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Abstract

The goal of this research project was to construct a state-of-the-art database of earthquakes for the Central and Eastern U.S. (CEUS) that can be accessed and queried for data that can be used for research and analyses, especially for seismic hazard analyses. For example, the database can be used to provide input into the National Seismic Hazard Maps (NSHM) calculations. The database is focused on all earthquakes with magnitudes of approximately Mw 4.0 or greater since 1700 for the CEUS and adjacent Canada, defined in this project as the area between 100°W and 66°W longitude and between 25°N and 49°N latitude. Earthquake catalogs for the entire CEUS were accumulated and then combined into a single database that includes all earthquakes equal to or greater than magnitude 3.7 on any magnitude scale. The hypocentral and magnitude parameters from the most authoritative source were included in the database. In addition to the hypocentral and magnitude data, information about the seismic moment, focal mechanism, source time function, rupture area, and fault slip were entered into the database for all events for which these parameters are known. Access to the database will be through a web page that will allow users to query the database for earthquakes and earthquake parameters. An analysis of the completeness thresholds of the database suggests that the full catalog is complete back to 1922, but if foreshocks and aftershocks are removed from the database, a completeness date of 1884 is inferred. Completeness thresholds for subregions of the country vary widely from one subregion to another due to dates of settlement and amount of seismicity in each subregion. On Gutenberg-Richter recurrence plots, the datapoints for both the entire dataset and for the dataset after foreshocks and aftershocks have been removed are quite linear from M4.0 to about M6.0. Above about M6.5 the observed number of earthquakes exceeds least squares lines fit to the data. The recurrence curves suggest mean repeat times for the database region ranging from 1-2 years for M≥5 earthquakes to almost 100 years for M≥7 mainshocks.

Introduction

The goal of this research project was to construct a state-of-the-art earthquake catalog database for the Central and Eastern U.S. (CEUS) that can be accessed and queried for data that can be used for research and analysis purposes, such as for input into the National Seismic Hazard Maps (NSHM) calculations. The database focuses on all earthquakes with magnitudes of approximately Mw 4.0 or greater since 1700 for the CEUS and adjacent Canada, defined in this project as the area between 100°W and 66°W longitude and between 25°N and 49°N latitude. The database has several significant improvements over existing CEUS earthquake catalogs. First, it is constructed as a true database (rather than a simple flat-file earthquake catalog) so that relational inquiries about the data can be carried out quickly and easily. Second, because of the great capacity of modern computers to store large amounts of data and to process large amounts of data quickly, the database incorporates many types of information that have not been included in traditional flat-file earthquake catalogs. Such items can include scans of data and analysis results for earthquakes, uncertainties in all parameters included in the database, information about the sources from which the data have been obtained, and multiple determinations of some parameters (such as moment magnitudes and focal mechanisms) from different investigators. Third, the database is being constructed to be queriable with access through a web browser, so any user with internet access can interrogate the database. Finally, the database can be easily updated with new information, and new fields of information can be added with little difficulty as future needs and developments dictate.

This database directly addresses aspects of NEHRP Priority Elements I: National and regional earthquake hazards assessments. The database can be used directly by USGS and other investigators who are carrying out the computations for the next set of NSHM or other seismic hazard analyses, especially if they want to accumulate information about the larger earthquakes that have taken place in the CEUS. In addition, the databse will be accessible to all other users who want to interrogate the database for information that it contains. The database includes not only information about the date and time, hypocenter, and magnitude of each earthquake, but it also contains information on the seismic moment, focal mechanism, and fault rupture where known for each event. Uncertainties in all parameters and information on the original source of the data in the database are also contained in the database. The database is comprised of information on over 1000 earthquakes.

