THE NEW ENGLAND SEISMIC NETWORK

Award Number 04HQAG0020

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Abstract

From February 1, 2004 to December 30, 2006 Weston Observatory continued to operate a 12-station regional seismic network to monitor earthquake activity in New England (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) and vicinity. The purpose of this monitoring is to compile a complete database of earthquake activity in New England to as low a magnitude as possible in order to understand the causes of the earthquakes in the region, to assess the potential for future damaging earthquakes, and to better constrain the patterns of strong ground motions from earthquakes in the region. The NESN coordinates earthquake monitoring in the northeastern U.S. (NEUS) with the Lamont Cooperative Seismic Network (LCSN) of Lamont-Doherty Earth Observatory as part of the Advanced National Seismic Network (ANSS) northeast center for earthquake monitoring (ANSS-NE). It also coordinates its activities with the National Earthquake Information Center (NEIC) of the US Geological Survey in Golden, CO and with the Earthquakes Canada group of the Geological Survey of Canada (GSC) in Ottawa, Ontario.

At all of the Weston Observatory stations the sensors were CMG-40T feedback geophones with a flat response to ground velocity between roughly 30 Hz and 30 sec. Initially, seven of the stations had Nanometrics, Inc. 16-bit digitizers with gain-ranging, digitized at a rate of 100 samples per second per channel, while five of the stations had Reftek, Inc. 130-01 broadband 24-bit digitizers sampled at 40 samples/second. Telemetry from five of the Nanometrics stations was by internet communications via Earthworm, while from the other two Nanometrics stations the telemetry was via dial-up telephone connection. Telemetry from the Reftek stations was by internet communications via Earthworm. In 2005 the digitizers at the five internet Nanometrics stations were replaced with Reftek 130-10 digitizers using internet communications into the Earthworm system. Event detection at all stations is carried out using a wavelet-transform (WT) based automated event detector and identifier. This system was developed for the Earthworm datastream and was operational throughout the course of this reporting period. It has been tuned so that it successfully detects and identifies many quarry blasts, most teleseisms, and many local earthquakes.

There were 124 local and regional earthquakes with magnitudes from -0.2 to 5.3 that were detected and located by the NESN stations from February 1, 2004 to December 21, 2006, along with many microearthquakes and some other signals that were possible earthquakes. The largest recorded earthquake from the northeastern U.S. was an MLg 4.2 earthquake on October 2, 2006 that caused some rockfalls in Acadia National Park in Maine near the epicenter and was felt throughout almost all of the state of Maine. There were 79 earthquakes centered in (or offshore of) New England proper. From 2004 to 2006 the earthquake activity in New England at had a lower b value than that from 1975-1986 and from 1938-1986. The lower b value for recent earthquakes might mean that New England should expect an increase in the number of stronger earthquakes during the next few years.

Investigations

Weston Observatory continued to operate its regional seismic network from February 1, 2004 through December 2006 to monitor earthquake activity in New England (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) and vicinity. The purpose of this monitoring is to compile a complete database of earthquake activity in New England to as low a magnitude as possible in order to understand the causes of the earthquakes in the region, to assess the potential for future damaging earthquakes, and to better constrain the patterns of strong ground motions from earthquakes in the region. The New England Seismic Network (NESN) is operated by Weston Observatory of Boston College. The NESN also coordinates earthquake monitoring in the northeastern U.S. (NEUS) with the Lamont Cooperative Seismic Network (LCSN) of Lamont-Doherty Earth Observatory (LDEO) as part of the Advanced National Seismic Network (ANSS) northeast center for earthquake monitoring (ANSS-NE). It also coordinates its activities with the National Earthquake Information Center (NEIC) of the US Geological Survey in Golden, CO and with the Earthquakes Canada group of the Geological Survey of Canada (GSC) in Ottawa, Ontario who operate the Canadian National Seismic Network (CNSN).

Network History through the Report Period

At the beginning of the period of this report (February 2004) Weston Observatory had 12 seismic stations in New England comprising its NESN. At that time, each of the NESN stations was comprised of one of two different types of seismic instrumentation. Five of the stations (BRY, FFD, HNH, QUA2 and WES) had new RefTek 130-01 dataloggers from Refraction Technology, Inc. for digitizing and transmitting the seismic data at the remote stations. These systems, which were installed in September 2003, use 24-bit digitization and RTP to USGS for data transmission. The sensors, which had been installed previously, were CMG-40T feedback geophones with a flat response to ground velocity between roughly 30 Hz and 30 sec. The digitization rate at these sites is 40 samples/second. Six of the other NESN sites were using older PC-based data logging systems with on-site recording, three-component broadband sensors, and dial-up telephone telemetry or direct internet links to the central station at Weston Observatory. The sensors at these sites were also CMG-40T feedback geophones. The digitizers were Nanometrics 16-bit digitizers with gain-ranging, yielding effectively 136 db dynamic range. The sensor signals were being digitized at a rate of 100 samples per second per channel. One station (TRY at Troy, NY) was not operational at the beginning of this reporting period as it awaited new station equipment.

While the number and locations of the NESN seismic stations did not change during the period of this report, there were changes in the equipment at a number of the stations. During the late summer of 2005, five NESN stations (EMMW, PQI, TRY, WVL, and YLE) were upgraded with RefTek 130-01 units, making the NESN almost completely uniform in instrumentation. This is important as it greatly eases management and debugging problems for an already stretched network staff, and also because it makes it much easier to provide metadata (e.g., instrument response information) to others who use the NESN data, since instrument response is now identical across almost all stations of the NESN. Of the remaining two stations, VT1 continues to operate with the older Nanometrics equipment. Because this site is very noisy, it must be moved before it can be upgraded with a Reftek digitizer. The station at Boston College (BCX) is also awaiting the purchase and installation of a Reftek digitizer to replace its older Nanometrics equipment.

Weston Observatory has been exploring the possibility of installing several new NESN stations in New England to improve the monitoring of the earthquake activity in the region. We have already had contact and discussions for the installation of three new stations in Maine (at the U. of Maine at Orono, the U. of Maine at Farmington, and at the U. of Southern Maine in Gorham) and two new stations in New Hampshire (at the U. of New Hampshire in Durham and at Keene State College). We are seeking a site near Burlington, VT to replace the noisy VT1 site. We are also seeking a site for a station in northeastern Vermont. The stations in Maine would increase the station density in that poorly instrumented part of New England, while the stations in New Hampshire and Vermont are designed to improve the network coverage around the active seismic zones in southern and western New England. Figure 1 shows the configuration of the NESN, the locations of the proposed new seismic stations, and the locations of some other seismic stations that are operating in the region.

