THE NEW ENGLAND SEISMIC NETWORK

Award Number 01HQAG0022

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Abstract

From February 1, 2001 to January 31, 2004 Weston Observatory operated an 11-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 also coordinates earthquake monitoring in the northeastern U.S. (NEUS) with the Earth Resources Laboratory of the Massachusetts Institute of Technology (MIT) and 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).

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, all of the stations had Nanometrics, Inc. 16-bit digitizers with gain-ranging, digitized at a rate of 100 samples per second per channel. The software controlling the stations stored the signals from the sensor in a continuous disk loop at the remote site, preserving approximately 21 days of continuous data. In 2003 the digitizers at five stations were replaced with new Reftek, Inc. 130-01 broadband 24-bit digitizers sampled at 40 samples/second. Telemetry to Weston Observatory from these new stations as well as most of the older stations was through the internet using the Earthworm software package. Event detection at all stations is carried out using an STA/LTA threshold detector. A new effort to implement a wavelet-transform (WT) based automated event detector and identifier was developed for the Earthworm datastream. This system has been tuned so that it successfully detects and identifies many quarry blasts, most teleseisms, and some local earthquakes.

There were 69 local and regional earthquakes with magnitudes from 1.9 to 5.1 that were detected and located by the NESN stations from February 1, 2001 to January 31, 2004, along with some microearthquakes and some other signals that were possible earthquakes. The largest recorded earthquake from the region was an ML 5.1 earthquake on April 20, 2002 that caused minor damage in New York near the epicenter and was felt across most of New England. There were 36 earthquakes centered in (or offshore of) New England proper. From 2001 to 2004 the annual rate of earthquake activity in New England at all magnitude levels was only about 50% of that from 1975 to 1982. The seismicity of New England was found to have a non-Poissonian temporal pattern with more short-term pairs of $m_{Lg} \geq 2.7$ earthquakes than would be expected from a Poisson process. This information is used to make short-term earthquake probability forecasts on the Weston Observatory web site (http://www.bc.edu/westonobservatory).

Investigations

Weston Observatory continued to operate its regional seismic network from February 1, 2001 to January 31, 2004 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 cooperatively operated by Weston Observatory of Boston College and the Earth Resources Laboratory of the Massachusetts Institute of Technology (MIT). The NESN also 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).

Network History through the Report Period

At the beginning of the period of this report (February 2001) Weston Observatory was operating 11 seismic stations in New England. The number and locations of the NESN seismic stations did not change during the period of this report, although there were changes in the equipment at a number of the stations. Also, a station TRY at Troy, NY was prepared but was not made operational during this reporting period. All of the Weston Observatory stations operating in February 2001 were PC-based 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 were CMG-40T feedback geophones with a flat response to ground velocity between roughly 30 Hz and 30 sec. The digitizers were Nanometrics 16-bit with gain-ranging, yielding effectively 136 db dynamic range. The sensor signals were digitized at a rate of 100 samples per second per channel. The output from the digitizer was sent to a PC computer running OS/2, a multitasking operating system, at the recording site. The software controlling the stations stored the signals from the sensor in a continuous disk loop, preserving approximately 21 days of continuous data. Also examining the data stream from the digitizer was a program that uses a filter and STA/LTA scheme to test for possible events. When the STA/LTA threshold is exceeded, a notation of the time and duration of the exceedance is added to a text file on the recording computer.

Using software developed by Nanometrics, Inc., seismic data from most of the NESN stations was being transferred via the internet to the USGS National Earthquake Information Center (NEIC) for incorporation into the U.S. National Seismic Network (USNSN) data stream. Throughout the period of this report, nine of the sites (BCX, BRY, EMMW, HNH, PQI, QUA2, WES, WVL, and YLE) were available via internet connections to Weston Observatory, seven of which (BRY, EMMW, HNH, PQI, QUA2, WES, WVL) were also sending their data to the USGS NEIC in Golden, Colorado. In 2003 an internet connection was established at station FFD, and those data also began being fed to the NEIC and Weston Observatory.