Assembly of the Database

The starting point for assembling the database in this project was to accumulate earthquake catalogs for the entire CEUS and then to combine those catalogs into a single database where duplicate entries have been deleted. The earthquake catalogs that were used to assemble the database are listed in Table 1. Note that a request was made to obtain a copy of the earthquake catalog that was used for the CEUS Seismic Source Characterization (CEUS-SSC) project conducted by EPRI, but that catalog was not

Table 1. Earthquake Catalogs Used in the Construction of the M≥4 CEUS Earthquake Database

Catalog Name	Data Range	Created by	Where catalog was obtained from	Definition
ANSS	1928 - present	Advanced National Seismic System	http://www.ncedc.org/anss/catalog-search.html	ANSS global earthquake catalog
CNMSN	1974 - present	1974-1992: TEIC earthquake bulletin and St Louis Regional Catalog, 1993-1994: Saint Louis University and Central Mississippi Valley Earthquake Bulletins, 1995-present: earthquakes reported by SLU and/or CERI, 2003-present: addition of CERI East TN earthquakes and contributions from the SEUSSN bulletins	http://www.ceri.memphis.edu/seismic/catalogs/cat_nm.html and http://folkworm.ceri.memphis.edu/catalogs/html/cat_nm.html	Cooperative New Madrid Seismic Network (CNMSN) monitors New Madrid Seismic Zone and Surrounding Regions
DNAG	? - 1985	Engdahl and Rinehart, 1988, 1991	**http://www.ngdc.noaa.gov/hazard/data/cdroms/Seismicity_v1/data/dnag/**	GSA DNAG Decade of North American Geology Project - Map 004 / SEISMICITY MAP OF NORTH AMERICA, 1987, four folded sheets, - 3 -, $ 45
EBELCAT10.ALL	1534 - present	John E. Ebel, Weston Observatory, NESN	Weston Observatory	Northeastern U.S. and adjacent Canada - References from many Networks and Special Reports
emb02.crw	1534 - 2006	Chuck Mueller et al.	via email from Russ Wheeler wheeler@usgs.gov can also be obtained from http://earthquake.usgs.gov/hazards/products/conterminous/2002/data/catalogs/emb2001.txt	Compilation of catalogs for the 2002 & 2008 USGS National Seismic-Hazard Maps
EPIC.D	6/29/1974 - 6/30/1992	SLU Regional Seismic Network, Memphis State Univ., Univ. of Kentucky, Univ. of Kansas, Univ. of Oklahoma, Univ. of Michigan	via email from Russ Wheeler wheeler@usgs.gov	Central Mississippi Valley Earthquake Catalog
epic.d	1975 - 1994	Saint Louis University	http://www.eas.slu.edu/Earthquake_Center/earthquake_dos.html	Regional Seismic Netwrok Catalog for New Madrid
LCSN	1990 - 2005	LDEO Lamont-Doherty Earth Observatory	http://www.ldeo.columbia.edu/LCSN/catalog.html	Lamont-Doherty Cooperative Seismographic Network
NCEER-91	1627 - 2/1985	Seeber and Armbruster, 1992	http://www.ceri.memphis.edu/seismic/catalogs/cat_nceer.html	National Center for Earthquake Engineering Research - covers central and eastern US and adjacent Canada
NEDB Canada	1627 - present	NRCAN GSC	http://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php	National Earthquake Database of Canada
Nuttli	1810 - 1980	Otto W. Nuttli, 1979	http://www.eas.slu.edu/Earthquake_Center/earthquake_dos.html	Catalog of Central US Earthquakes
PDE	1973 - present	USGS/NEIC	http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_rect.php	Earthquake catalog of the globe named Preliminary Determination of Epicenters, quakes located by the USGS NEIC and its predecessors in the U.S. Coast and Geodetic Survey, the National Oceanic Survey, and the Environmental Research Laboratories of the Department of Commerce.
SEUSSN	1977 - 2005	Charleston Southern Univ., Delaware GS, Georgia Institute of Tech., Maryland GS, Univ. of Tennessee/TVA JIEE Institute, USGS/NEIC, Univ. of Florida, Univ. of Memphis, Univ. of SC, Virginia Tech, Westinghouse Savannah River Co.	http://www.geol.vt.edu/outreach/vtso/anonftp/catalog/bulletin_readme.txt	Southeastern US Seismic Network
SRA	1886 - 1986	USGS - Stover et al., 1984 (C.W. Stover, B.G. Reagor, and S.T. Algermissen)	http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_rect.php	Earthquakes in the Eastern, Central, and Mountain States of the U.S.
USHIS	1774 - 1989	USGS - Stover, C.W. and Coffman, J. L., 1993	http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_rect.php	Significant U.S. Earthquakes, Damaging U.S. Earthquakes

