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Seismic Hazard and Risk and Stable Continental Earthquakes in Eastern North America

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ABSTRACT

Canada and the United States east of the Rocky Mountains make up Eastern North America, one of the nine stable continental regions (SCR) of the world. Its crust is old and for the most part tectonically stable. A recent study for the Electric Power Research Institute has shown that the seismic potential of SCR crust is not uniform but varies according to the degree of rifting or crustal extension that it underwent in the geologic past. This paper identifies three types of Eastern North America crust—unrifted, failed intracontinental rift complexes, and Mesozoic rifted passive margins—and provides an accounting of the known largest earthquakes and seismic activity of each. Such an approach allows seismic hazard and risk estimates for Eastern North America to be refined.

INTRODUCTION

An understanding of the seismic hazard and risk of midplate regions such as eastern North America is aided by comparison with better-known seismic regions. Japan, for example, divides its earthquakes, hence its seismic hazard, into two categories. The first and best known originates from the major and great earthquakes of the highly active subduction zone plate boundaries lying offshore. The second, less studied and less understood, is what they call their *inland* earthquakes, which arise from active faulting in the active intraplate region that is onshore Japan. The recent devastating Kobe earthquake was of this latter type.

An analogous dual classification also serves well for eastern Canada or, more broadly, eastern North America (ENA). The analog to the offshore plate-margin events of Japan are the offshore passive margin events of ENA. And the inland earthquakes of Japan have an analog in stable continental regions (SCR) such as ENA: the cratonic or Appalachian fold belt earthquakes that reactivate a tiny proportion of the abundant old faults of these regions. Thus for seismic hazard analysis inland SCR earthquakes may be divided into those occurring in crust that has not suffered rifting (extension) since the Precambrian (~570 mya) and those occurring in Paleozoic or Mesozoic rifted crust. A generalized mapping of the three types of continental crust is shown in Figure 1 for ENA.

Explaining and defining the characteristics of these categories of ENA earthquakes is the purpose of this paper. Its conclusions provide a framework for the estimation of ENA seismic potential and hazard.

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1. THE ENA OFFSHORE PASSIVE MARGIN

The most obvious characteristic of the world's continental passive margins is that their outboard margin marks the transition boundary between continental and oceanic crust. This boundary is a first-order feature of the Earth's surface layers. True oceanic crust is basaltic, no more than 10-15 km thick, and averages only ~7 km. Typical continental crust is granitic, of ~40 km average thickness with extremes of ~70 km and ~20 km. Typically the continental-oceanic boundary (COB) is abrupt, occurring over a lateral dimension of 10-20 km, but it can be transitional, extending over 100 km or more. The crust of the continental shelf out to the COB is typically thinned and faulted due to the rifting process and often intruded with magma. These effects may extend for hundreds of kilometers inboard of the COB.

The analogy between the offshore subduction zones of Japan and ENA's passive margin COB cannot be taken too far. The fundamental difference is the sustained relative motion between tectonic plates that takes place at the offshore Japan zones guarantees sustained generation of large earthquakes there. The COBs do not have this component of relative movement between plates; rather they are the sites of profound change in crustal properties within a single plate (in this case the North American plate). This change cannot guarantee large earthquakes in the sense of the Japanese offshore subduction zones. It does, however, seem to concentrate midplate earthquake activity for reasons that are not completely understood. Stein et al. (1989) provide a comprehensive analysis of stress concentration mechanisms at passive margins that may be important in explaining COB earthquakes. Alternatively, earthquakes may concentrate there because of the abundant faults—originally formed in the rifting process that opened the ocean basin—available for reactivation. An important question for the ENA COB is whether deglaciation stresses make formerly glaciated passive margins more susceptible to large earthquakes than never-glaciated margins.

Based on fairly sparse focal mechanism data (Johnston et al. 1993), most of the SCR passive margins of the world appear to be under compression with P-axes roughly aligned with absolute plate motion vectors. This suggests that locally generated stresses such as from deglaciation, sediment loading or crustal density contrasts are secondary to the tectonic stress regime imposed by global plate interactions. However, these secondary stresses are localized at or near the COB and produce there a concentration and/or perturbation of the regional stress field not found in the continental interior.

Worldwide, the COB and its inboard passive margins are the sites of some of the largest SCR earthquakes. As tabulated by Johnston et al. (1993), nine of the 15 known SCR earthquakes of moment magnitude **M** $\geq$ 7.0 occurred in passive margin crust: four of the nine were COB events. The largest of these was 1933 Baffin Bay (Figure 1) for which an early seismic moment determination (Stein et al. 1979) yields **M**7.7, but **M**7.3 estimated from its surface-wave magnitude (M_S 7.3) is probably more accurate. Bent (1995*a*) has recently determined that the 1929 Grand Banks earthquake was a complex strike-slip rupture of **M**7.2. The two largest inboard passive margin earthquakes in the world were both historical: the 1604 event in the Taiwan straits, estimated **M**7.6 (Johnston et al. 1993), and the 1886 Charleston event (Figure 1), estimated **M**7.4 (Johnston 1995).