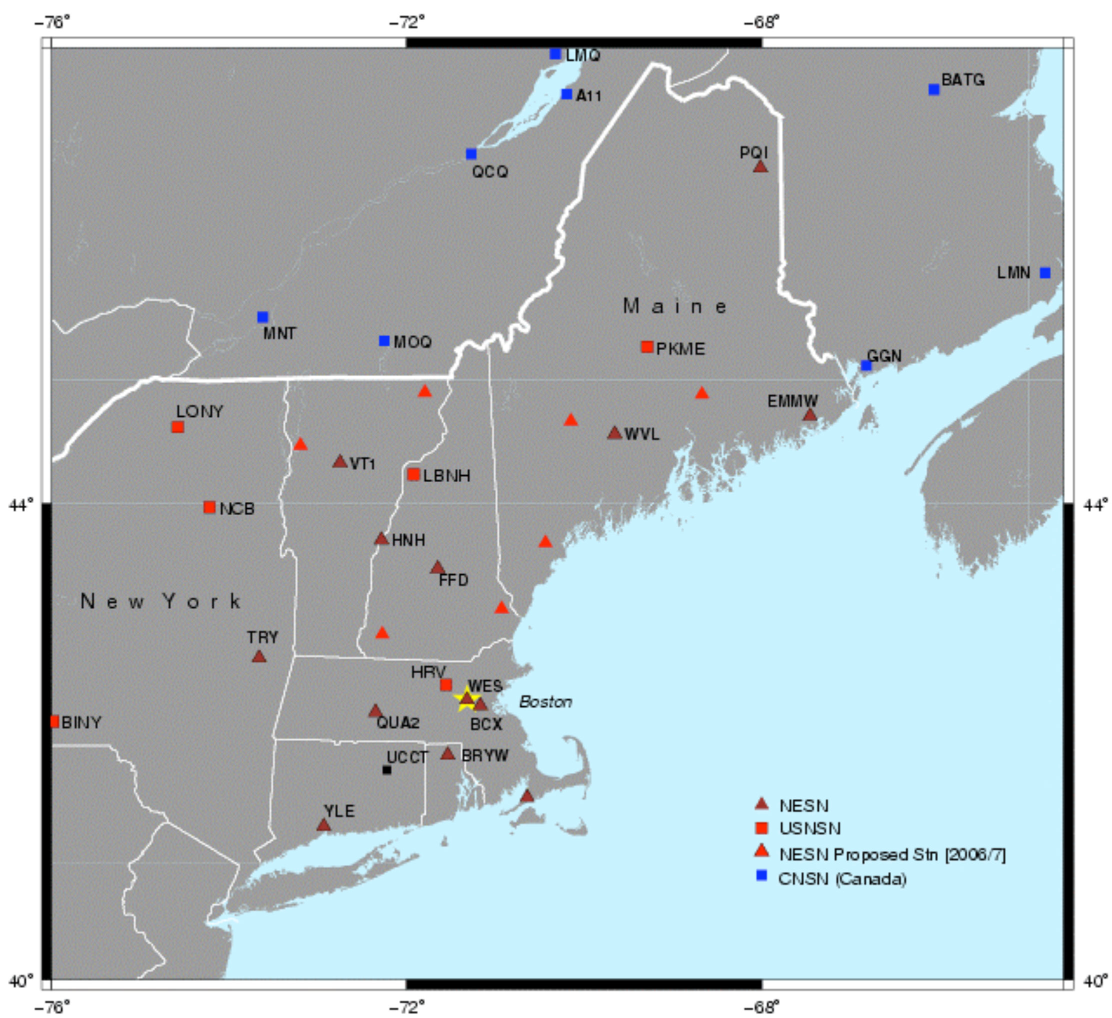


Figure 1. Locations of seismic stations in New England and vicinity as of December 2006.

There was one important personnel change in the team operating the NESN during this reporting period. Ned Johnson retired at the project engineer during the summer of 2004, and Dr. Michael Hagerty was hired in January 2005 to replace him. Mike has prior experience with the hardware used by the NESN, web page creation abilities, a thorough understanding of the analysis of seismic data, and the ability to find solutions to the sometimes very challenging problems of associated with running a modern digital seismic network with internet communications. His efforts have contributed greatly to the data quality and reliability of the NESN. Stacy Macherides-Moulis has continued on a part-time basis to analyze, document and archive the NESN data. Dr. John Ebel, the PI on this project, continues to oversee the operation of the network, assist with the creation of data analysis tools, and carry out research on the data collected.

Data Telemetry and Sharing

With the exception of station VT1, data telemetry from the NESN seismic stations is through continuous internet connections from the remote station sites to Weston Observatory, from which the data are then sent to other cooperating organizations. From the seismic stations with the Reftek dataloggers, Earthworm data packets currently are sent to an RTPD server which then sends the data to an Earthworm server, both of which are at Weston Observatory. The data from these stations are transmitted via internet connection from the Earthworm server to the USGS NEIC in Golden, Colorado, to LDEO in New York for use with the LCSN data, and to the GSC in Ottawa, Canada for incorporation with the CNSN data. In return, Weston Observatory receives seismic data from in Earthworm format via the internet from the USNSN stations in New England and New York, from some LCSN stations in eastern New York and Vermont, and from some CNSN stations that surround New England. Data from all of the stations shown in Figure 1 were being received by the Weston Observatory Earthworm server as of December 2006.

Web pages of the seismic data from the NESN stations are posted for viewing at http://quake.bc.edu:8000/. This NESN web site has lists and maps of the current NESN stations, and it also has pages that display NESN station waveforms. The NESN waveforms can be displayed in their raw broadband form, or they can be filtered (high-pass to look for local events or low-pass to look at teleseismic waveforms). Waveforms from the USNSN stations being received at Weston Observatory can also be viewed at http://quake.bc.edu:8000/ using the same display software.