In the summer of 2003 Weston Observatory received from the USGS five new Reftek, Inc. 130-01 broadband digitizers to replace the older Nanometrics equipment at some of the NESN stations. These digitizers were installed in September 2003 at the following stations: BRY, FFD, HNH, QUA2 and WES. The Reftek 130-01 units are 24-bit digitizers that transmit data sampled at 40 samples/second through the internet using the Earthworm software package. Routine event detections are carried out using an STA/LTA detector. The stations with the new Reftek equipment were configured to transmit their data directly to the USGS NEIC, which then retransmits the data via Earthworm to Weston Observatory as well as to all other interested users. Plans were being made at the end of this report period to replace the outdated Nanometrics digitizers at more of the remote NESN stations later in 2004.

In 2001 a computer with the Earthworm software was installed at Weston Observatory to receive USNSN data. During the period of this grant, the number of data streams from the northeastern U.S. was increased as experience was gained with the operation and capabilities of the Earthworm system. Initially, data from six stations were being delivered to Weston Observatory via Earthworm, and in 2003 this number was increased to twelve. By the end of this reporting period, the stations that were being received via Earthworm at Weston Observatory were the NESN stations BRY, EMMW, FFD, HNH, PQI, QUA2, WES and WVL along with USNSN stations BINY, HRV, LBNH and NCB. In all cases, the data streams from the seismic stations were sent directly to NEIC, from which they were returned to Weston Observatory through the Earthworm system.

The NESN station configuration as of January 2004 is shown in Figure 1 (including the sites of the former MIT NESN stations). The MIT stations ceased operation sometime in 2002 and were not restarted through the end of this reporting period. The magnitude threshold above which earthquakes can be completely detected and located by the NESN shown in Figure 1 is estimated to be about mLg 2.7 throughout New England. Smaller earthquakes can be detected and located in southern New England (from central New Hampshire and Vermont to the southern border of New England), although it is likely that not all earthquakes with mLg < 2.7 are being detected and recorded in this region. In northern New England, the capabilities for earthquake detection and location are augmented by a number of seismic stations operated in Quebec and New Brunswick provinces of Canada by the Canadian Geological Survey.

To decrease the magnitude of the completeness level for event detection and location, Weston Observatory began investigating several sites in New England for the installation of new seismic stations. In one effort, Weston Observatory personnel were working with the Maine Geological Survey to site a USNSN national backbone station in central Maine. An acceptable site has not yet been confirmed, although a possible candidate was being investigated as of the end of this reporting period. Possible new station sites in southwestern New Hampshire, western Maine and east-central Maine were also being negotiated. It is the long-term goal of Weston Observatory to approximately double the number of regional seismic network stations that it is operating in the region. If this goal can be met, the completeness threshold for event detection and location should be reduced to between mLg 2.3 and 2.0.

One important development in the routine analysis of regional seismic network data at Weston Observatory is a new effort to implement a wavelet-transform (WT) based automated event detector and identifier. Such a system was initially created and tested by Gendron et al. (2000) for the PC-based regional seismic network stations operated by Weston Observatory. Unfortunately, the operation of that system had to be halted due to unresolveable conflicts with the data acquisition systems on the computers at the remote field sites, where the WT software for event detection and identification had been installed. With the implementation of the Earthworm system at Weston Observatory, a new effort was started to adapt and improve the Gendron et al. (2000) system to make use of the triggered and continuous data arriving via Earthworm. It was decided to implement this new system using Matlab, making it relatively platform independent (i.e., any computer running Earthworm and Matlab can run this system). An initial version of a wavelet-based automated event detector and identifier began being tested under routine operating conditions in August 2003. A number of programming bugs and system configuration problems were worked out during the fall and early winter of 2003-2004, and by the end of this reporting period the system was being used on a daily basis to assist with event detection and identification. The system has been tuned to the point where it successfully detects and identifies many quarry blasts, most teleseisms, and some local earthquakes detected by the network stations.

