Earthquakes in the Charlevoix Seismic Zone, Québec, Canada

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With four earthquakes in the magnitude (M) 6 range since 1663 and more than 200 micro-earthquakes recorded there every year, the Charlevoix Seismic Zone (CSZ) is the most seismically active region of eastern Canada (Figure 1). Damaging earthquakes have occurred there in 1663, 1860, 1870 and 1925. The 1663 event caused landslides in Charlevoix and in the Quebec North Shore regions as well as along the Saguenay and St-Maurice rivers. The 1925 earthquake caused damage locally and as far away as 200 km where local soil conditions enhanced the level of ground shaking. Local landslides and lake disturbances suggest the occurrence of large prehistoric earthquakes. Despite these large earthquakes, no surface rupture has ever been reported in the geological maps, in the historical accounts, or in the scientific reports on the 1925 earthquake. A seismic reflection profile across the St. Lawrence River has not revealed the existence of a rupture beneath the River (Lamontagne, 2002).

Large CSZ earthquakes had local and regional impacts, a consideration taken into account in the seismic provisions of the National Building Code of Canada (NBCC). For the St. Lawrence valley, the seismic provisions of the upcoming NBCC are strongly influenced by the interpreted connection between earthquakes and rift faults in the CSZ and in other regions worldwide. According to the interpretation of the Geological Survey of Canada, the rift faults located along the St. Lawrence valley have a seismic potential higher than what is shown by their rather low level of historic seismic activity (Adams et al., 1996).

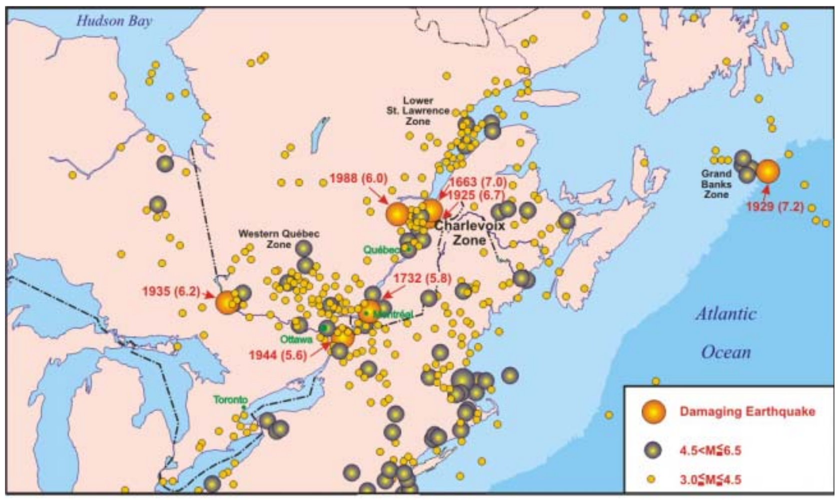

Figure 1. Earthquakes in eastern Canada. Earthquakes were selected on a completeness basis to insure a fair representation of the seismicity (historical and instrumentally recorded). Damaging earthquakes, with magnitudes in brackets, include: 1663 and 1925 in Charlevoix; 1732 near Montréal; 1929 Grand Banks; 1935 Timiskaming; 1944 Cornwall-Massena; and 1988 Saguenay. Most eastern Canadian earthquakes occur in these seismic zones: Grand Banks; Western Quebec; Lower St. Lawrence and Charlevoix.

The CSZ is remote from most large dams of Quebec, but relatively close to a large number of smaller dams and dykes. Following recommendations of Hydro-Québec (2001), the new regulations for these dams and dykes are based on the historical seismicity zoning developed by the Geological Survey of Canada (Adams et al, 1996). Thus, the seismic provisions are different from the GSC "robust" approach, which includes the geology-based zoning derived from the rift hypothesis model. In this historical model, the CSZ has a preferred M_X of 7.5.