available until January 2012, a time after this project was to be completed. For this reason, the CEUS-SSC catalog was not included in this database.

In assembling the database, all earthquakes with magnitudes larger than 3.7 (on any magnitude scale reported in the catalog) were extracted from each earthquake catalog. The reason for this is that within typical magnitude uncertainties, some earthquakes with listed magnitudes as small at 3.7 may in fact have been Mw 4.0 or greater. The dates, times and epicenters were compared in order to identify common events in the different catalogs. The common listings for each earthquake were gathered, and the event parameters from the most authoritative source were included in the database. The

authoritativeness of each event was determined based on the location of the event, the date at which the catalog was compiled, and the compiling entity (whether it was an earthquake observatory, a research scientist studying past earthquakes, or an earthquake catalog compiler who did not examine the original earthquake data). For some events, the hypocentral parameters were taken from one catalog and the event magnitude was taken from another catalog or from another source. This happened in cases where recent studies determined new magnitudes for older events but did not compute new hypocenters for those events. Because the database has entries for the source of each parameter listed in the database, users of the database can easily trace the source of all information in the database.

Although the goal of this project was to compile a database of all earthquakes with Mw≥4.0, that goal was only indirectly met in this project. The database almost certainly includes all earthquakes with Mw≥4.0, but only for the largest earthquakes are there explicit Mw determinations that have been reported by investigators. There are many Mw values that come from regional moment-tensor determinations, and some that come from teleseismic Mw measurements on the largest events in the database. Especially for smaller events before the 1990s, there are no direct Mw measurements for most of the events. Because there is no consistent way to estimate Mw for these events if there are no seismic moment determinations that have been made, no Mw values are contained in the database for many of the events. Thus, while the database very likely contains all events of Mw≥4.0 for the region of this study, specific Mw values for many events in the database are not included.

Figure 1 shows a map of the region of eastern North America for which the database was assembled, and it also shows the locations of all of the earthquakes that are included in the database.

Completeness Threshold Analysis of the Database

One important question to address is the completeness of the database. In this study the completeness date of the earthquake dataset was determined in the following manner. First, a histogram of the number of earthquakes for each year was constructed from the database. This was done for M≥4.0, M≥5.0 and M≥6.0 using the most authoritative magnitude for each event. Next, each histogram was visually inspected to identify the year after which there appears to be an approximately steady level of activity over the long term. That date was then identified as the completeness threshold date for the catalog. Figure 2 shows the histogram of annual seismicity for the entire database catalog of earthquakes. Except for a spike in 1886 that apparently is associated with the 1886 Charleston, SC earthquake, the histogram shows a relatively steady increase in the seismicity rate into the 1930s, a relatively high rate of annual seismicity from then to the early 1980s, and then a decrease to a somewhat lower mean seismicity rate to the present time. From this chart the completeness date appears to be about 1922.

