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# Earthquakes in and near the northeastern United States, 1638-1998 – Construction of the earthquake catalog for an outreach map (paper edition)

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## ABSTRACT

This report provides documentation for a large-format map that is aimed at the lay public. The map shows epicenters of known earthquakes of magnitude 3 and larger over the northeastern United States and adjacent parts of Canada and the Atlantic Ocean. The map area covers more than 1.3 million square kilometers, and part or all of 14 States and four Canadian Provinces. No existing earthquake catalog provided current, uniform coverage down to magnitude 3, so a catalog had to be made for the map. Because the map is an outreach product, in each State or Province it had to match the way earthquakes are represented by whatever source is regarded as authoritative by the citizens and agencies of that State or Province. This report outlines procedures that produced the catalog for the map.

## INTRODUCTION

The goal of this effort was to make a map for the lay public. The purposes of the map are to inform the audience and to provide a useful outreach tool for the hazards community in the map area. The map shows three and a half centuries of earthquakes across a large area down to magnitude 3 (Wheeler and others, 2001). (Throughout this report, "magnitude" without a specified scale refers to $m_b$ or an estimate of it.) Magnitude 3 was chosen because it approximates the threshold above which shocks would be felt within the map area. The area spans long. 66°-81° W. and lat. 38°-48° N., a polygon more than 1,100 km on a side. It covers all of ten States and parts of another four States and four Canadian Provinces. No existing earthquake catalog provided current, roughly uniform coverage of the area. Instead, parts of the area are covered by two regional seismograph networks and the Canadian national network, and several States maintain or are compiling their own lists of earthquakes from various sources. Accordingly, making the map required compilation of a catalog.

## RATIONALE

Catalog construction was guided by the principle that the map should show each State's earthquakes in a manner consistent with the way that State's authoritative persons or organizations show them. This principle of consistency with authoritative sources in each State was urged by one State geologist within the map area, and it was welcomed by members of other State geological surveys who were contacted during catalog construction. Accordingly, I contacted each State geological survey and the Geological Survey of Canada to determine to which person, catalog, list of earthquakes, or other authority they directed inquiries about earthquakes. In some States, the authoritative source is the operator of a local or regional network. In others, a geologist had been tasked with compiling a list of the State's earthquakes. In some of these latter instances, World Wide Web-based regional catalogs or published catalogs could be used, in collaboration with the compiling geologist, to enhance the State's existing compilation. In each State and Canada, the result of these contacts and collaborations is that the map shows the same or virtually the same earthquakes as does the source or sources that are regarded as locally authoritative, down to magnitude 3.0.

The resulting catalog is based on approximately the same primary and secondary sources that would have been used had a single seismologist compiled the catalog as a research

task. However, probably there are two main differences between this catalog and one that would result from a seismologist's research. First, I have not examined the original seismographic or intensity data. Second, the combination of sources used and the relative preference given to each source changed from State to State, and from Canada to the United States. However, the map still shows accurately the relative differences of seismicity between States and large parts of States. The larger damaging earthquakes have been vetted individually by local seismologists.

## SOURCE CATALOGS USED IN VARIOUS PARTS OF MAP AREA

Emb.cc: This catalog was compiled for use in making the 1996 USGS national seismic hazard maps (Frankel and others, 1997; Mueller, Hopper and Frankel, 1997). Within the map area emb.cc extends through June 16, 1995, and is dominated by contributions from the NCEER-91 catalog (Seeber and Armbruster, 1991) through February, 1985 and from the USGS PDE afterward. Emb.cc uses the $m_b$ scale and extends down to $m_b$ 3.0. I obtained a digital version of the part of emb.cc that covers the map area (C. Mueller, written commun., September 24, 1998), and added records from the USGS PDE through 1998 (URL http://wwwneic.cr.usgs.gov/neis/epic/epic.html).

LCSN: The Lamont Cooperative Seismic Network has been operated since 1990 by the Lamont-Doherty Earth Observatory and cooperating institutions in New York, New Jersey, Vermont, and Delaware. The LCSN and NESN are the successors to the NEUSN. Records include one or more of $M_c$, $m_b$, and $M_N$. I obtained a digital catalog covering 1991 through 1998 (W.-Y. Kim, oral and written communs., May 14 and 20, 1999).