The seismic activity rate of the COB cannot be estimated with any confidence. Seismographic coverage sufficient to monitor the COB for small and moderate events has been inadequate for most of this century. I will, however, provide estimates for the COB and Mesozoic margins in combination with the interior rift complexes in a later section.

The passive margins discussed in this section are the current ones for ENA, produced by the Mesozoic (~200 mya) opening of the present-day Atlantic Ocean. Wheeler (1995) recognizes a 'fossil' passive margin limit (Figure 1) produced by the rift-opening of the Iapetan Ocean at the beginning of the Paleozoic Era (~550-600 mya). It was the closure of the Iapetan Ocean that produced the ENA Appalachian fold belt during the Paleozoic; the crust between the Iapetan and Mesozoic margin limit consists mainly of Appalachian fold belt and Grenville province (1.0-1.2 by) rocks. Its largest earthquake is the 1897 **M**5.8 Giles County, Virginia event. Other notable events include a pair of mid-**M**5 shocks in New Hampshire in 1940 and the **M**5.5 New Brunswick earthquake in 1982. Major **M**≥7 earthquakes, such as Grand Banks, Baffin Bay, New Madrid, or Charleston, are not observed in this type of crust. In this respect the Iapetan margin crust does not differ from unrifted SCR crust.

2. CRATONS AND FOLD BELTS: UNRIFTED SCR CRUST

In September 1993 in the Killari-Latur region of peninsula India an **M**6.1 earthquake killed approximately 10,000 people. In magnitude, shallow focus, thrust faulting mechanism, surface rupture and geologic setting in unrifted Precambrian craton, it was a virtual twin of ENA's largest known earthquake in unrifted crust, the 1989 **M**6.0 Ungava earthquake in northern Quebec, which killed no one. This stark contrast highlights an aspect of ENA seismic risk that both comforting and troubling. Since European settlement Canada and the U.S. combined have experienced at least 15 SCR earthquakes of **M** ≥ 6.0. Yet the deadliest, 1886 Charleston, killed only ~60 people. In this century not a single life has been directly taken by an ENA earthquake (the tsunami from the 1929 Grand Banks event did kill ~30 people). Is the ENA seismic risk truly insignificant as this century's record suggests or have we just been lucky? Presently there is no scientific means to gauge whether significant ENA earthquakes will continue to miss urban areas. Our only useful approach to assess ENA seismic hazard is to quantify ENA seismic activity rates.

Earthquakes such as Ungava and Killari-Latur—with magnitudes **M** ≥ 6 and foci in ancient Precambrian cratons—are perhaps the rarest and least explainable type of earthquake that we know of. About the best we can say is that such events must be reactivations of ancient faults or shear zones stressed to failure by tectonic stresses transmitted from the plate boundaries to the interiors. It is possible but not demonstrated that stress localization or concentration mechanisms are a factor, as they almost certainly are at the COB. Continental cratons worldwide are densely packed with these ancient shear zones; at present it is impossible to forecast which may be the more likely sites for future Ungava-type earthquakes. Therefore the best way to characterize the seismic potential of unrifted SCR crust is with a seismic activity rate normalized to a given unit of crustal area. This is done in the Conclusions section in comparison with rifted crust.

3. RIFTED SCR CRUST

Only two intracontinental (or intracratonic) rifted regions are shown in Figure 1: the St. Lawrence rift complex, which includes the Saguenay and Ottawa grabens, and the Reelfoot rift complex, which is drawn to include the Rough Creek and Wabash Valley grabens, although it is controversial whether they do indeed link up with Reelfoot. Other minor ENA rifts or grabens that probably are not through-going crustal features are not shown, nor are Precambrian rifts such as the huge Midcontinent rift system of Grenville age. Because of their age these latter features are considered to be incorporated into the craton; worldwide, in all SCRs, Precambrian rifts, where identified, are aseismic to background seismicity levels.