A research effort is currently under way to improve the reliability of the WT event identifications. This new identifier is based on an analysis of the frequency spectra deduced from the WT transforms of detected events (Zhu and Ebel, 2004; Ebel, 2004). Further development, improvement and testing of this new system will take place during the coming year. It is the long-term goal of this project to use the WT system not only for automated event detection and identification, but also for the determination of event locations and magnitudes in near real-time. The added information provided by the wavelet transform over that from simple STA/LTA systems is necessary to overcome the inherent limitations of a sparse, widely scattered regional seismic network such as that being operated by Weston Observatory in New England and vicinity.

Data Analysis, Archiving and Availability

During the grant period, scanning of the seismic data for possible earthquakes was done manually by an analyst, who would then determine the locations and magnitudes for all detected earthquakes. Due to manpower cutbacks resulting from limited funding, the routine scanning of the seismic data for earthquakes took place only between 1 and 3 times each week when our part-time seismologist was available. At the beginning of the period covered by this report, the analyst used a PC computer as the master computer for routine scanning for earthquakes and for network data collection, analysis and archiving. From this computer, the remote stations were contacted for event detection lists and to extract the waveforms for times of suspected events. The waveform data arrived at Weston Observatory from the remote stations in Nanometrics, Inc. "Y-file" format, where the waveform data were scanned, arrival times were read, and archiving was carried out. The waveform data were archived on hard disk and floppy disk in Nanometrics "Y-file" format. Nanometrics has provided a routine to convert data from their format to SEED and to SAC format. Unfortunately, the SEED files generated so far that have been sent to the IRIS DMC have not been acceptable for that archive because of some bad header data. We are working on this problem and intend to solve it, which would allow all Weston Observatory NESN waveforms to be archived at the IRIS DMC. Weston Observatory maintains an archive of all of its waveform data for local and regional earthquakes, and it also saves the first few minutes of teleseismic arrivals. These data are available upon request from Weston Observatory.

With the development of the Earthworm data transmission system and the WT event detector and identifier in 2003, changes were made in the routine scanning procedures. Station waveforms from the Earthworm system for WT event detections that were identified as possible teleseisms, regional earthquakes, local earthquakes, or local blasts were examined individually by an analyst using the Waveviewer program accessing the Earthworm data streams. For local earthquakes, arrival times of the P and S waves were read from all possible stations, and these readings were augmented with arrival time, amplitude and period measurements made from the older Nanometrics-style NESN stations that could only be accessed by remote dial-up or direct internet connection. Computations of the locations and magnitudes of local events were carried out as before, using a modified version of HYPO78.

Weston Observatory produces a quarterly seismic network bulletin for the New England area that summarizes the detected earthquake activity within the New England region. This bulletin is posted on the Weston Observatory web site. Weston Observatory contributes hypocentral data to the CNSS composite catalog on a routine basis. It also maintains web pages with lists of recent earthquakes, and other information pertinent to the earthquakes of the region. The Weston Observatory main web site with links to information about local earthquakes is:

- http://www.bc.edu/westonobservatory

Seismic Stations - 2004

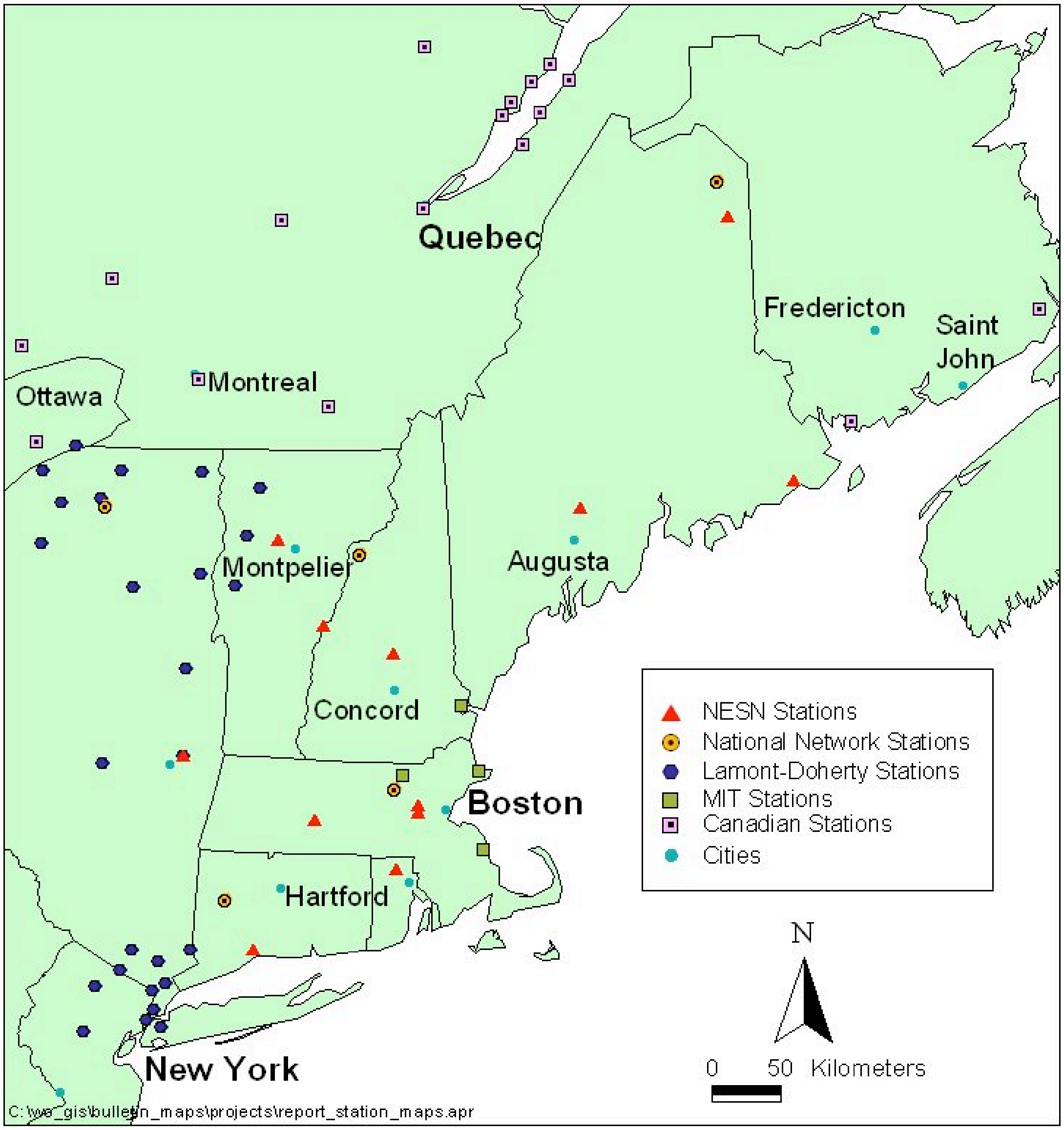

Figure 1. Locations of seismic stations in New England and vicinity as of January 2004. The MIT stations had not been operational since 2002, but the locations of the station sites are shown for reference.

Seismicity

Figure 2 shows the epicenters of local and regional earthquakes recorded by Weston Observatory from February 1, 2001 to January 31, 2004. A total of 69 local and regional earthquakes with magnitudes from 1.9 to 5.1 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 2, there were 36 earthquakes centered in (or offshore of) New England. Five of the New England earthquakes were aftershocks, one was a foreshock, and one was part of a pair of similar-sized earthquakes.

