodi, NJ
2005-05-11	02:34:10.4	45.230	69.124	1	2.4n	16 km NE of Dover, ME (WES)
2005-05-25	19:22:13.0	46.27	75.62	18	3.7n	29 km SE from Maniwaki, QC
2005-05-31	13:49:04.0	44.945	74.079	18	2.5c	20 km NE of Malone, NY
2005-05-31	13:49:05.0	44.945	74.079	10	2.5c	20 km NE of Malone, NY
2005-06-05	01:00:29.0	44.880	74.070	8	1.8c	18 km E of Malone, NY
2005-06-06	03:13:46.0	44.118	73.021	13	2.1c	16 km NE of Middlebury, VT
2005-06-12	04:54:10.0	44.991	74.175	12	1.1c	19 km NE of Malone, NY
2005-06-12	22:24:01.0	45.67	73.43	18	2.2n	14 km SW from Vercheres, QC
2005-06-14	04:43:37.0	47.11	76.45	18	2.7n	89 km NW from Ferme-Neuve, QC
2005-06-23	18:16:21.0	46.06	75.05	18	2.5n	35 km SW from Labelle, QC
2005-06-23	18:32:08.0	46.06	75.05	18	2.7n	35 km SW from Labelle, QC
2005-07-01	11:06:26.0	44.509	73.694	7	2.2c	29 km SW of Plattsburgh, NY
2005-07-01	13:05:08.0	46.06	75.06	18	2.7n	35 km SW from Labelle, QC
2005-07-04	11:47:13.0	46.24	76.91	18	3.3n	46 km N from Fort-Coulonge, QC
2005-07-10	04:51:07.0	46.48	81.18	1	3.1n	Sudbury, ON
2005-07-11	22:20:12.0	46.23	74.99	18	2.5n	21 km W from Labelle, QC
2005-07-21	20:10:54.0	47.05	75.77	18	2.6n	46 km NW from Ferme-Neuve, QC
2005-07-23	02:48:16.0	47.04	75.79	18	3.5n	46 km NW from Ferme-Neuve, QC
2005-07-27	11:24:32.0	45.41	73.34	18	2.5n	7 km SW from Chambly, QC
2005-08-02	09:36:56.0	46.63	76.32	18	2.7n	39 km NW from Maniwaki, QC
2005-08-04	23:19:46.0	46.19	75.76	18	2.5n	26 km SE from Maniwaki, QC
2005-08-30	16:03:47.0	45.62	74.80	18	2.7n	9 km W from L'Orignal, ON
2005-09-06	02:58:45.0	45.72	75.36	18	2.5n	16 km N from Buckingham, QC
2005-09-06	14:10:51.0	46.27	75.29	18	3.6n	35 km SE Mont-Laurier, QC
2005-09-19	16:12:12.0	45.10	74.22	18	2.1n	4 km NW from Huntingdon, QC
2005-09-21	03:36:31.0	46.54	80.98	0	2.9n	Felt by many people in Sudbury
2005-09-25	03:08:57.9	45.03	67.28	6	3.4n	11 km S St. Stephen, NB
2005-10-01	07:01:46.0	46.63	76.52	13	3.1n	52 km NW of Maniwaki, QUE

