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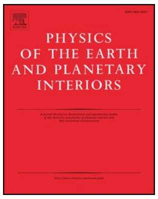

Have we seen the largest earthquakes in eastern North America?

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ABSTRACT

The assumed magnitude of the largest future earthquakes, M_{max}, is crucial in assessing seismic hazard, especially for critical facilities like nuclear power plants. Estimates are made using various methods and often prove too low, as for the 2011 Tohoku, Japan, earthquake. Estimating M_{max} is particularly challenging within tectonic plates, where large earthquakes are infrequent, vary in location and time, and often occur on previously unrecognized faults. For example, it is unclear whether the short historical record includes the largest possible earthquakes along the eastern continental margin of North America. We explore this issue by generating synthetic earthquake histories and sampling them over a few hundred years. Due to the short histories, the maximum magnitudes appearing most often in a sub-catalog, M_{max}^{a}, are often smaller than the maximum magnitude in the parent catalog, M_{max}^{p}, that can occur. Future earthquakes along the continental margin may thus be significantly larger than those observed to date. More generally, these simulations demonstrate that the largest earthquake in a catalog likely reflects a combination of catalog length, a region's earthquake productivity, and relative proportion of small to large events. For regions with low seismicity, small variations in b value, the ratio of large to small events, due to sampling has a significant impact on the expected recurrence times of large magnitude earthquakes. Although the precise likelihood of observing M_{max}^{p} depends on the distribution of recurrence times, a catalog shorter than an earthquake's mean recurrence time will likely not contain an event of that size. As a result, M_{max} cannot always be reliably estimated from earthquake catalogs.

1. Introduction

The 2011 Virginia earthquake that shook much of the northeastern U.S. showed that earthquakes large enough to cause significant damage do occur in eastern North America (Wolin et al., 2012) (Fig. 1). Assessing the hazard of such earthquakes poses major unresolved issues. Hazard maps, giving the maximum shaking expected in an area with a certain probability in some time period (Cornell, 1968), require assuming where and how often large earthquakes will occur and how large they will be. However, the recent Tohoku, Sumatra, and Wenchuan earthquakes illustrate that earthquakes much larger than previously expected occur in many places (Stein and Okal, 2007; Geller, 2011; Stein and Okal, 2011; Peresan and Panza, 2012; Wyss et al., 2012; Gulkan, 2013). Such surprises arise because parameters required to reliably estimate the hazards are often poorly known (Stein et al., 2012).

A crucial parameter is M_{max}, the magnitude of the largest earthquake expected on a fault or in an area (Stein et al., 2012). The Tohoku, Sumatra, and Wenchuan earthquakes were more damaging than expected because their magnitudes were much larger than the M_{max} assumed in hazard planning (Kanamori, 2011; Sagiya, 2011). Unfortunately, inferring M_{max} is difficult. Even where we know the long-term rate of motion across a plate boundary fault, or the deformation rate across an intraplate zone, neither predict how strain will be released although some models, like UCERF3 (Field et al., 2017), provide detailed probabilistic earthquake rupture forecasts. Estimates from the expected fault dimensions often prove incorrect. Strain release can occur seismically or aseismically, and seismic strain release can occur via earthquakes with different magnitudes and rate distributions.

As a result, quite different M_{max} estimates can be made using different methodologies (Kijko, 2004; Wheeler, 2009; U.S. Nuclear Regulatory Commission, 2012; Kagan and Jackson, 2013). Because all one can say with certainty is that M_{max} is at least as large as the largest earthquake in the available record, it was earlier practice to use that magnitude or add an ad hoc increment. However, because catalogs are often short relative to the average recurrence time of large earthquakes (McGuire, 1977; Stein and Newman, 2004; Bell et al., 2013), earthquakes larger than anticipated often occur. Long paleoseismic records, such as in Cascadia (Goldfinger et al., 2017), containing multiple earthquake cycles likely do a better job of estimating M_{max} than shorter historical catalogs. Some studies identify faults and use relations between fault length and earthquake magnitude (Wells and Coppersmith, 1994) to infer M_{max}. Other approaches extrapolate from current catalogs (Kijko, 2004) or combine areas presumed to be geologically similar