An examination of the earthquake database reveals that it contains a number of foreshocks and aftershocks that show up as localized bursts of earthquake activity. Most

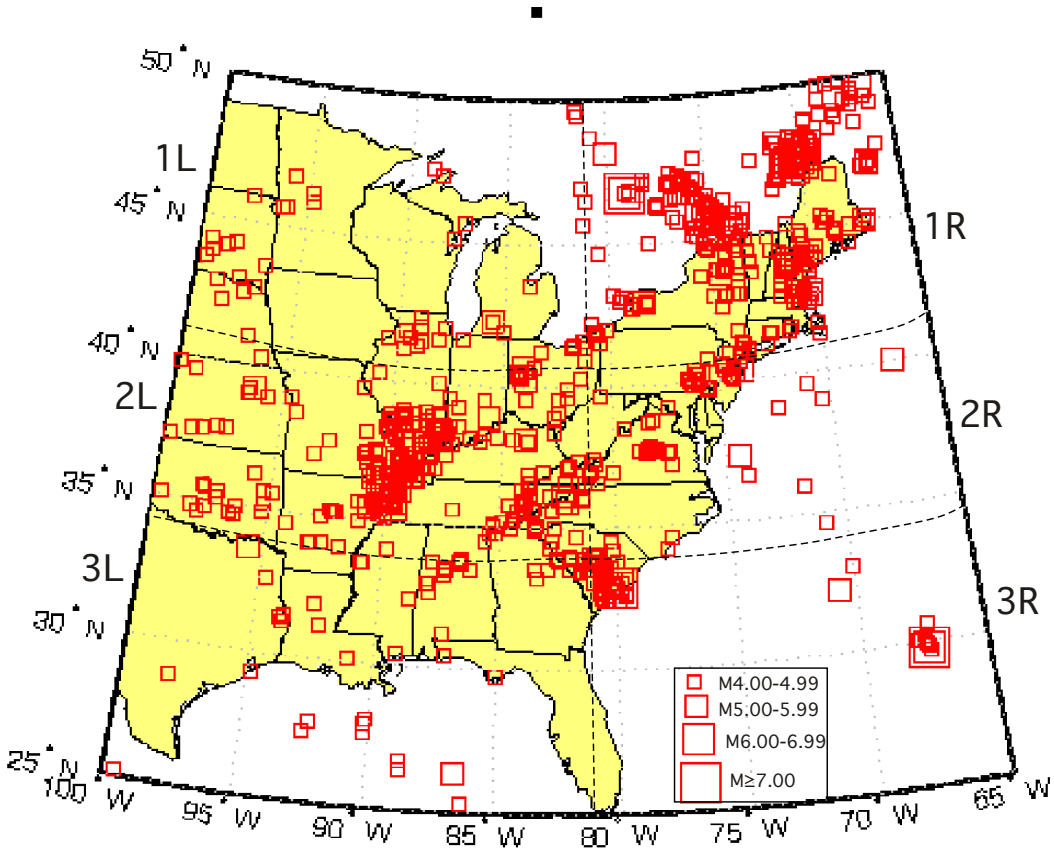

Figure 1. Map of the earthquake database assembled in this study. Analyses of the dates of the completeness thresholds for each subregion (1L, 2L, 3L, 1R, 2R, and 3R), which are delineated by the dashed lines, are discussed in the text.

of these bursts of activity are aftershocks of strong earthquakes that have taken place in the region. The bursts of activity show up on the annual histogram of Figure 1 as large peaks that are well above the mean annual rate of seismicity. For this reason, it was decided to reestimate the completeness threshold of the earthquake database after foreshocks and aftershocks had been identified and removed from the dataset. The determination of which events were foreshocks and aftershocks was made using the distance and time windows of Gardner and Knopoff (1974). From an original database of 1019 events, 97 were identified as foreshocks and 182 were identified as aftershocks, leaving 740 events that were classified as mainshocks. The histogram with foreshocks and aftershocks removed is also shown in Figure 1. On this plot the time period of high seismic activity from the 1930s until about 1980 is still seen, but the average rate of M≥4.0 seismicity seen since about 1980 seems to extend back to the middle 1880s. For the dataset with foreshocks and aftershocks removed, a completeness threshold of 1884 is selected. The fact that the unusual time period of increased M≥4.0 earthquake activity from the 1930s until about 1980 did not disappear when foreshocks and aftershocks were removed suggests that these few decades likely had a higher average seismicity rate than