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Date Year-Mo-Da	Time (hr:mn:ss)	Lat. (°N)	Long. (°W)	h (km)	Mag (Mn)	Location
2005-10-12	06:27:32.0	35.61	84.77	8	3.6b	75 km SW of Knoxville, KY
2005-10-15	07:02:14.0	41.14	74.15	8	1.1c	3 km N of Suffern, NY
2005-10-20	21:16:29.0	44.66	80.49	18	3.9n	12 km N of Thornbury, ONT
2005-10-24	01:53:26.0	44.65	74.57	5	1.9c	31 km SW of Malone, NY
2005-10-31	23:59:29.0	43.28	77.32	3	2.6c	12 km NE of Webster, NY
2005-11-01	02:38:17.0	43.39	77.26	0	1.5c	24 km NE of Webster, NY
2005-11-13	11:02:16.0	41.83	81.20	6	2.1c	13 km N of Painesville, OH
2005-11-17	06:24:22.0	44.89	73.92	11	1.5c	30 km E of Malone, NY
2005-11-29	23:24:33.0	45.06	74.18	11	1.4n	22 km S of Valleyfield, QUE
2005-12-09	03:35:46.0	40.97	74.38	5	2.1c	16 km W of Franklin Lakes, NJ
2005-12-09	04:31:28.0	40.97	74.38	5	1.3c	15 km W of Franklin Lakes, NJ
2005-12-11	05:20:02.0	41.95	80.80	10	2.0c	8 km N of Ashtabula, OH
2005-12-12	00:50:22.0	43.62	73.95	10	1.9c	42 km NW of West Glens Falls,
2005-12-18	05:11:39.0	44.86	74.76	7	0.9c	13 km SE of Massena, NY
2005-12-28	18:25:30.0	41.01	74.31	4	1.2c	17 km NW of Fair Lawn, NJ
			2006			
2006-01-06	10:18:14.0	44.91	74.81	8	1.1c	7 km E of Massena, NY
2006-01-09	15:35:40.0	45.03	73.88	13	3.7	32 km SE of Valleyfield, QUE
2006-01-13	15:32:17.0	41.66	81.43	7	2.4c	16 km SW of Painesville, OH
2006-01-31	09:59:32.0	44.99	74.43	8	1.6c	19 km NW of Malone, NY
2006-02-01	07:29:45.0	44.17	74.83	5	1.1c	55 km SE of Canton, NY
2006-02-03	01:02:24.0	44.63	74.79	7	1.6c	16 km E of Potsdam, NY
2006-02-07	04:07:22.0	46.22	75.25	7	2.8n	42 km SE of Mont Laurier, QUE
2006-02-10	13:30:40.0	41.80	81.43	7	2.4c	18 km NW of Painesville, OH
2006-02-16	23:43:22.0	41.16	74.54	8	2.6c	22 km NE of Newton, NJ
2006-02-17	00:00:30.0	41.16	74.56	8	0.9c	20 km NE of Newton, NJ
2006-02-18	03:01:43.0	44.80	74.68	8	1.2c	22 km SE of Massena, NY
2006-02-21	00:31:18.0	41.16	74.55	5	1.3c	20 km NE of Newton, NJ
2006-02-25	01:39:22.0	45.63	75.20	11	4.0	15 km SW of Ripon, QUE
2006-02-26	04:09:22.0	45.53	74.72	14	3.2	11 km SW of Hawkesbury, ONT
2006-03-11	12:27:17.0	41.83	81.45	8	3.0c	21 km NW of Painesville, OH
2006-03-19	06:38:29.0	41.05	73.99	0	1.1c	3 km SE of Pearl River, NY
2006-03-21	11:36:09.0	41.07	73.98	5	1.3c	3 km E of Pearl River, NY
2006-03-27	17:24:31.0	41.79	81.45	8	2.0c	18 km NW of Painesville, OH
2006-04-06	12:03:51.0	43.14	77.72	7	1.8c	9 km W of Rochester, NY
2006-04-07	08:31:41.0	47.38	70.46	25	4.1n	61 km SW of La Malbaie, QUE (GSC)
2006-04-10	05:55:53.0	41.97	80.82	10	2.0c	10 km N of Ashtabula, OH
2006-04-16	17:29:12.0	40.23	75.95	2	1.0c	12 km S of Reading, PA
2006-04-17	01:27:03.0	40.27	76.04	2	1.2c	12 km SW of Reading, PA