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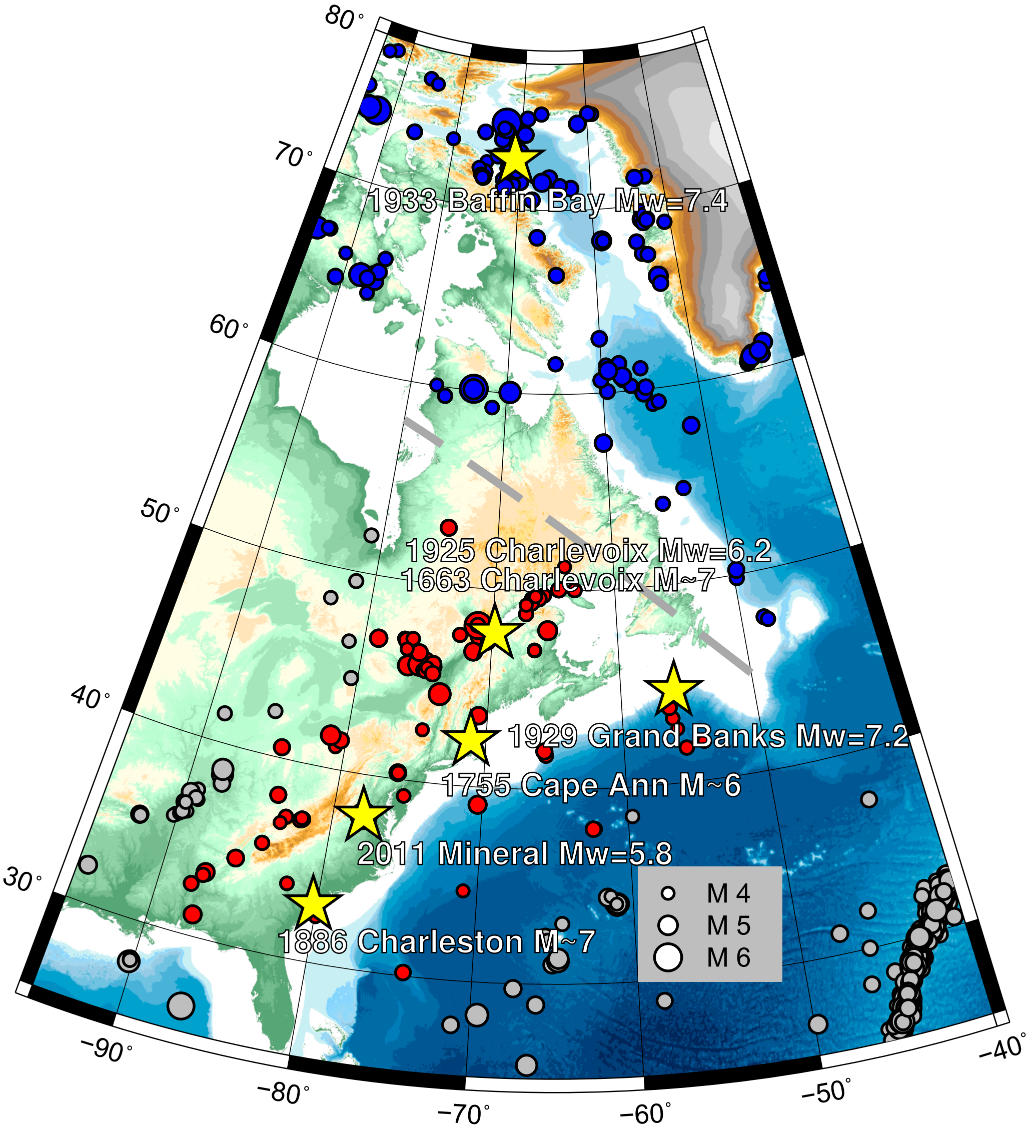

Fig. 1. Seismicity of the eastern North America continental margin taken from the ANSS catalog from 1985 through 2017. Red and blue dots correspond to seismicity along the southern and northern North America margins, respectively. Grey dots correspond to inland and oceanic earthquakes not included in the analysis. Grey dashed line indicates boundary between southern and northern margins. Major historical events are also shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to sample more large earthquakes (U.S. Nuclear Regulatory Commission, 2012; Kagan and Jackson, 2013).

Estimating M_{max} is challenging at plate boundaries, where known plate motion rates can be compared to earthquake records on known faults to infer the slip in, and thus magnitude of, large earthquakes (McCaffrey, 2008). The situation is even more complicated within plates, where deformation rates are poorly known, large earthquakes are rarer and variable in location and time, and often occur on previously unrecognized faults (Crone et al., 2003; Camelbeeck et al., 2007; Stein et al., 2009; Clark et al., 2011; Liu et al., 2011; Leonard et al., 2014). As a result, it is unclear whether apparent differences in M_{max} between various intraplate regions are real or artifacts of the short catalogs available (Vanneste et al., 2016).

Before continuing, we should note that M_{max} has slightly different meanings depending on the assumed frequency-magnitude distribution. Some distributions assume a "hard" M_{max} that the frequency-magnitude distribution truncates at or asymptotically approaches. Other distributions, assume a "soft" M_{max} where larger earthquakes are allowed but with a much lower frequency than predicted by the un-truncated Gutenberg-Richter relationship (Kagan, 2002). In a "soft" M_{max} distribution, M_{max} is a slight misnomer as some earthquakes are expected to exceed this threshold, although they would be exceedingly rare. Whether the use of a "hard" or "soft" M_{max} is more appropriate for hazard planning, is not addressed in this paper.

We explore the M_{max} estimation via earthquake catalog problem for eastern North America. Notable events along the southern North America margin include the 1755 Cape Ann (Massachusetts), 1886 Charleston, and 1929 Grand Banks earthquakes (Fig. 1). Larger earthquakes are known along the northern margin, notably the 1933 Baffin Bay event. This passive continental margin, like others, is not inert since it experiences moderate levels of seismicity (Stein et al., 1979; Stein et al., 1989; Schulte and Mooney, 2005; Wolin et al., 2012).

A challenge in assessing the earthquakes' hazard is that we know little about their causes, partly because they are relatively rare due to the slow deformation at such margins. Along plate boundaries, relative plate motion is the primary driver of seismicity. Geodynamic modeling, however, predicts that stresses from variations in topography and crustal structure across the margin, combined with sublithospheric