NCEER-91: The National (now Multidisciplinary) Center for Earthquake Engineering and Research funded L. Seeber and J. Armbruster of the Lamont-Doherty Earth Observatory at Columbia University to compile existing catalogs for the central and eastern U.S., and to find and incorporate a wealth of archival intensity reports of historic and early instrumental earthquakes. Results improved locations, magnitude estimates, and completeness (Seeber and Armbruster, 1991). The catalog extends through 1985 and down to magnitude 3. The magnitude scale used is $m_b$ (Sibol, Bollinger and Birch, 1987). NCEER-91 is represented on the map by having been incorporated into emb.cc, and through comparison of numerous records of individual earthquakes to entries in NCEER-91 (URL http://elwe.ceri.memphis.edu/~seisadm/cat_nceer.html).

NESN: The New England Seismic Network has been operated jointly by Weston Observatory of Boston College and the Massachusetts Institute of Technology since 1990. The LCSN and NESN are the successors to the NEUSN. Weston and MIT each compiled their own digital catalogs from 1991 through 1997. Since then, Weston and MIT have produced a joint digital catalog. Records include one or more of $M_c$, $m_b$, and $M_N$. I obtained the Weston, MIT, and joint digital catalogs (J. Ebel, C. Doll, oral and written communs., May 14 and 19, 1999).

NEUSN: The catalog of the Northeastern U.S. Seismic Network covered most of the map area through 1990, with contributions dominantly from Weston Observatory of Boston College, the Massachusetts Institute of Technology, and the Lamont-Doherty Earth Observatory. Funding cuts forced the breakup of the network at the end of 1990. The NEUSN was succeeded by the LCSN and the NESN. NEUSN records include one or more of $M_c$, $m_b$, and $M_N$. I obtained the digital version of the catalog (J. Ebel, written and oral communs., May 14, 1999).

NOTTIS: Nottis (1983) critically evaluated, edited, and corrected a previous unpublished catalog of E. F. Chiburis and others. Nottis's catalog covers most of the map area and adjoining parts of Canada to the north and east. It includes earthquakes through 1980. Most magnitudes are $m_{bLg}$ but some are $M_L$. There is no lower magnitude limit.

SEUSSN: The catalog of the Southeastern U.S. Seismic Network is compiled at Virginia Tech from data supplied by network members throughout the region. Magnitudes reported for the map area are mostly $M_c$ and $M_N$. I obtained a digital version of the SEUSSN catalog for Virginia

and West Virginia (M. Chapman, oral and written communs., March 3 and May 12, 1999, respectively).

SHEEF: The Seismic Hazard Earthquake Epicentre File of the Geological Survey of Canada was compiled for use in making the 1995 national seismic hazard maps of Canada (Adams, et al., 1996). Magnitudes are $M_N$. The portion of SHEEF that I used spans the map area, extends through 1994 and down to $M_N$ 3.0, and was obtained in digital form from the Geological Survey of Canada after earthquakes from 1995 through 1998 were added from another Canadian catalog (S. Halchuk, written commun., February 26, 1999).

STOVER AND COFFMAN: Stover and Coffman (1993) compiled damaging earthquakes of the U.S. They defined "damaging" as at least MMI VI or magnitude 4.5 for the States of the map area. These authors reexamined and reassigned intensities according to uniform criteria, which led to revision of some locations. The catalog extends through 1989. Magnitude scales used for earthquakes within the map area are mostly $m_b$, $M_N$, and **M**.

## CATALOG CONSTRUCTION FOR VARIOUS PARTS OF MAP AREA

CANADA: Earthquake hazards in Canada are addressed by the national geological survey (Franklin, 1999). Accordingly, earthquakes in the Canadian portion of the map are represented almost entirely by SHEEF. The few exceptions occurred during 1995-1998 after SHEEF was completed, and were obtained from another Canadian catalog. Canadian earthquakes before 1930 that are listed in both emb.cc and SHEEF have magnitudes that average 0.4 units higher in SHEEF (Wheeler, unpub. results). The cause of the difference is unknown. Comparison of the current map with an early draft that used emb.cc instead of SHEEF for Canadian earthquakes showed that the current map shows more Canadian earthquakes with magnitudes of 3.0 or slightly larger than it would if the map had been compiled strictly from U.S. sources. For the 1925 Charlevoix, Quebec earthquake, the map uses $m_b$ 6.5 (Bent, 1992) instead of the 6.7 listed in SHEEF. Bent's analysis used previously unstudied seismograms that were unavailable to previous workers.

DELAWARE: The Delaware Geological Survey maintains its own list of earthquakes (S. Baxter, oral and written communs., March 26-July 15, 1999). The Delaware survey operates its own seismograph network as part of the LCSN. The survey has critically evaluated seismological data and intensity reports of events within and near Delaware. Results include some revisions of epicenters and magnitudes that are listed in standard sources. I used the survey's catalog for earthquakes within the boundaries of the State.