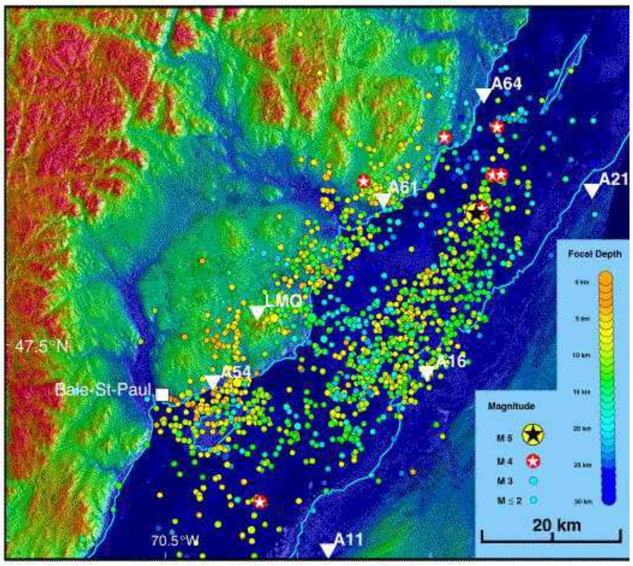

Figure 2. Chromo-stereoscopic image (about 80 km by 90 km; 30-m pixel size) that integrates a RADARSAT ortho-image with terrain elevation and seismicity (each data set with its own colour range). For the elevation, the colour range varies from 0 m in blue to 1100 m in red. The topography of the north shore is a mixture of rugged highlands plateaus and valleys separated by dramatic changes in elevation. A Devonian (350 Ma) meteorite impact created a semicircular depression 56 km in diameter. The earthquake hypocenters (circles) for January 1978-September 1999 are overlain, with colors related to focal depth. White triangles are the stations of the Charlevoix Local Seismograph Network, part of the Canadian National Seismograph Network

Looking at the CSZ earthquakes in detail reveals a very complex distribution pattern. Between 1977 and 2003, the local seismograph network recorded more than 3000 earthquakes with magnitudes between -1.0 and 5.0. The epicenters define a 30 by 85 km ellipse with the major axis parallel to the St. Lawrence River (Figure 2). Most of the larger events (star symbol in Figure 2) tend to concentrate at both ends of the CSZ, at the periphery of the Charlevoix meteor impact structure. At depth, CSZ earthquakes occur solely in the Precambrian basement from the surface to 30 km depth, with two thirds between 7 and 15 km. From the magnitude-recurrence curves, the return period of magnitude 6 earthquakes is approximately 75 years (Figure 3).

From a total of 25 focal mechanisms of M 2.0 to 6.2 earthquakes, it is known that CSZ earthquakes are produced by strike-slip to reverse faulting on fault planes with varied orientations (Lamontagne, 1999). For the larger events, such as the 1925 M 6.2 and the 1979 M 5.0 earthquakes, focal mechanisms suggest that N to NE trending paleo-rift faults are being reactivated in response to regional compression.

Earthquakes are not distributed uniformly across the seismic zone, but concentrate in groups separated by less active areas. Remote sensing imagery and geophysics (seismic methods, gravity, magnetics) highlight geological faults of the Precambrian, at the surface and at depth under the Appalachian nappes (Lamontagne et al., 2000).

The three large regional faults, the St-Laurent, South Shore and Charlevoix faults, seem to bound active volumes rather than being active themselves (Figure 4). For lower magnitude earthquakes, smaller fractures with various orientations might be reactivated by local stresses. A simultaneous hypocenter-velocity inversion has revealed that hypocenters occur in rocks that surround the lowest velocity regions and tend to avoid those with high velocity (Vlahovic et al., 2003).

The complexity of CSZ seismicity is tentatively explained by a combination of factors. CSZ fault zones may be irregular surfaces, surrounded by highly fractured rocks. These highly fractured zones respond primarily to regional stresses; however, for some smaller events, they may respond to local changes in stress and/or strength. The whole process can be enhanced, especially for deeper events, by high pore-fluid pressures.