Both rift systems have produced major earthquakes. The St. Lawrence rift includes the Charlevoix zone, second in ENA only to the Reelfoot rift's New Madrid seismic zone's record of large earthquakes. The principal **M**≥6 Charlevoix earthquakes include: 1663, **M**~6.6; 1860, **M**~6; 1870, **M**~6.5; and 1925, **M**=6.2 (Bent 1992). The intensity data of the historical events is poor so their magnitudes have an uncertainty of about ±0.5 **M** units. Elsewhere in the St. Lawrence system, large earthquakes occurred in 1732, **M**~6.2, near Montreal; 1935, **M**=6.1 (Bent 1995*b*) near Timiskaming at the western extreme of the Ottawa graben; and 1988, **M**=5.8, in the Saguenay graben. The 1989 Ungava earthquake mentioned above is the only known **M**≥6 earthquake in unrifted ENA crust.

The New Madrid seismic zone (NMSZ) of the Reelfoot rift system is infamous for its protracted sequence of very large earthquakes during the winter of 1811-1812. At least five of these events were felt throughout the eastern United States, and three of them were felt into Canada, one as far as Québec City. These are the largest known SCR earthquakes; magnitudes for the three largest have been recently estimated as **M**7.8-8.1 (Johnston 1995) with uncertainties of ±0.4-0.5 **M** units. The only other central U.S. **M**>6 earthquakes were also NMSZ events: 1843, **M**6.5, in northeastern Arkansas and 1895, **M**6.8, near the Missouri-Illinois border. All these earthquakes were in the nineteenth century; in contrast, the largest NMSZ earthquake of the twentieth century has been only in the low-**M**5 range. Because of its 1925 and 1935 **M**>6 earthquakes, the St. Lawrence rift has generated a greater seismic moment release in this century than the NMSZ.

The St. Lawrence and Reelfoot rifts are failed rifts or aulacogens that never reached the stage of producing oceanic crust. The Mesozoic passive margins represent one side of the successful Atlantic rift that separated North America from Europe and Africa. Thus both represent continental crust that has been 'damaged' by the rifting process. Johnston et al. (1993) have assessed the seismic activity rate for this combined category of rifted crust. This is conveniently expressed in terms of total rate of production expressed as an average time interval between occurrences of independent **M**≥5 and **M**≥6 events and normalized to per 10^5 km^2 of crust. Rifted crust ENA activity is compared to that of unrifted crust in the Conclusions section.

CONCLUSIONS

The crust of Eastern North America was divided into the basic categories of unrifted crust and crust that experienced post-Precambrian rifting. The later category may be further subdivided into imbedded intracontinental rift systems and Mesozoic passive margins, including the COB. In terms of seismic activity the distinction between rifted and unrifted crust is significant as shown in this concluding table extracted from Johnston et al. (1993):

Independent SCR and ENA Earthquake Activity Rates

Category	Area	Total: yrs. per M≥5.0	Total: yrs. per M≥6.0	per 10^5 km^2: yrs. per M≥5.0	per 10^5 km^2: yrs. per M≥6.0
SCR total	$132x10^6$ km^2	0.20	1.9	246	2450
SCR rifted	$37x10^6$	0.33	2.5	119	916
SCR unrifted	$96x10^6$	0.49	7.6	468	7178
ENA total	$24x10^6$	1.4	7.5	331	1770
ENA rifted	$8x10^6$	3.1	17.5	254	1420
ENA unrifted	$16x10^6$	2.7	16.4	426	2630

When uncertainties are accounted for, ENA's normalized production of **M**≥5 and **M**≥6 earthquakes is not significantly different from the global SCR average. However, the normalized rates for ENA rifted crust are nearly twice those of ENA unrifted crust. The unnormalized rates are roughly equal because there is twice as much unrifted as rifted ENA crust. For total SCRs, normalized rates for rifted crust exceed those for unrifted crust by a factor of 4 at **M**≥5, increasing to a factor of 8 at **M**≥6. If the St. Lawrence and Reelfoot failed rifts were computed separately, their normalized rates would far exceed all other ENA crust (except perhaps the COB whose area is unknown) because of their relatively small size and relatively high rate of **M**≥6 earthquakes. The highest priority to further refine these activity rates for hazard assessment is to understand the mechanism(s) that localize seismic activity along the ENA passive margins and within the imbedded rift systems.

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REFERENCES

Bent, A.L. 1992. A Re-examination of the 1925 Charlevoix, Québec, Earthquake. *Bull. Seism. Soc. Am.*, 82, 2097-2113.

Bent, A.L. 1995*a*. A Complex Double Couple Source Mechanism for the M_s 7.2 1929 Grand Banks Earthquake. *Bull. Seism. Soc. Am.*, submitted.

Bent, A.L. 1995*b*. An Improved Source Mechanism for the 1935 Timiskaming, Quebec Earthquake from Regional Waveforms. *Pure Appl. Geophys.*, submitted.

Johnston, A.C. 1995. Seismic Moment Assessment of Stable Continental Earthquakes, Part 3: 1811-1812 New Madrid, 1886 Charleston and 1755 Lisbon. *Geophys. J. Int.*, submitted.