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Date Year-Mo-Da	Time (hr:mn:ss)	Lat. (°N)	Long. (°W)	h (km)	Mag (Mn)	Location
2006-05-02	06:57:14.0	44.96	73.80	1	2.3c	40 km NW of Plattsburgh, NY
2006-05-04	08:29:57.0	45.53	73.94	18	1.9n	27 km W of Montreal, QUE (GSC)
2006-05-04	14:50:15.0	43.48	79.71	5	2.7n	34 km SW of Toronto, ONT (GSC)
2006-05-07	03:48:05.0	43.46	79.46	7	2.2	27 km S of Toronto, ONT
2006-05-11	06:35:39.0	46.23	72.71	5	3.0	13 km SW of Trois Rivieres, QU
2006-05-11	06:51:40.0	46.26	72.67	7	1.9	13 km SW of Trois Rivieres, QU
2006-05-15	08:25:26.0	40.86	74.15	8	2.0c	9 km S of Fair Lawn, NJ
2006-05-21	07:16:18.0	46.40	75.28	7	2.8	25 km SE of Mont Laurier, QUE
2006-05-23	04:05:24.0	46.15	74.99	10	2.8	45 km N of Ripon, QUE
2006-05-25	04:31:34.0	44.60	73.68	5	1.6c	21 km SW of Plattsburgh, NY
2006-06-01	06:20:22.0	43.82	77.85	7	2.4c	76 km N of Rochester, NY
2006-06-05	11:18:49.0	45.46	76.00	10	2.5	24 km W of Ottawa, ONT
2006-06-08	01:49:45.0	45.86	74.58	17	2.6	29 km N of Hawkesbury, ONT
2006-06-08	02:13:32.0	45.85	74.58	18	2.1	28 km N of Hawkesbury, ONT
2006-06-13	21:27:04.0	45.98	74.87	12	2.3	32 km NE of Ripon, QUE
2006-06-18	08:01:29.0	45.82	74.98	10	2.1	13 km NE of Ripon, QUE
2006-06-20	20:11:18.0	41.85	81.23	2	3.4c	15 km N of Painesville, OH
2006-07-01	07:37:48.0	45.81	74.79	15	2.2c	20 km NE of Montebello, QUE
2006-07-08	19:38:45.0	44.25	75.46	6	1.9c	45 km SW of Canton, NY
2006-07-14	09:34:48.0	46.88	68.68	14	3.9n	51 km W of Caribou, ME
2006-07-15	08:00:30.0	45.19	75.64	7	1.7	26 km S of Ottawa, ONT
2006-07-15	14:52:37.0	45.91	76.86	11	2.2	86 km SW of Maniwaki, QUE
2006-07-21	16:45:33.0	44.68	75.36	7	1.5c	10 km E of Ogdensburg, NY
2006-07-23	10:38:00.0	45.71	75.25	9	1.8	12 km SW of Ripon, QUE
2006-08-13	20:54:29.0	45.21	73.89	10	1.9	19 km E of Valleyfield, QUE
2006-08-18	02:16:12.0	45.65	73.68	5	1.6	18 km N of Montreal, QUE
2006-08-24	01:34:25.0	45.42	73.88	11	1.9	24 km W of Montreal, QUE
2006-08-26	13:08:44.0	45.62	74.52	11	2.8	14 km W of Lachutte, QUE
2006-08-27	01:27:58.0	44.46	73.63	10	1.3c	30 km SW of Plattsburgh, NY
2006-08-31	14:44:52.0	46.18	75.27	10	2.0	45 km SE of Mont Laurier, QUE
2006-08-31	15:36:09.0	44.51	74.53	9	2.0c	38 km NW of Saranac Lake, NY
2006-09-11	05:53:35.0	45.85	73.52	11	1.9	21 km S of Joliette, QUE
2006-09-12	23:59:19.0	45.01	75.22	6	1.6c	27 km W of Massena, NY
2006-09-15	15:50:06.0	45.80	74.82	7	1.9	18 km NE of Montebello, QUE
2006-09-19	08:00:53.0	44.74	75.30	5	1.3c	16 km E of Ogdensburg, NY
2006-09-22	10:39:22.0	44.43	68.18	11	3.2c	23 km SE of Ellsworth, ME
2006-09-23	03:53:00.0	44.15	75.14	7	2.1c	49 km S of Canton, NY
2006-10-03	00:07:38.0	44.37	68.15	10	4.0w	Bar Harbor, ME
2006-10-08	07:16:56.0	43.87	73.32	7	1.4c	20 km SW of Middlebury, VT