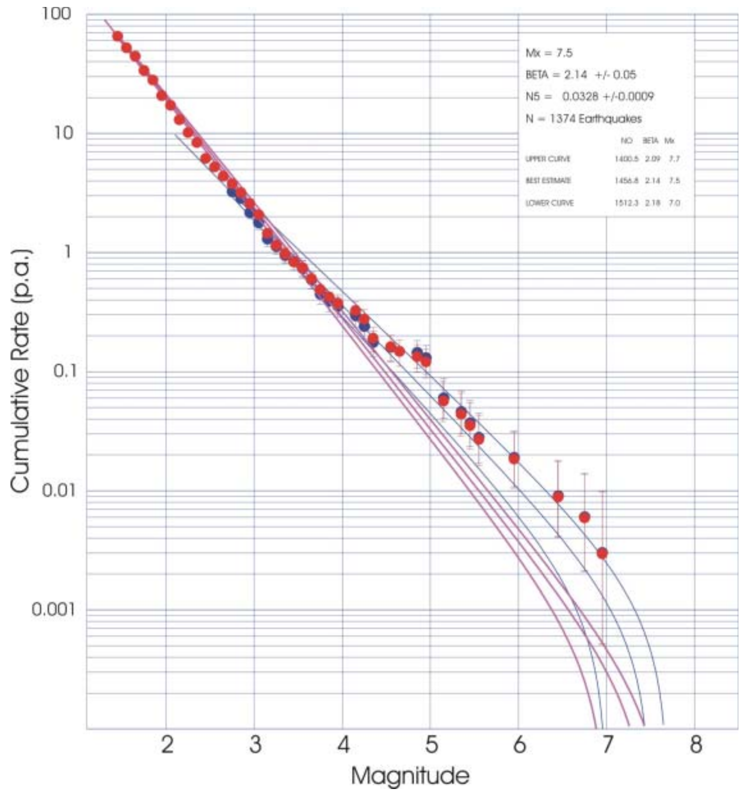

Figure 3. Magnitude-recurrence curves for the CSZ. The data points in red represent some 1374 earthquakes of the 1977-1997 period that meet the magnitude completeness criteria. The red curves represent the magnitude-recurrence curves (minimum-average-maximum) based on the data set. The blue dots and the blue curves represent the obtained curves without the data points that meet our completeness criteria for 1977-1997 (less than 300 points). From Lamontagne, 1999.

Even with the addition of all local stress contributors, the CSZ is not subject to substantially higher stress difference levels than the rest of Eastern Canada. Consequently, the anomalous CSZ earthquake activity must be due to inherent crustal weakness and/or high pore fluid pressure. Although the presence of a gouge may weaken some faults, we suggest that the existence of pervasive high pore-fluid pressure coupled with a high degree of fracturing explains the weak crust that gives rise to earthquake activity. Some rift faults may act as conduits to crustal fluids under pressure, triggering earthquakes on these faults and in neighbouring fractured volumes. Similar conclusions were found for the Lower St. Lawrence Seismic Zone, located in the estuary of the St. Lawrence River (Figure 1; Lamontagne et al, 2003).

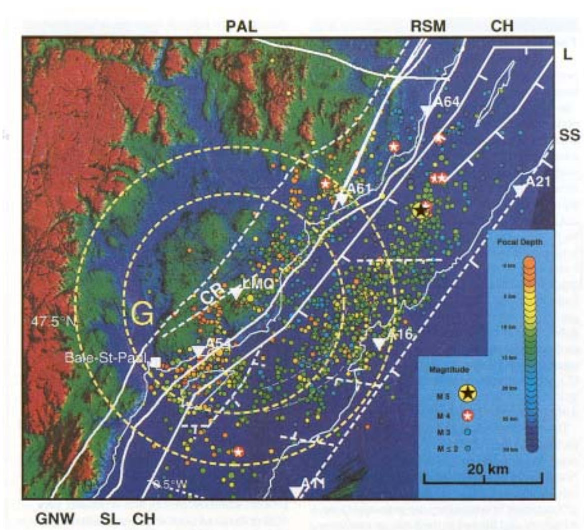

Figure 4. Geological structures of the CSZ. Acronyms used: PAL: Palissades fault; RSM: Rang Sainte-Mathilde fault; SL: Saint-Laurent fault; CH: Charlevoix fault; L: Lièvres fault; SS: South Shore fault; G: peripheral graben of the impact structure; CR: crater fault; GNW; Gouffre NW fault. See Figure 2 for hypocentre and station information.

The absence of any apparent CSZ surface rupture suggests that the current rates of seismic strain release are geologically recent. Had these rates existed over millions of years, evidence of this activity would have been mapped in the field and seen in the seismic reflection profiles. The earthquake activity likely started some thousands of years ago, possibly right after the last glaciation, when conditions were most favourable for reverse faulting in the CSZ. In all likelihood, the current conditions that create CSZ earthquakes may persist for thousands of years in the future. The current stress field depends mainly on factors that change on geological time scales, such as plate motions, and to a lesser extent, postglacial rebound and other stress contributors that will continue to play a role for thousands of years to come.

References

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Maurice Lamontagne obtained his first degree in Geological Engineering from Université Laval in Québec City. After gaining an MSc in geophysics from the University of Western Ontario in London, Ontario, he obtained his Ph.D. in Earth Sciences at Carleton University in Ottawa. Since 1985, he has been working with Natural Resources Canada as an earthquake seismologist specialized in eastern Canadian seismicity. His papers described earthquakes in seismic zones of Canada, including Charlevoix, the Lower St.Lawrence and Western Quebec. He participated in various field programs, analyzing the recorded data and correlating the results with the geological faults. He was involved in the analysis of induced earthquakes near the hydroelectric dams of Quebec, including the induced activity in the Sainte-Marguerite 3 (SM3) reservoir. Since September 2002, he is working with the new Canadian Program of Natural Hazards and Emergency Response.