MARYLAND: The map shows mainly earthquakes from the catalog emb.cc and from the SEUSSN catalog (M. Chapman, written commun., May 12, 1999). The Maryland Geological Survey maintains its own list of earthquakes (J. Reger, oral and written communs., May 11-13, 1999). Comparison of emb.cc, the SEUSSN catalog, Gordon and Dewey (1999), and the list from the Maryland survey resulted in several improvements and additions to this map and the Maryland list.

NEW ENGLAND: The State geological surveys of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, and Connecticut all use Weston Observatory of Boston College as their authoritative source for earthquake matters. None of these surveys maintains their own lists of earthquakes. Accordingly, the map shows only the NEUSN and NESN catalogs for New England.

Ebel (2000) revised the location and magnitude of the damaging Newbury, Massachusetts earthquake of 1727. Previously the earthquake had been assigned a location 18 km offshore from northeastern Massachusetts. From a new compilation of aftershocks and analysis of a sequence of small earthquakes that occurred near Newbury in 1999, Ebel (2000) increased the 1727 magnitude from the previous estimate of $m_{bLg}$ 5.0 to $m_b$ 5.6, and moved the estimated epicenter onshore to approximately 10 km north of Newbury.

The location of the 1755 Cape Ann, Massachusetts earthquake is uncertain. Hitherto the earthquake had been assigned a location offshore from Cape Ann. However, Ellis and de Alba (1999) performed geotechnical analyses of sites at which liquefaction was reported in 1755, and suggested an onshore epicenter west of Boston. In contrast, the geographic distribution of intensity reports from the Cape Ann mainshock and the paucity of aftershock reports favor an offshore location. Pending resolution of this discrepancy, the map shows the standard offshore location.

The 1638 earthquake is the oldest shown on this map. Its location is uncertain by 100-200 km or more. From intensity data Ebel (1996) estimated a location on the Vermont-New Hampshire border but possibly ranging from northeastern New York State to central Maine. Ebel (2000) noted that more recent epicenters of smaller earthquakes in central New Hampshire form two diffuse alignments that trend north and northeast. Ebel (2000) speculated that either alignment might represent aftershocks of the 1638 mainshock. Ebel (1999) suggested that the 1638 epicenter might have been near Northfield, New Hampshire, and the map shows the earthquake at Northfield.

NEW JERSEY: The New Jersey Geological Survey maintains its own list of earthquakes in and near the State (D. Dombroski, oral and written communs., May 12 – June 15, 1999). The list was compiled from numerous sources, chief among them the NEUSN bulletins, the USGS PDE, and USGS monthly and annual publications. I obtained a digital copy of the State survey's earthquake list (D. Dombroski, written commun., June 10, 1999). NCEER-91 provided some missing magnitudes and improved locations, and the LCSN catalog provided records of recent earthquakes. J.G. Armbruster provided an improved location for the magnitude 5.2 earthquake of October 10, 1884, outside New York harbor (written commun., January 9, 1999). The new location moved the estimated epicenter across the New York boundary, slightly into New Jersey. By informal agreement with the New Jersey Geological Survey, for the 1884 shock I used the magnitude estimate of 5.2 from NCEER-91 instead of the estimate of 5.5 from Stover and Coffman (1993), because NCEER-91 was produced by seismologists of the Lamont-Doherty Earth Observatory. Within New Jersey, Lamont is likely to be the chief seismological authority.

NEW YORK STATE: New York has three organizations that members of the public in different parts of the State might regard as authoritative sources of earthquake information. (1) The New York State Geological Survey has headquarters in Albany in the east-central part of New York. The survey generally consults two published earthquake catalogs by Nottis (1983) and Stover and Coffman (1993). (2) The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is in Buffalo in western New York. The center funded production of the NCEER-91 catalog (Seeber and Armbruster, 1991). (3) The Lamont Cooperative Seismic Network is operated from the Lamont-Doherty Earth Observatory in Palisades in southeastern New York. The network contributed results to the NEUSN catalog through 1990 and to the LCSN catalog since then. Accordingly, the list of earthquakes to be shown on the map includes contributions from each of these authoritative sources within New York State. The core of the list is New York earthquakes listed in the NEUSN and LCSN catalogs, because these catalogs are primary sources of instrumental epicenters and magnitudes. To this core were added earthquakes, mostly pre-network, from Nottis (1983) and the catalog emb.cc; the emb.cc additions are nearly all from NCEER-91. Finally, the few locations or magnitudes of damaging earthquakes that did not match the values of Stover and Coffman (1993) were changed to match. The resulting catalog of New York State earthquakes is dominated by NCEER-91 before approximately 1940, then by NEUSN, and after 1990 by LCSN.