The largest earthquake that took place in the northeastern U.S. and southeastern Canada during the time period of this report was an ML 5.1 earthquake on April 20, 2002. This event was centered near Au Sable Forks, NY, and caused some minor damage in the epicentral area (http://www.ldeo.columbia.edu/LCSN/NYQuake_2002/damage.html, http://neic.usgs.gov/neis/eq_depot/2002/). It was felt throughout most of New England, the middle Atlantic states, and the southern parts of Quebec and Ontario provinces in Canada (the CIIM web page for this earthquake can be linked from http://pasadena.wr.usgs.gov/shake/ne/). The Au Sable Forks mainshock was followed by a number of aftershocks ranging in magnitude up to 4.0 (Seeber et al., 2002). The ground motions from this earthquake at the NESN stations of Weston Observatory were comparable to those predicted by published ground-motion attenuation relations for the region (Atkinson and Sonley, 2003; Ebel, 2003).

Of the events shown in Figure 2, the largest earthquake in New England proper took place on July 22, 2003. This mLg 3.6 event was centered about 58 km ENE of Gloucester, MA. Ground shaking from this earthquake was felt in northeastern Massachusetts, southeastern New Hampshire and southernmost Maine, and it was also felt by a number of residents along the coast south of Boston (see the CIIM web page for this earthquake at http://pasadena.wr.usgs.gov/shake/ne/archives.html). There were almost no felt reports from the city of Boston or adjacent suburbs from this earthquake. The epicenter of this event (offshore east of Cape Ann) was located in an area where about a dozen earthquakes have been detected since 1975. Ebel (2002) argued that this offshore area was the probable epicenter of the M6 1/4 Cape Ann earthquake of 1755, the largest damaging earthquake in New England history. Following the "paleoseismicity" model of Ebel et al. (2000), the 2003 earthquake may have been an aftershock of the 1755 event or of perhaps an even larger, earlier earthquake.

Another interesting sequence of events took place at Bethlehem, NH in October 2001. On October 2 there was a magnitude 2.6 earthquake that was felt noticeably at Bethlehem and nearby communities. During the next week or so, a number of residents contacted Weston Observatory reporting that they had heard and sometimes felt what they thought were small earthquakes. Examinations of the seismic data from the nearby USNSN station LBNH confirmed that many of the residents' reports were indeed small earthquakes. These were very likely very small aftershocks (magnitude 1.7 or less, including several below magnitude 1.0) of the 2.6 mainshock. The Bethlehem residents were probably very close to the earthquake hypocenters of these aftershocks since events of such small magnitudes cannot be felt or heard very far from their epicenters. This observation confirms that the epicenter of this earthquake sequence was under the town of Bethlehem.