NESN Automated and Manual Data Processing

The seismic data from the NESN stations along with the contributed LCSN, CNSN and USNSN stations are processed both automatically in near-realtime and later by hand at Weston Observatory. Weston Observatory operates an automated system written by John Ebel to accurately detect, identify, locate and compute magnitudes for all seismic events contained in the Earthworm data streams that are coming into Weston Observatory (Ebel, 2006a). This automated system was developed because none of the existing software packages for realtime event detection and analysis was capable of handling the unique aspects of earthquake monitoring faced by the NESN in New England: a sparse, widespread seismic network; earthquakes scattered throughout the region with no one area of focus; sites with frequent transient noise bursts (due to vehicles, footsteps, etc.); and the necessity to pick arrival times from emergent body-wave phases in order to accumulate sufficient arrivals times for constrained earthquake locations.

The system that has been developed and now operates at Weston Observatory for the NESN is an expansion and improvement of the wavelet-transform (WT) event detector and identifier that was developed by Gendron et al. (2000) for computing event locations and magnitudes for sparse networks like the NESN (Figure 2). Every three minutes the automated system computes a discrete WT to 8 scales using the latest data for each station received at Weston Observatory. For each station, the software then checks to see if the WT coefficient values have increased, indicating a possible seismic event. If a possible event is detected, the system measures and records several parameters for the detection: the time, scale and energy of the beginning of the event detection, the time scale and energy of the point where the highest energy was found during the time the event detection threshold was exceeded, and the time of the end of the event when the WT coefficients at all 8 scales has dropped back below the event detection threshold. After the seven parameters have been measured for a station detection, the software uses a Bayesian scheme to calculate the probability that the detection was a teleseism, a regional earthquake, a local earthquake, a quarry blast, the Rg wave only from a quarry blast (a common detection in New England), or transient noise at the station. Finally, for possible local and regional earthquakes, the time difference between the time of the peak energy (assumed to be the Lg wave) and the begin energy (assumed to be the first P arrival) is used to estimate the distance of the station to the epicenter as well as the origin time of the event. This information is combined with the energy of the peak arrival to estimate the Lg magnitude of the event and with the end time of the detection to estimate the coda wave magnitude of the event. The event detection parameters, event identification probabilities, and event source parameters for each detection are then written to a daily event detection file.

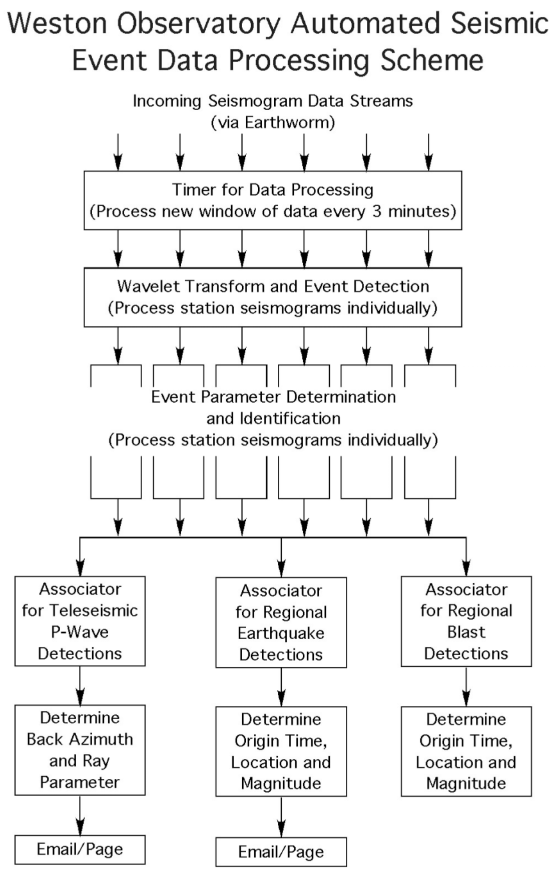


Figure 2. Flowchart of the automated data processing scheme at Weston Observatory.

Once the single-station event parameters and event identification probabilities have been determined, this information is then sent through a bank of three different event associators. One event associator has two parts that together attempt to associate detections for regional and local earthquakes. First, the single-station origin time determinations for event detections with at least a 30% probability of being a local or regional earthquake are associated. Those detections from different stations that have single-station origin times that are close in time (within a few seconds) are associated. Second, if a single-station event detection has at least a 30% probability of being a local or regional earthquake, then the peak arrival times (assumed to be the Lg wave) for other station detections are checked to see if they fall within the expected Lg arrival time window for a local earthquake. If so, these stations are associated as Lg-only detections. This second method associates Lg arrival times for stations at large distances from the epicenter where the detector missed the P wave. A simple earthquake location scheme solves for origin time and epicenter only, since focal depth is not a parameter with this methodology. The event Lg and coda magnitudes are also computed using the peak energies and event durations at the individual stations. As soon as a local event location and magnitude have been determined, the event source information is sent via e-mail and text message to the Weston Observatory staff. Typically for small local earthquakes (less than magnitude 4.0), this information is sent out within 3-7 minutes of the earthquake. The goal of the location program is to get an immediate location that is good to within about 30 km of the true epicenter. From experience this expectation is usually met and is often greatly exceeded. The event magnitudes determined automatically seem to be particularly robust, usually differing by no more than about .2-.3 magnitude units from the final reviewed magnitude determinations.

Another event associator tries to associate detections of the waveforms from quarry and construction blasts. This associator works in an identical manner to the associator for local and regional earthquakes, except that it assumes that the peak energy is in the Rg wave rather than the Lg wave. The event locator also uses the same algorithm as that for local and regional earthquakes. Because local quarry blasts are almost invariably small, they seldom are detected on enough stations for a location to be attempted.

A third associator is a teleseismic P wave associator. A maximum time window for associating teleseismic P waves is predetermined based on the size of the network. If 3 or more detections with at least a 30% chance of being a teleseismic P wave associate, then a plane wave is fit to the arrival times and the back azimuth and ray parameter of the associated arrival times are computed. These are then used to estimate the latitude and longitude of the teleseismic source location, while the beginning energy of the detection is used to estimate the m_b of the teleseismic detection. The teleseismic source information is then e-mailed and sent via text message (within a few minutes of the detection) to the Weston Observatory staff.