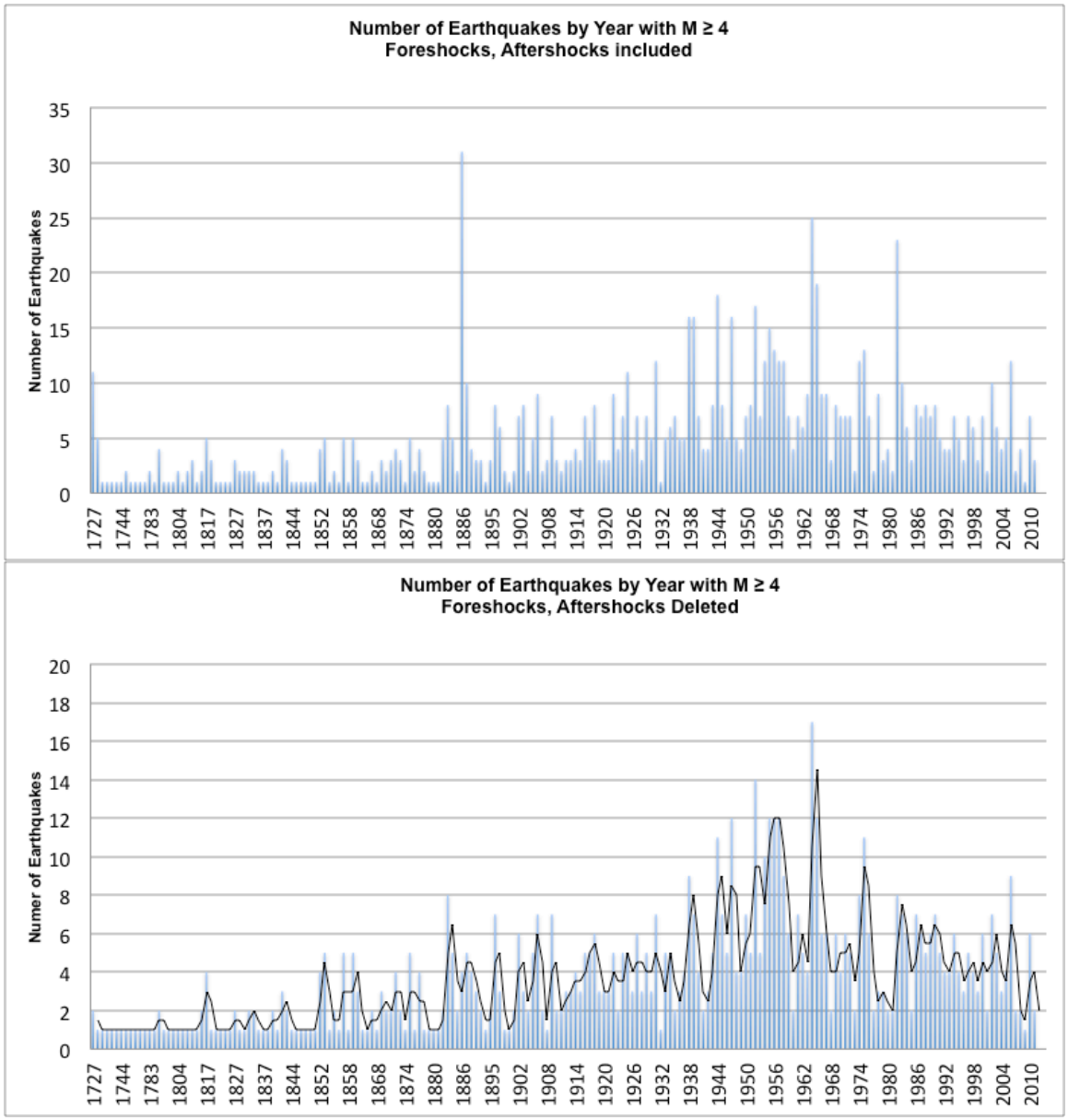

Figure 2. (top) Histogram of the number of earthquakes in each year with M≥4.0 in each year in the database starting with 1727. From this histogram, a completeness of about 1922 is suggested. (bottom) Histogram of the number of earthquakes in each year with M≥4.0 in each year in the database starting with 1727 after foreshocks and aftershocks have been removed. From this histogram, a completeness of about 1884 is suggested.