FAR OFFSHORE: Several sources listed differing numbers of earthquakes 100-300 kilometers offshore in the New York Bight, east of New Jersey and south of New England. Most were smaller than magnitude 3.0. The eight shown on the map were derived from the NEUSN and Weston catalogs, except one in 1847 of magnitude 3.5 that was attributed to Canadian sources by the New Jersey Geological Survey.

OHIO: The Ohio Geological Survey maintains its own list of earthquakes (M. Hansen, oral and written communs., May 6 and 10, 1999). The map shows three small earthquakes in the northeasternmost county of Ohio. Their records were obtained from the Ohio survey, Seeber and Armbruster (1993), and Gordon and Dewey (1999).

PENNSYLVANIA: The Pennsylvania Bureau of Topographic and Geologic Survey maintains its own list of earthquakes (R. Faill, oral and written communs., December 2, 1998 to March 9, 1999). The list was compiled from numerous sources, chief among them the bulletins of the NEUSN and LCSN, Gordon and Dewey (1999), the USGS PDE (Preliminary Determination of Epicenters) and related USGS digital catalogs and paper publications, and publications on specific areas or groups of earthquakes in the State. Faill and I consulted extensively with the aim of insuring that our catalogs for Pennsylvania matched. We discussed each earthquake individually, but some general guidelines emerged from frequent use. First, C. K. Scharnberger summarized evidence indicating that several events might be mine blasts instead of earthquakes (oral and written communs., January 7 to 18, 1999). To be conservative we retained most of these events in the State compilation and on this map, pending Scharnberger's planned publication of the evidence that some are blasts. Therefore, some blasts might remain on the map. Second, we preferred primary sources over secondary ones, and instrumental results over macroseismic locations or magnitudes. Third, we preferred results of Gordon and Dewey (1999) over those of the NCEER-91 catalog for early instrumental earthquakes, because Gordon and Dewey (1999) is more likely to be regarded as authoritative by the lay audience in Pennsylvania.

VIRGINIA: The State survey deferred to the Seismological Observatory at Virginia Tech. Accordingly, the map shows earthquakes from the SEUSSN catalog (M. Chapman, oral and written communs., March 30 and May 12, 1999), with a few small changes derived from comparison with emb.cc.

WEST VIRGINIA: The State survey deferred to the USGS. Accordingly, the map shows earthquakes from the SEUSSN catalog (M. Chapman, oral and written communs., with a few small earthquakes added as a result of comparison with emb.cc.

## DEPENDENT EARTHQUAKES

Aftershocks and foreshocks were detected and eliminated by inspection of each State's earthquake list. Criteria were subjective and some dependent earthquakes probably remain on the U.S. portion of the map. More than three fifths of the mapped earthquakes occurred in Canada. Thus, Canadian earthquakes are too numerous to attempt subjective detection of aftershocks or foreshocks. However, nearly all dependent earthquakes in the U.S. part of the map area occurred at locations that are indistinguishable from the mainshock epicenter at the scale of the map. Therefore, retaining dependent U.S. earthquakes would not have materially changed the appearance of the map, and the same is presumed to be true of Canadian shocks. If this presumption is valid, the only Canadian aftershocks or foreshocks that are likely to affect the appearance of the map are those of magnitude 5.0 or larger. These larger earthquakes are identified on the map by their years of occurrence. Accordingly, inclusion of dependent earthquakes larger than magnitude 5.0 would cause a visible excess of year labels on the map. Therefore, I examined each earthquake of magnitude 5.0 or larger for proximity in time or space to a larger shock. In this manner, seven aftershocks and one foreshock larger than 5.0 were detected and deleted, all of them in Canada.

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Langston, C.K. Scharnberger, L. Seeber, and M.N. Toksöz examined early drafts of the map and parts of its catalog and suggested numerous improvements. M.C. Chapman, Doll, Ebel, W.-Y. Kim, S. Halchuk, and Mueller graciously supplied digital data sets. Adams, S. Baxter, Chapman, D.R. Dombroski, Faill, M.C. Hansen, G.N. Nottis, J.P. Reger, and Scharnberger discussed the earthquakes of individual States and Canada, sometimes at a length and with a frequency that must have appalled them. The manuscript of this report was improved by suggestions from J.W. Dewey. Errors and omissions are mine alone.

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