While the automated system has become increasingly dependable at detecting local and regional earthquakes along with teleseisms, its performance must be checked regularly by a seismologist. Every few days, the analyst visually checks the station waveforms at times where suspected local earthquakes, regional earthquakes, and quarry blasts were indicated by the automated system. When local or regional earthquakes are verified or suspected, the analyst manually filters the station waveforms and picks the P and S arrivals as well as Lg wave-amplitudes and periods and coda wave durations for location and magnitude determinations. Arrival times from LCSN and CNSN stations are obtained as needed. Final event locations are computed by the seismic analyst using the HYPO78 software. Event Lg magnitudes are determined using the formula of Ebel (1994), while estimates of the event moment magnitudes are computed using the coda-wave amplitude method of Biswas and Aki (1984) as calibrated by Macherides (2002). If the event is centered in Canada or west of New England, the Weston Observatory analyst promptly sends the NESN arrival time and amplitude readings to the LCSN and/or CNSN seismologists.

For all local earthquakes, information on the time, location and magnitude of the events are posted on the Weston Observatory web site (http://www.bc.edu/westonobservatory). Persons who felt an earthquake can follow a link from the Weston Observatory web site to the USGS "Did You Feel It?" web site. Following the end of each calendar quarter, a quarterly bulletin of the seismicity recorded in the region for that quarter is posted on the Weston Observatory web site. Also posted on the Weston Observatory web site is a link to the weekly felt earthquake probabilities for the next 7 days. These earthquake forecast probabilities are based on the discovery of a non-Poissonian component of the seismicity in the New England region by Ebel and Kafka (2002), who showed that felt earthquakes in New England are more clustered in time over a time period of a week or so than expected from Poissonian seismicity, even when aftershocks are removed from the earthquake catalog.

Data Analysis

The implementation and refinement of the automated event detection, identification, association and event location/magnitude determination system has made an enormous improvement in ability of one part-time seismic analyst to accurately and efficiently cull earthquakes, quarry blasts and other events of interest from the continuous incoming data streams from the remote seismic stations. When installed in the 1990s, the NESN stations were located at sites such as the basements of university buildings where frequent noise bursts can be a problem. Due to a very limited budget for earthquake monitoring in New England, the sites were selected for their free internet access, security of the station equipment, stability of ownership, and absence of site rental fees. Unfortunately they suffer from frequent false triggers due to human activity. In order to try to detect as many earthquakes as possible, it was decided to keep the event detection thresholds low and risk many noise detections, but then to use the WT event detection and identification system to screen the noise detections from those that are more likely to be real seismic events like earthquakes and quarry blasts. Table 1 shows the total number of event detections for all of the stations received via Earthworm at Weston Observatory for four sample days (2 in winter and 2 in summer) in 2006. In addition, the total number of these detections that were visually scanned by the seismic analyst to see if they were a real seismic event (teleseism, local or regional earthquake, or quarry blast) and the total number of real seismic events that were verified by the analyst are listed. Even though there are as many as 2000 or more automatic event detections every day from the station data received by Weston Observatory, Table 1 indicates that no more than about 4% of these daily event detections at individual stations need to be examined by the seismic analyst. Furthermore, from this relatively small subset of detections that are visually checked, a number of real events (teleseisms, regional earthquakes, local earthquakes or quarry blasts) are regularly found. Spot checking of other detections that have a very high noise probability invariably shows that they are indeed detections of transient noise bursts. This indicates that the automated system appears to be quite robust at identifying noise detections and at successfully discriminating those detections that have a higher likelihood of being a real seismic event. Table 2 summarizes the total number of seismic events detected by the NESN and supplementary stations received via Earthworm at Weston Observatory during the first 7 months of 2006. For example, from Table 2 it can be seen that during the summer the New England region averages 8-10 quarry blasts per day that must be examined and discriminated from earthquake waveforms by a seismic analyst.

Another benefit of the improved system to automatically detect, identify and locate seismic events is that the number of small earthquakes found during the routine NESN data analysis described in the previous paragraphs has significantly increased during the past few years. The automated WT event detection and identification system began running routinely in the summer of 2003, was improved in the summer of 2004, and was further improved in the summer of 2005. Table 3 shows the number of earthquakes with epicenters within New England that have been detected annually from 10/1/2001 through 9/30/2006. The number of events for the time period from 10/1/2005 to 9/30/2006 is much higher than for the other years due to a very active foreshock and aftershock sequence that took place at Bar Harbor, ME in September 2006. From Table 3 it is quite clear that the number of small earthquakes (magnitudes less than 2.0) that are detected and located has greatly increased during the past 2 or so years. On the other hand, the number of earthquakes above magnitude 2.0 centered in New England has not changed significantly during the past few years. Taken together, the observations in Table 3 strongly support the contention that the recent increase in the number of detected events, especially earthquakes below magnitude 2.0 that are not felt, is due to the improved automatic event detection and identification system at Weston Observatory. Furthermore, this improvement in earthquake monitoring capabilities demonstrated in Tables 1, 2 and 3 has been achieved without any increase in the workload of the part-time seismic analyst.

Table 1
Examples of Automatic and Analyst Verified Seismic Event Detections by Weston Observatory

Day	**2/17/2006**	**2/22/2006**	**8/4/2006**	**8/5/2006**
Total # of Automatic Event Detections at all Stations	1392	1740	2175	1687
Total # of Detections Visually Analyzed by a Seismologist	20	37	81	36
# of Quarry Blasts Identified	6	5	23	0
# of Local and Regional Earthquakes Identified	0	0	0	1
# of Teleseisms Identified	0	1	1	1

Table 2
Monthly Number of Detected Seismic Events by Weston Observatory During 2006

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**
# Quarry Blasts	15	68	161	194	245	281	298
# Local Earthquakes	3	0	1	2	2	2	1
# Regional Earthquakes	1	4	0	1	5	2	1
# Teleseisms	8	7	19	25	41	27	111

Table 3
Number of Earthquakes Centered in New England Detected by Weston Observatory from October 1, 2001 to September 30, 2006

Year	**Total # Earthquakes**	**# M >= 2.0 Earthquakes**	**# M < 2.0 Earthquakes**	**# Earthquakes Not Felt**
10/1/05-9/30/06	43	8	35	12*
10/1/04-9/30/05	15	5	10	8
10/1/03-9/30/04	7	5	2	2
10/1/02-9/30/03	9	7	2	0
10/1/01-9/30/02	17	12	5	0

* Does not include the small earthquakes detected in September 2006 from Bar Harbor, ME since it not known how many of those events were felt and how many were not felt.