the several decades before and since. A number of M≥5.5 earthquakes took place in eastern North America during this time period, and so these data may suggest that times of increased M≥4.0 earthquake activity throughout the region are times when M≥5.5 earthquakes are more likely to occur.

The same kind of completeness analysis as that described above for M≥4.0 earthquakes was carried out for M≥5.0 and M≥6.0 events. For M≥5.0 the completeness

date for the data both with and without aftershocks appears to be about 1861. For the M≥6.0 dataset there are very few events and there is not evident change in the rates of events throughout the entire duration of the data contained in the database. There are 20 events in the full M≥6.0 dataset and 15 events in the M≥6.0 dataset. Of the 5 events that were removed as foreshocks or aftershocks, 4 of these were from the 1811-1812 New Madrid earthquake sequence.

The time periods of completeness of the database are not uniform across the country. Obviously, the coastal regions were settled before the inland regions, and so the earthquake catalogs for the coastal regions are complete down to magnitude 4.0 starting at earlier dates than for inland areas. To assess the spatial distribution of the time periods for which the earthquake catalog is complete, the CEUS region was divided up into six subregions, as shown in Figure 1. For each subregion the M≥4.0 seismicity per year was plotted as a function of time, and the time after which the seismicity has an approximately constant rate was identified, as was described above for the database as a whole. For each subregion, this analysis was carried out for all M≥4.0 events and for all M≥5.0 events. The results of this analysis on the completeness dates of the subregions are given in Table 2. There are fewer events in the inland areas (such as region 1L) and those areas were inhabited later than the coastal areas. Also, there are relatively in the Gulf Coast area (e.g., region 3L), making the selection of the completeness year more difficult than for regions with more abundant seismicity. For these reasons, there is likely greater uncertainty in the completeness thresholds for these areas than for the Atlantic coastal areas (such as region 1R) that experienced early and frequent immigration from Europe along with locally higher rates of earthquake activity.

Table 2. Complete Threshold Year for Each Subregion

Subregion	Completeness Year, M≥4	Completeness Year, M≥5
1L	1882	1882
2L	1875	1875
3L	1874	1874
1R	1935	1890
2R	1737	1737
3R	1799	1799

Information Included in the Database

The database was populated many different types of information that is relevant to scientific studies of seismic hazard. The basic hypocentral and magnitude information from all of the catalogs for each earthquake were found, and the most authoritative information as described above was included in the database. In addition to this basic data, information about the seismic moment, focal mechanism, source time function, rupture area, and fault slip were entered into the database for those earthquakes for which these parameters or images had been determined and published in the scientific literature or posed on the internet. The sources of all information are included in the database. Table 2 lists all of the database fields.

Table 2. Information Included in the CEUS M≥4 Database

Year (integer, max: 4 characters)
Month (integer, max: 2 characters)
Day (integer, max: 2 characters)
Hour (float)
Minute (float)
Second (float)
Foreshock (Y/N)
Aftershock (Y/N)
Latitude (float)
Longitude (float)
Depth (float)
Reference for hypocenter (string)
MMI Max (integer, max: 2 characters)
Reference for intensity (string)
Magnitude value (float, max: 2 characters)
Magnitude name (string)
Magnitude type (string)
Reference for magnitude (string)
State/Prov. (string, such as MA or ON, max: 2 characters)
Location (string, such as Boston or 120 Km N of Fredericton)
Stress drop (float)
Stress drop units (string)
Stress drop uncertainty (float)
Basis of stress drop determination (string)
Reference for stress drop (string)
Fault length (float)
Fault width (float)
Fault radius (float)
Fault area (float)
Basis of fault dimension determination (string)
Reference for fault dimension (string)
Fault strike (float)
Fault dip (float)
Fault rake (float)
Basis of focal mechanism determination (string)
Reference for focal mechanism (string)
Corner frequency (float)
Basis of corner frequency determination (string)
Reference for corner frequency (string)
Corner frequency uncertainty (float)
Time function (image)
Time function duration (float)
Time function uncertainty (float)
Basis of time function (string)
Reference for time function (string)
Seismic moment
Seismic moment units (string)
Seismic moment uncertainty (float)
Basis of seismic moment determination (string)
Reference for seismic moment (string)
Finite fault slip (image)
Method of finite fault determination (string)
Reference for finite fault slip (string)