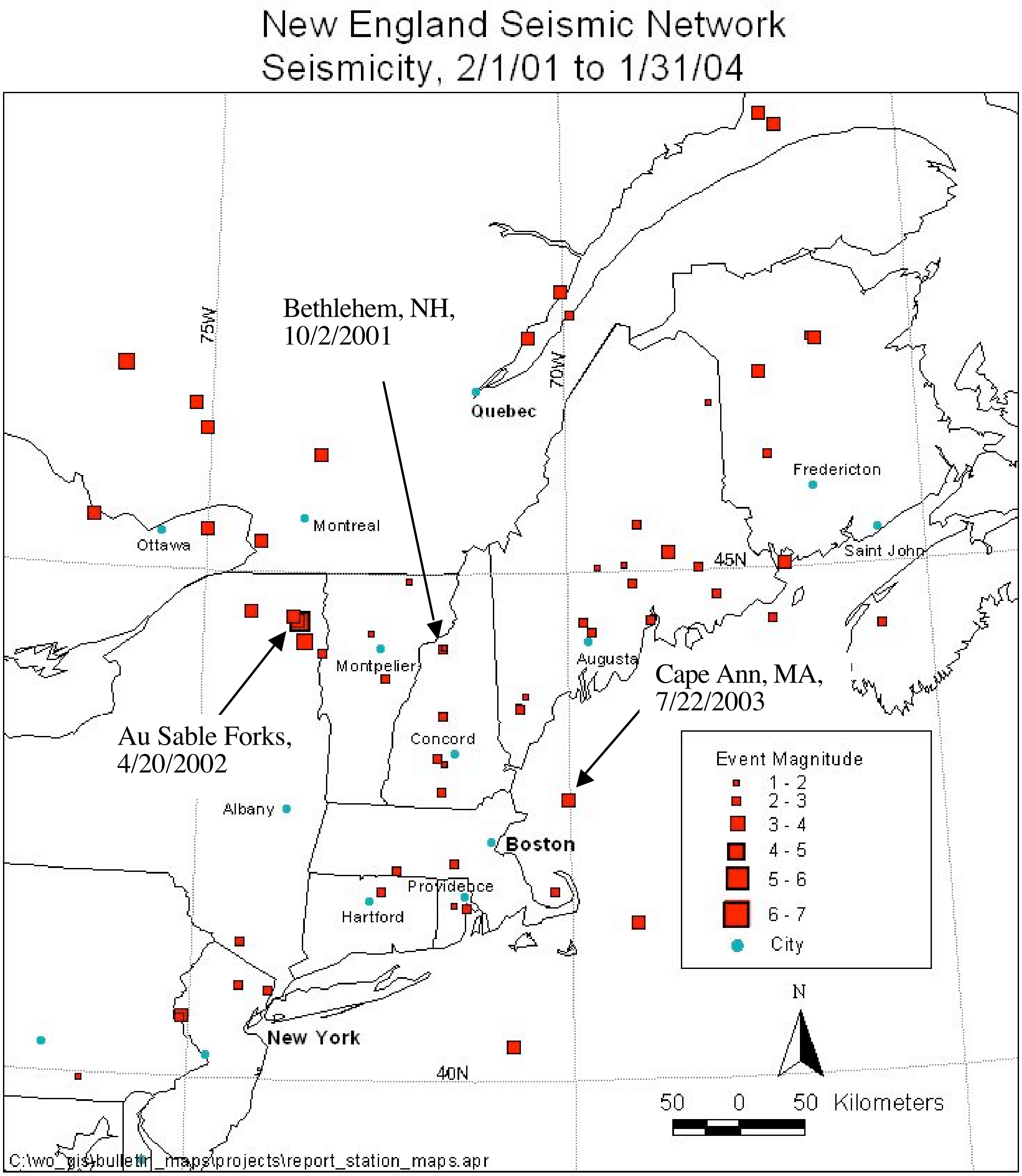

Figure 2. Seismicity of New England and vicinity from February 1, 2001 to January 31, 2004 as recorded by the seismic stations of Weston Observatory of Boston College.

Discussion

The rate of seismicity during this reporting period was quite comparable to that of the prior three-year period of network monitoring. During this six-year time period, the seismicity in the region was stable both in its temporal rate and in its spatial distribution. However, the rate of earthquake activity in New England during this period was significantly lower than it was during the late 1970's and early 1980's, a time 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 22 earthquakes of M≥2 and 3 earthquakes of M≥3. Thus, from 2001 to 2004 the annual rate of earthquake activity in New England was only about 50% of that from 1975 to 1982.

Figure 3 illustrates that this lower rate from 2001 to 2004 is at all magnitude levels. Shown in Figure 3 is the cumulative number of earthquakes for the time period from 2001-2004 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 3 are two recurrence curves from Ebel (1987) computed for the New England region for a three-year time period. These recurrence curves are based on data from the northeastern U.S. (NEUS) from 1938 to 1986 and from 1975 to 1986. The Ebel (1987) recurrence curves indicate seismicity rates about a factor of 2 greater than that shown by the observed 2001-2004 data points down to M2.5, below which the catalog incompleteness becomes increasingly evident. This decrease in the 2001-2004 seismicity rate compared to that from the late 1970's and early 1980's is likely not an artifact of changes in station configuration or magnitude calculations. While New England has only about 1/3 the number of seismic stations that it had in the early 1980's, there are still a sufficient number of stations since the late 1990's that all earthquakes above magnitude 2.7 should have been detected and located. Also, Weston Observatory is using the same coda-magnitude formulas as it used in the 1970's and early 1980's. Thus, the mean seismicity rate in New England so far during the first decade of the twenty-first century is about 50% less than it was about two decades earlier.