NESN Data Archiving and Seismic Information Exchange

As mentioned earlier in this report, seismic data from the NESN stations currently are transmitted continuously from the remote stations via the internet and into an Earthworm data server at Weston Observatory. The Earthworm echoes the NESN station data to the USGS NEIC, to LDEO for incorporation with its LCSN data, and to the GSC for incorporation with its CNSN data. In return, data streams from several LCSN and CNSN stations are sent to Weston Observatory for incorporation with the NESN data. Prior to the establishment of the Earthworm data server at Weston Observatory in 2005, the Earthworm data from the NESN stations was transmitted directly to the NEIC, from which it was echoed back to Weston Observatory and to other users. Arrival time readings from VT1, the one NESN station that is not transmitting data via Earthworm, are sent manually to LDEO and the GSC as needed. Weston Observatory also provides all of its arrival time, amplitude and period readings to LDEO and the Canadian Geological Survey as requested for earthquakes both inside and outside New England.

Weston Observatory maintains a back-up archive of the waveforms of all seismic events that are detected on the NESN and other stations that it monitors. For the time period from 1994 to 2003 (before the Reftek dataloggers were installed and the Earthworm data streams came online at Weston Observatory), the data from the NESN sites were saved in Nanometrics Y-file format, which had been created by the Nanometrics digitizers. Since 2003, station data that have been received at Weston Observatory via Earthworm have been stored in SAC format in the archive, and since 2005 Weston Observatory has maintained an archive of all continuous NESN waveform data. Weston Observatory waves waveforms for all teleseisms, local and regional earthquakes, quarry blasts, and other special events that were detected. During the 1990s and into the early 2000s, the complete waveforms for local and regional earthquakes as well as quarry blasts were saved, but only the first few minutes of the P wave arrival of teleseisms were saved due to the difficulty of downloading large amounts of data from the remote stations accessed via dial-up telephone telemetry. With the advent of continuous data transmission to Weston Observatory via the internet using Earthworm, it is significantly easier to extract large time segments of station waveform data into a data file for archival purposes, and much longer stretches of teleseismic data are now being saved in the Weston Observatory waveform archive from its seismic network stations.

Weston Observatory makes public all of its processed earthquake information for New England in several ways. Since 1994 Weston Observatory has had a memorandum of understanding (MOU) with the Massachusetts Emergency Management Agency (MEMA) concerning all felt earthquakes in the New England region. According to the MOU, whenever a felt earthquake is reported to the authorities of any New England state, that information is relayed to MEMA. MEMA is charged with contacting a seismologist at Weston Observatory, who then verifies or denies the occurrence of an earthquake. If an earthquake has occurred, a seismic analyst from Weston Observatory then manually determines the origin time, location and magnitude of the earthquake and immediately telephones that information to MEMA. MEMA in turn then sends that information to a distribution list of emergency management agencies and other important government agencies in all of the New England states. Weston Observatory also immediately transmits its earthquake source information to the USGS NEIC (via email or telephone) and publishes the source information on the Weston Observatory web page http://www.bc.edu/westonobservatory.

Within a month or so after the end of each calendar quarter, Weston Observatory publishes all of its earthquake locations, phase readings, and amplitude information in quarterly seismicity reports via the Weston Observatory web page. These quarterly reports of seismicity contain the final, fully reviewed event locations and magnitudes for all earthquakes in New England and vicinity, and they also contain the Weston Observatory phase and amplitude readings for regional earthquakes that were centered outside of New England. Each quarterly report includes a map of the local and regional seismicity detected during that quarter from New England and vicinity. In addition, the report contains a map that shows the instrumentally located earthquakes over the past 30 or so years. Annual summaries of the seismic activity detected by the NESN have been submitted to the USGS by Weston Observatory and are posted on the USGS web site http://erp-web.er.usgs.gov/ under the link Reports.

A major effort during the past three years has been a project to archive at the IRIS DMC the NESN waveform data recorded with the Nanometrics dataloggers. This has proven to be unexpectedly challenging. Nanometrics, Inc. had provided Weston Observatory a software program to convert seismic waveforms from their own Y-file format to SEED format. While the program does create SEED format files, checks by the IRIS DMC indicated several problems with the SEED headers that did not pass the quality control checks at the DMC. In particular, there is an ambiguity in the reported response parameters for the CMG-40T sensors that are used at the NESN stations. Weston Observatory has been working with Guralp Systems, Nanometrics and the IRIS DMC to resolve this parameter ambiguity before it begins to download its archived data to the DMC. Once a solution to this instrument response problem has been implemented, Weston Observatory will transmit SEED volumes of its archived data to the IRIS DMC.

The deployment of the Reftek dataloggers has required Weston Observatory to determine the instrument response of these dataloggers in combination with the CMG-40T sensors that Weston Observatory operates at its NESN stations. This instrument response has been determined, and Weston Observatory is prepared to create dataless SEED headers for the NESN stations with the Reftek dataloggers. The parameter ambiguity described in the previous paragraph regarding the CMG-40T sensor response also plagues the dataless SEED headers that we need to generate for the NESN stations with the Reftek dataloggers. Once this problem is resolved, Weston Observatory will submit our dataless SEED headers for the Reftek stations to the IRIS DMC. Immediately following this step, Weston Observatory will begin submitting continuous NESN data to the IRIS DMC via the internet using Earthworm for a full archiving of all NESN data.

Seismicity

Figure 3 shows the epicenters of local and regional earthquakes recorded by Weston Observatory from February 1, 2004 to December 1, 2006. A total of 124 local and regional earthquakes with magnitudes from -0.2 to 5.3 were detected and located by the NESN stations, some of which were felt by those living near the epicenters. Also recorded throughout the time period of this report were some microearthquakes or other events that were possible earthquakes but with insufficient data to compute a location. Of the seismicity shown in Figure 3, there were 79 earthquakes centered in (or offshore of) New England. The largest earthquake in New England during this time period was MLg 4.2 centered near Bar Harbor, ME on October 3, 2006.