Accessing the Database

The database has been designed and populated with data as of the time of writing of this report. However, the interface for making the database publicly available on the internet is still not operational. However, once it is operational, there will be a web page that will allow users to query the database for earthquakes and earthquake parameters. Behind the public web page will be computer code that will generate SQL queries of the database. Instruction for querying the database will be available on web pages associated with the main database web page. The public internet availability of this database is expected to be completed sometime later in 2012.

Earthquake Recurrence Curves Computed Using Data from the Database

As a test of the information in the database, Gutenberg-Richter (GR) recurrence curves were computed for the earthquakes in the database with M≥4.0 since 1922. In addition, a GR curve was computed using the mainshocks (foreshocks and aftershocks deleted using Gardner and Knopoff, 1974) since 1884. These GR curves are shown in Figures 3 and 4, respectively. In both figures, the datapoints are quite linear from M4.0 to about M6.0, and above about M6.5 the observed number of earthquakes exceeds the least squares lines fit to the data with the exception of the M7.0 datapoint in Figure 4. Table 3 shows the mean repeat times of large earthquakes in the study region computed using the regression lines shown in Figures 3 and 4. For example, earthquakes of the size of the M5.8 Mineral, Virginia earthquake on August 23, 2011 are computed to have a mean repeat time of 3.8 years using the GR curve from the full dataset and 8.2 years using the GR curve from the dataset after foreshocks and aftershocks are removed.

Acknowledgments

Ron Ko is thanked for creating the template for the Oracle database that was used in the this study. He also created web pages that facilitated data input, and he programmed the web page output for the database.

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Gardner, J.K., and L. Knopoff (1974). Is the sequence of earthquakes in southern California with aftershocks removed Poissonian?, *Bull. Seism. Soc. Am.* **64**, 1363-1367.

Publications Based on This Research

Ebel, J.E., F. Alvarado-Blohm and A. Macherides Moulis (2011). A Database of M≥4 earthquakes for the Central and Eastern U.S., Abstract S11B-2215. presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec.