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Date Year-Mo-Da	Time (hr:mn:ss)	Lat. (°N)	Long. (°W)	h (km)	Mag (Mn)	Location
2006-10-10	06:20:28.0	43.89	73.31	8	2.8c	18 km SW of Middlebury, VT
2006-10-11	11:33:09.0	46.13	75.36	7	2.4	46 km NW of Ripon, QUE
2006-10-26	13:03:03.0	43.52	71.60	4	1.9n	11 km W of Laconia, NH
2006-11-02	05:32:35.0	45.41	74.54	7	1.7	23 km S of Hawkesbury, ONT
2006-11-04	11:42:08.0	43.78	77.98	7	2.4c	63 km N of Brockport, NY
2006-11-08	14:23:51.0	43.67	77.79	8	1.7c	52 km N of Greece, NY
2006-11-08	20:29:54.0	45.93	74.82	13	2.0	31 km N of Montebello, QUE
2006-11-10	23:51:37.0	46.17	76.85	7	3.1	71 km W of Maniwaki, QUE
2006-11-19	18:55:11.0	45.90	74.97	7	1.7	21 km NE of Ripon, QUE
2006-11-25	23:10:10.0	46.16	76.02	9	2.2	24 km S of Maniwaki, QUE

* Mag=Magnitude: b = 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; default magnitude is n = Mn, Nuttli's mb(Lg) reported by Geological Survey of Canada, Ottawa or by the Weston Observatory, Boston College, MA.

Table A4. Earthquakes Located near Bar Harbor, Maine since 22 Sept. 2006*

Date Year/Mo/Dy	Time (UTC) (hr:mn:s)	Lat (°N)	Long (°W)	h (km)	Mag (Mn)	
2006/09/22	00:04:21	44.34	68.17	5.0	1.8	Foreshock
2006/09/22	08:24:17	44.34	68.16	5.0	2.4	Foreshock
2006/09/22	09:21:05	44.35	68.16	5.0	2.4	Foreshock
2006/09/22	10:12:57	44.36	68.15	5.0	2.2	Foreshock
2006/09/22	10:39:21	44.35	68.19	5.0	3.4	Second largest shock (WES)
2006/09/22	11:03:57	44.31	68.15	5.0	2.1	Aftershock
2006/09/22	11:50:18	44.31	68.15	5.0	2.4	Aftershock
2006/09/22	12:45:20	44.43	68.14	5.0	2.0	Aftershock
2006/09/22	13:25:08	44.32	68.14	5.0	2.5	Aftershock
2006/09/23	01:21:23	44.34	68.11	5.0	1.9	Aftershock
2006/09/23	01:33:07	44.35	68.15	5.0	2.1	Aftershock
2006/09/26	02:48:16	44.31	68.15	5.0	1.9	Aftershock
2006/09/26	04:46:46	44.33	68.14	5.0	1.6	Aftershock
2006/09/28	13:52:47	44.36	68.17	5.0	2.6	Aftershock
2006/09/28	13:58:59	44.35	68.16	5.0	2.2	Aftershock
2006/10/03	00:07:37	44.33	68.17	5.0	4.2	Mainshock (Mw 4.0 LCSN)
after deployment of the local seismographic network						
2006/10/15	04:25:35	44.20	68.19	5.0	2.0	aftershock
2006/10/17	05:39:03	44.33	68.16	5.0	1.8	aftershock
2006/10/22	18:34:31	44.35	68.17	5.0	2.2	aftershock
2006/10/22	21:36:26	44.34	68.14	5.0	2.9	aftershock (NEIC)
2006/10/22	22:49:40	44.35	68.16	5.0	2.1	aftershock

* Time=origin time of the events given in UTC (Universal Coordinated Time), which is four hours ahead of EDT (Eastern Daylight Savings Time). The origin time in EDT is UTC-4 hours, hence the largest event on 10/03/2006 at 00h 07m 37s is 10/02/2006 20h 07m 37s (EDT); Mag (Mn)=Nuttli's (1973) magnitude scale, which is about 0.1 magnitude units greater than M_L Richters local magnitude; event locations are either given by GSC (Geological Survery of Canada, Ottawa) or WES (Weston Observatory, Boston College).