An important sequence of earthquakes took place near Bar Harbor, ME starting on September 22, 2003. On this day there was an MLg 3.4 earthquake that was preceded by 5 foreshocks and followed by 11 aftershocks. Many of the foreshocks and aftershocks were reported felt by the residents of the town of Bar Harbor. The aftershocks occurred sporadically during the following days. Then on October 3 an MLg 4.2 earthquake took place in this same area. This earthquake caused a number of rock falls in Acadia National Park, forcing the closure of a number of hiking trails. It was felt throughout most of the state of Maine and into eastern New Hampshire. Following this earthquake, the USGS in Maine reported that the groundwater in a bedrock well that was being monitored started dropping, and after a few days the water level settled about 2 m lower than the water level before the earthquake. Aftershocks continued into November and December, with a total of 37 earthquakes having been recorded by December 21, 2006. Besides the MLg 4.2 and 3.4 earthquakes, there were 6 events with MLg between 2.0 and 2.9. Seismograms from all of the earthquakes from the Bar Harbor area have very strong Rg waves, suggesting that the focal depth of the earthquakes was no more than about 4 km. From reports by residents in the area, it appears that events down to about MLg 1.0 were heard or felt. Analysis of the data from this set of earthquakes continues at the time of this report. Almost no previous earthquake activity is known from within about 20 km of Bar Harbor, and the cause of this spate of earthquakes is not clear. No fault is mapped in the epicentral area, so the relationship of these earthquakes with the local geology is not understood at present.

Another interesting earthquake occurred about 60 km northwest of Presque Isle, ME on July 14, 2006. It took place in a sparsely populated area, and it was felt at a number of communities in northern Maine. At the time of its occurrence, this earthquake was the largest earthquake centered in New England since 1994. No aftershocks were observed from this event, although the sparse station spacing in this region and the lack of a seismic station close to the earthquake epicenter means that small aftershocks would probably have been missed by the current event detection system. This earthquake took place in an area of rather diffuse past seismicity that spreads across northern Maine.

Besides the earthquakes just discussed, much of the earthquake activity that took place in New England and nearby regions during this reporting period was centered in areas where past seismicity has been regularly recorded. In Figure 3, earthquake activity in central Maine near Dover-Foxcroft, around Concord, NH, and northwest of Boston, MA was located in areas where seismicity has been recorded regularly in the past. For example, small felt earthquakes take place near Littleton, MA, a suburb northwest of Boston, on average about once every 2 ½ years. An MLg 2.0 earthquake was felt at Littleton on October 8, 2004, and it was followed by a few small aftershocks. Previously, an MLg 1.4 earthquake had been felt at Littleton on June 8, 2000.

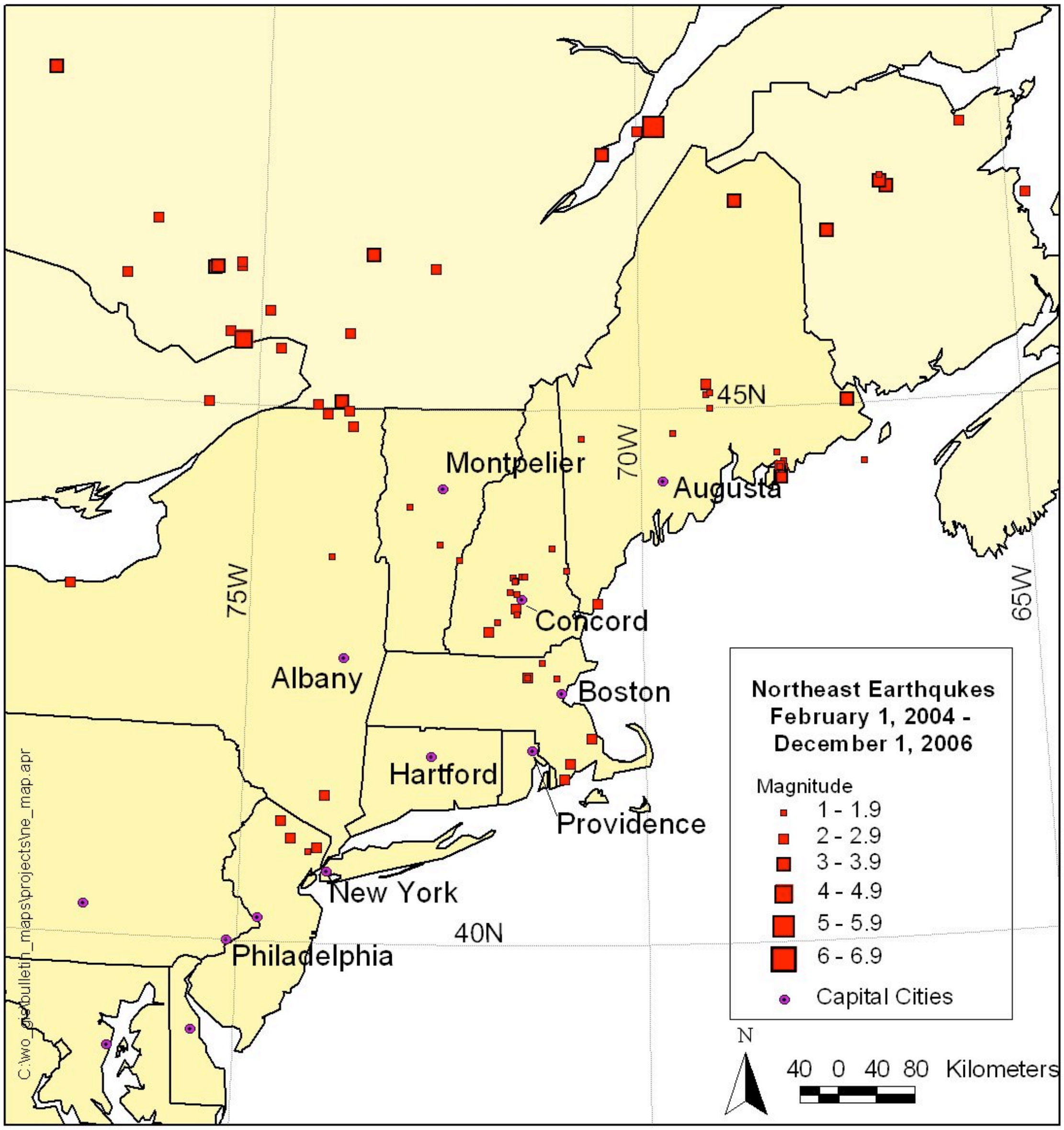


Figure 3. Seismicity of New England and vicinity from February 1, 2004 to December 1, 2006 as recorded by the seismic stations of Weston Observatory of Boston College.