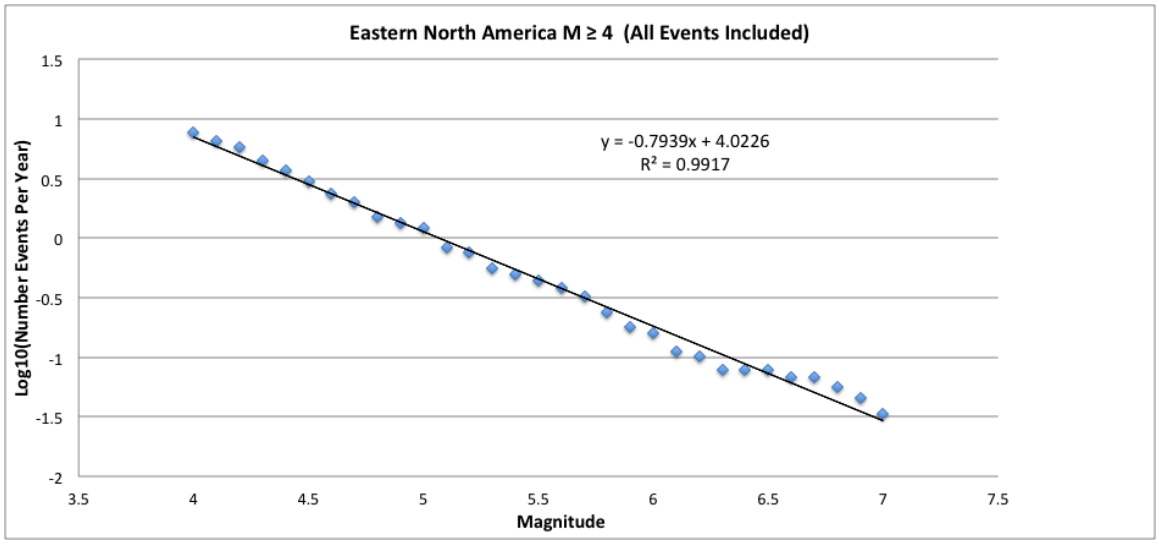

Figure 3. Gutenberg-Richter recurrence relation for all of the earthquakes in the dataset since 1922. The least-squares line that is fit through the data point is shown on the plot.

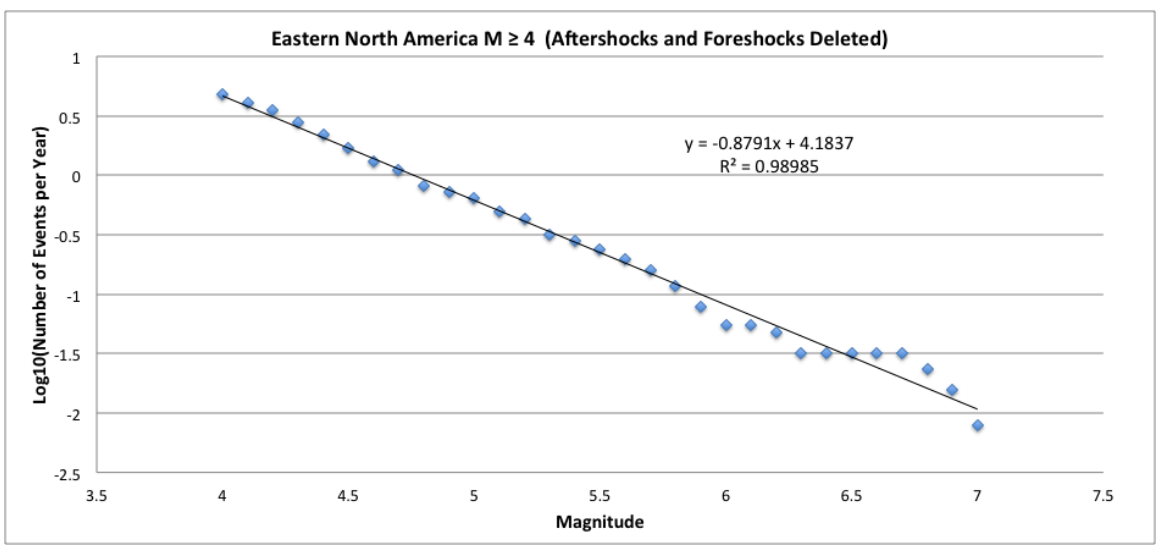

Figure 4. Gutenberg-Richter recurrence relation for the dataset since 1884 after foreshocks and aftershocks have been removed. The least-squares line that is fit through the data point is shown on the plot.

Table 3. Mean Earthquake Repeat Times for the Study Region Using the GR Recurrence Curves in Figures 3 and 4

Eastern North America
Repeat Times (Years)

Magniutde	M≥4 with aftershocks	M≥4 without aftershocks
5	0.9	1.6
5.5	2.2	4.5
6	5.5	12.3
6.5	13.7	33.9
7	34.3	93.3
5.8	3.8	8.2
a value	4.023	4.1837
b value	0.794	0.8791