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%. There is a 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).

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 (2000) reported on a study of the main shock and aftershocks of the 1727 M5.5 earthquake that probably was centered near Newburyport in northeastern Massachusetts. The study by Ebel (2000) stimulated some field investigations in nearby coastal New Hampshire that have uncovered evidence of liquefaction features and a suspected tsunami deposit from one or more strong earthquakes that took place in the area just over 2000 years ago (Tuttle, 2001; Tuttle et al., 2003). Further research is planned on investigating these geologic features to better document the size, location and dates of the past earthquakes in this area. This research supports the argument that regional seismic network monitoring provides important data for understanding the seismic hazard in northeastern North America.

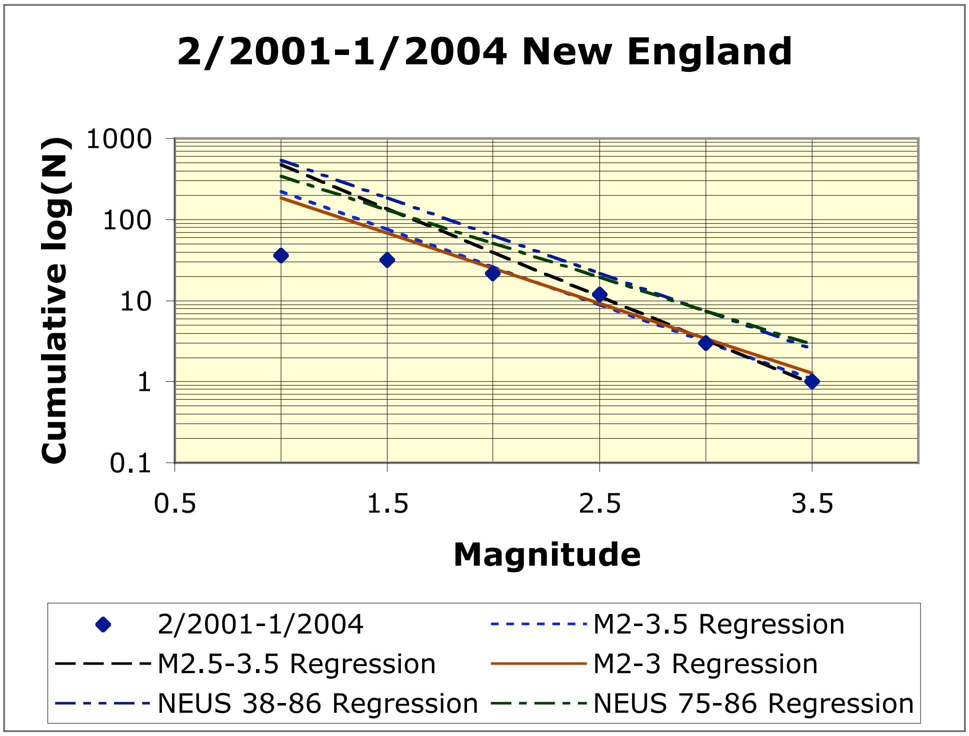

Figure 3. Gutenberg-Richter recurrence data for New England earthquakes from February 2001 through January 2004. Regression lines through the data points from magnitude 2.0 to 3.5, 2.5 to 3.5 and 2.0 to 3.0 are shown, as are recurrence curves for a three-year time period from Ebel (1987) from NEUS data from 1938 to 1986 and 1975 to 1986. For the Ebel (1987) recurrence curves, it was assumed that New England has half the spatial area of the entire northeastern U.S.

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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