Discussion

If the foreshocks and aftershocks at Bar Harbor, ME in 2006 are ignored, the rate of seismicity during this reporting period was quite comparable to that of the prior three-year period of network monitoring. Since the late 1990s the rate of earthquake activity in New England has been significantly lower than it was during the late 1970s and early 1980s, a time period when several earthquakes above magnitude 4.0 affected the region. According to Ebel (1984), from 1975 to 1982 New England averaged about 15 earthquakes per year of M≥2 and about 2 earthquakes per year of M≥3. For the three-year time period of this report, there were 14 earthquakes of M≥2 (annualized to about 5 per year) and 4 earthquakes of M≥3 (annualized to about 1 per year). Thus, since 2004 the annual rate of earthquake activity in New England was only about 33% to 50% of that from 1975 to 1982.

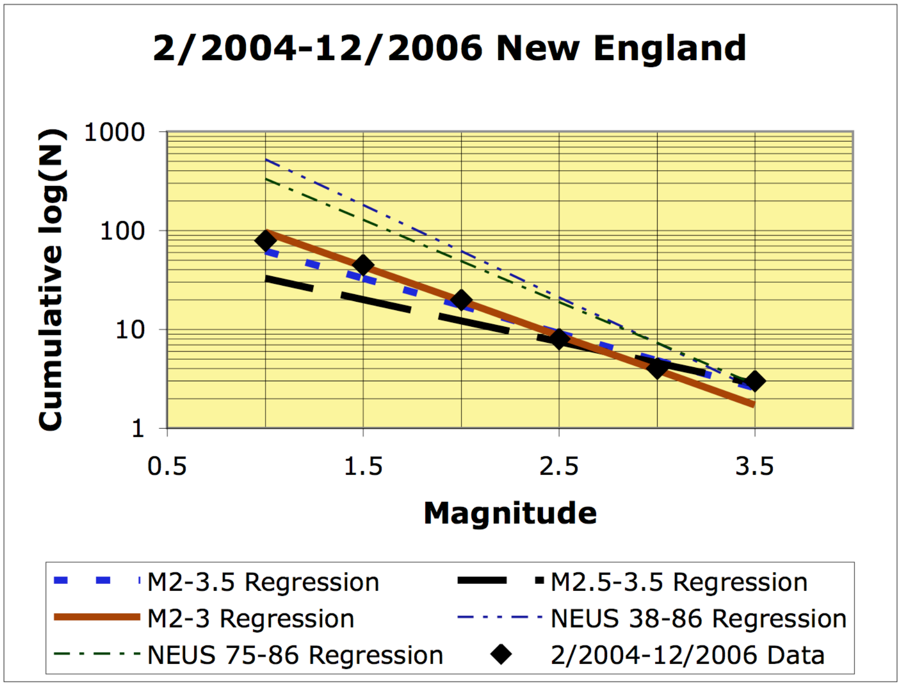
Figure 4 illustrates this lower rate of earthquake activity from 2004 to 2006 compared to that from earlier time periods. Shown in Figure 4 is the cumulative number of earthquakes for the time period from February 1, 2004 to December 21, 2006 along with three regressions of the data points (using the data points from M2 to M3.5, using the data points from M2.5 to M3.5, and using the data points from M2 to M3). Also shown in Figure 4 are two recurrence curves from Ebel (1987) computed for the New England region for a 35-month time period. These recurrence curves are based on data from the northeastern U.S. (NEUS) from 1938 to 1986 and from 1975 to 1986. Figure 4 shows the recurrence lines for the 2004-2006 data, both including and excluding the foreshocks and aftershocks that occurred at Bar Harbor, ME. What is immediately striking about the recurrence lines in Figure 4 is the large difference in b value between the 2004-2006 data and the recurrence lines for the earlier time periods. In Figure 4, the b values of the three recurrence lines computed from the 2004-2006 data range from .30 to .54, while the b values for the 1975-1986 and 1938-1986 regressions are .83 and .93, respectively. The number of earthquake of M≥3.5 detected from 2004-2006 is close to that expected from the 1975-1985 and 1938-1986 recurrence lines. However, as one goes to smaller magnitudes, one sees an increasing discrepancy between the number of earthquakes detected in 2004-2006 and the number expected from the earlier recurrence lines.

There are two possible explanations for the discrepancy discussed in the previous paragraph. One possibility is that the discrepancy is due to manmade changes in regional network monitoring or in the methods used to compute earthquake magnitudes. If the discrepancy is due to a rise in the completeness threshold for earthquake detection in New England since the late 1990s compared to earlier times, then the data in Figure 4 suggest that the completeness threshold for earthquake detection in New England must presently be at or above M 3.0. However, as discussed earlier in this report, improvements in the automated event detection and location system have increased the capabilities of the system for detecting smaller earthquakes. While no formal analysis of earthquake completeness thresholds for the NESN have been carried out, it is estimated that the network should be capable of detecting all earthquakes of MLg ≥ 2.2 throughout most or all of New England (perhaps excepting northern Maine). Also, Weston Observatory is using the same coda-magnitude formulas as it used in the 1970's and early 1980's. Thus, it is difficult to explain the discrepancy between the 2004-2006 data and the recurrence lines from earlier time periods as simply due to changes in station configuration and data analysis methods.

A second possible explanation for the discrepancy is that there has been a recent real change in the regional b value in New England. If this is true, then it might mean that New England should expect an increase in the number of stronger earthquakes during the next few years. Indeed, the MLg 4.2 earthquake at Bar Harbor, ME in October 2006 was the largest earthquake in New England since 1988. This Bar Harbor event followed by only a few months the MLg 3.8 earthquake near Presque Isle, ME in July 2006, itself the largest earthquake since 1994. Thus, the second half of 2006 witnessed the largest earthquakes that have take place in New England in over a decade. Whether this increase continues into the future remains to be seen.