Johnston, A.C., Coppersmith, K.J., Kanter, L.R., Cornell, C.A. 1993. The Earthquakes of Stable Continental Regions: Assessment of Large Earthquake Potential. *EPRI Report TR-102261*, Schneider, J.F. ed., Electric Power Research Inst., Palo Alto.

Stein, S. Sleep, N.H., Geller, R.J., Wang, S.C., Kroeger, G.C. 1979. Earthquakes along the Passive Margin of Eastern Canada. *Geophys. Res. Lett.*, 6, 537-540.

Stein, S., Cloetingh, S., Sleep, N.H., Wortel, R. 1989. Passive Margin Earthquakes, Stresses and Rheology. in Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound, Gregersen, S. and Basham, P.W, eds., Kluwer, Dordrecht, 231-259.

Wheeler, R.L. 1995. Earthquakes and the Cratonward Limit of Iapetan Faulting in Eastern North America. *Geology* (in press).

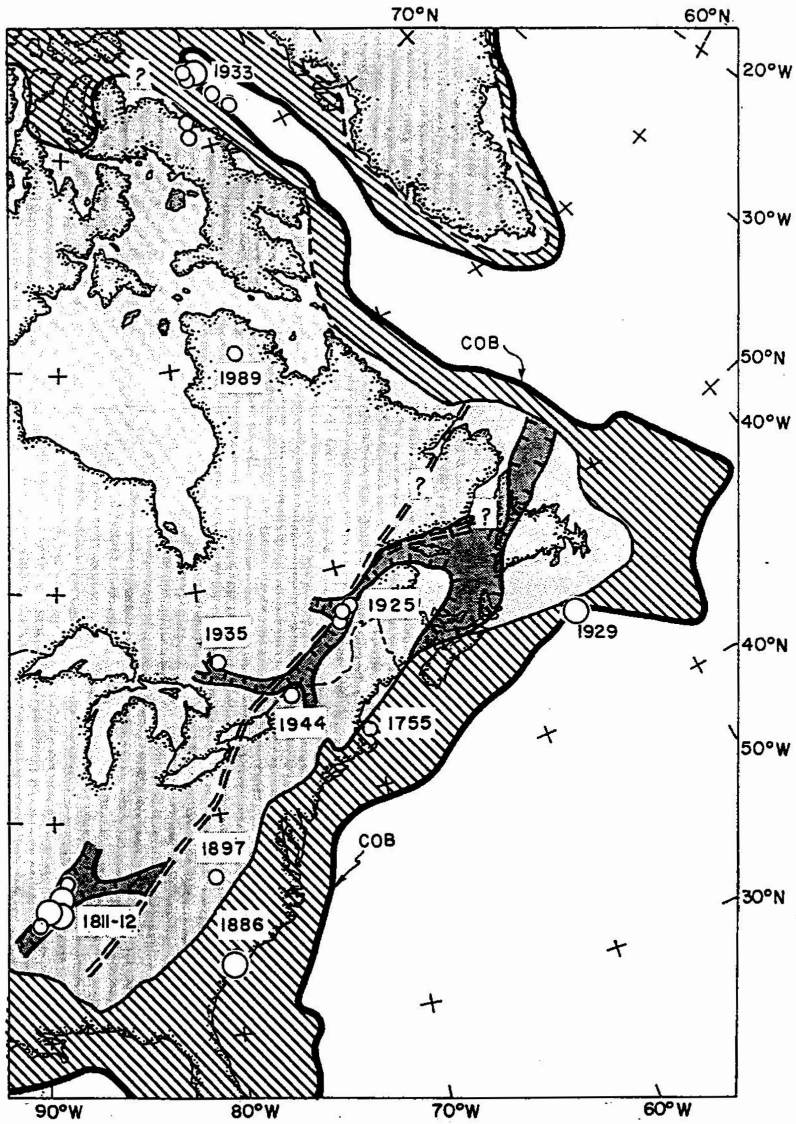

Figure 1. The three types of seismogenic continental crust of ENA. Diagonal pattern denotes the Atlantic passive margin with crust thinned and faulted to the inboard limit by the Mesozoic rift opening of the Atlantic. The Paleozoic Reelfoot (USA) and St. Lawrence (Canada) intracontinental rift complexes are shown by dark shading and tic-mark borders. Continental crust unrifted since the Precambrian is lightly shaded. Dual-dash line is the inboard limit of Iapetan (proto-Atlantic) rifting of Wheeler (1995). Major (**M** ≥ 5.8) ENA earthquakes are shown with dates; larger symbols denote **M** ≥ 7.0.