One goal of the NESN regional seismic monitoring in New England is to identify seismically active structures and to assess the probabilities of future occurrences of strong earthquakes on those structures. This long-term goal of the seismic monitoring is starting to pay dividends. Ebel (2006b) reported on a new analysis of the 1755 M 6¼ earthquake that probably was centered east of Cape Ann, Massachusetts. In this study Ebel (2006) uses information from historical accounts of this event as well as inferences from the modern earthquake activity that has been detected east of Cape Ann to argue for the location and magnitude of this important historical earthquake. He also uses reports of chimney damage to estimate the level of ground shaking that was experienced in Boston and other towns in the 1755 earthquake.

An important discovery from the routine earthquake monitoring in New England was the determination of a non-Poissonian element in the temporal pattern of the earthquake activity from 1975 to 2000, as reported by Ebel and Kafka (2002). Ebel and Kafka (2002) noted that the New England earthquake catalog has more earthquakes of MLg≥2.7 than would be expected from a Poisson process in which the occurrences of individual earthquakes are unrelated in any way to each other. This means that once an earthquake of MLg≥ 2.7 takes place in New England, there is an enhanced probability of another such event occurring somewhere in New England in the next several days. Specifically, the probability of a random earthquake of MLg≥2.7 during any 7-day period in New England is 11%. However, when an earthquake of MLg≥2.7 takes place, there is a 22% chance of another such event during the subsequent 7 days. Should the first event be MLg≥3.5, the probability of an MLg≥2.7 during the next 7 days is 35%. Throughout the time period of this report, Weston Observatory continued to maintain its link called "Earthquake Probability" on the Weston Observatory web site (http://www.bc.edu/westonobservatory) that shows the probability of a felt earthquake in New England for each upcoming 7-day period. Also shown on this web page is a map of those areas in New England that have about a 67% probability of being the epicenter of an earthquake of MLg 2.7 during the 7-day period. This map is based on the work of Kafka and Levin (2000) and Kafka (2002).



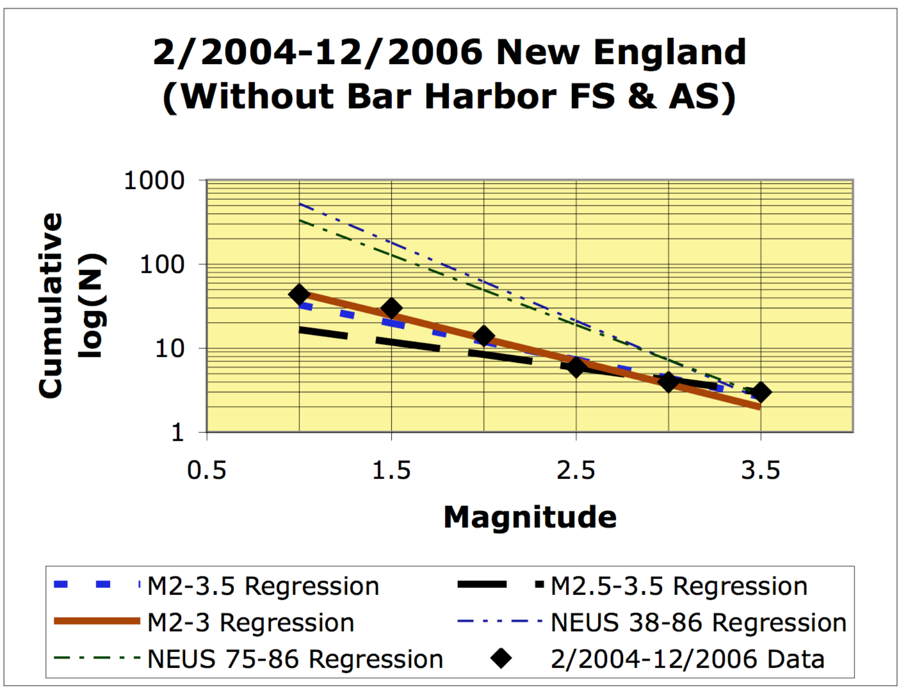


Figure 4. Gutenberg-Richter recurrence data for New England earthquakes from February 2004 through December 21, 2006. Regression lines through the data points from magnitude 2.0 to 3.5, 2.5 to 3.5 and 2.0 to 3.0 are shown, as are recurrence lines for a three-year time period from Ebel (1987) from NEUS data from 1938 to 1986 and 1975 to 1986. For the Ebel (1987) recurrence lines, it was assumed that New England has half the spatial area of the entire northeastern U.S. The top plot includes all New England earthquakes, while the bottom plot does not include the foreshocks and aftershocks of the MLg 3.4 and MLg 4.2 Bar Harbor, ME earthquakes in 2006.

Continued regional earthquake monitoring by the NESN is planned by Weston Observatory to acquire new data for research into the seismotectonics and seismic hazard in New England and vicinity. As new earthquakes are detected and located, new information will be gathered concerning the active tectonic structures in the region. Attention will be paid to any changes in the rates of earthquake occurrence in the region. The efforts described earlier to install more regional seismic monitoring stations in the region are intended to reduce the magnitude threshold and increase the number of earthquakes detected routinely by the NESN. Efforts are also planned to initiate the installation of strong-motion seismic stations in the region to better document the excitation and propagation of strong ground motions as well as to enable the computation of ShakeMaps for the region.

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Guest Speaker at the home of Ronne and Jerry Harris, "Major Historical Earthquakes in Northeastern North America and their Effects in Boston," April 3, 2005.

Workshop Organizer and Speaker, CEUS Workshop on National Seismic Hazard Maps, May 9-10, 2006; presentation on "Earthquakes in the Northeastern U.S.".

Speaker: Local Emergency Planning Committee Meeting Town of Needham, MA, November 20, 2006 – Spoke about earthquake history and risk.

Speaker: Local Emergency Planning Committee Meeting Town of Natick, MA, November 29, 2006 – Spoke about earthquake potential in New England.

Speaker: State Street's 2006 Continuity Awareness Conference, December 5, 2006 – Spoke about earthquake potential in New England and participated in a company planning exercise for a possible earthquake in the Boston area.