# ARTICLE

## Canada's Earthquakes: 'The Good, the Bad, and the Ugly'

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### SUMMARY
Much of Canada is 'earthquake country'. Tiny earthquakes (that can only be recorded by seismographs) happen every day. On average, earthquakes large enough to be felt occur every week in Canada, damaging earthquakes are years to decades apart, and some of the world's largest earthquakes are typically separated by intervals of centuries. In this article, we provide details on the most significant earthquakes that have been recorded in, or near, Canada, including where and when they occurred, how they were felt, and the effects of those earthquakes. We also provide a brief review of how earthquakes are monitored across Canada and some recent earthquake hazard research. It is the results of this monitoring and research, which provide knowledge on earthquake hazard, that are incorporated into the National Building Code of Canada. This, in turn, will contribute to reduced property losses from future earthquakes across Canada.

### SOMMAIRE
Un bonne partie du Canada est un 'pays de séismes'. De petits séismes (que seuls les séismographes peuvent enregistrer) s'y produisent quotidiennement. En moyenne, un séisme assez fort pour qu'on le ressente s'y produit à intervalle d'une semaine; assez fort pour causer des dommages s'y produit à intervalle de quelques années à quelques décennies; alors que l'intervalle de récurrence des plus grands séismes est de l'ordre des siècles. Dans le présent article on trouvera des détails sur les plus importants séismes s'étant produits sur ou à proximité du territoire canadien, incluant le lieu et le moment, leurs manifestations et leurs répercussions. On y décrit sommairement les moyens de détection déployés sur le territoire canadien ainsi que quelques-unes des recherches récentes sur les risques sismiques. Ce sont les résultats des efforts de surveillance et des recherches sur les tremblements de terre qui ont été intégrés dans le Code national du bâtiment du Canada. Et cela aidera à amoindrir les répercussions des séismes à venir sur la propriété.

### INTRODUCTION
It is easy to forget that large and damaging earthquakes have struck Canada because, typically, they occur decades apart, often located in offshore or remote, unpopulated regions. It is even easier to forget that some of the world's very largest earthquakes have struck within, or adjacent to, our country. These huge (magnitude (M) 8 or 9) earthquakes are typically centuries apart, and are often located in remote areas. In this article, we summarize Canada's 'good', 'bad', and 'ugly' earthquakes. We define 'good' earthquakes as those that either:

- have been widely felt, and therefore have made people more aware of (and perhaps better prepared for) future earthquakes; or
- those that are large enough to be 'scientifically useful'—they teach us about the potential impact of future earthquakes in Canada.

'Bad' earthquakes are those that have caused significant damage (including landslides, structural damage, and other effects) in Canada, and 'ugly' are some of the world's largest earthquakes (larger than M 8). The purpose of this article is twofold:

1. To summarize the effects of Canada's most significant earthquakes (reminding us that destructive earthquakes have struck Canada in the past, and will do so again in the future); and
2. To highlight new earthquake resources that constitute valuable tools for education and earthquake preparedness. This includes the new and updated 'Earthquakes Canada' website [http://www.earthquakescanada.ca] and the updated list of significant Canadian earthquakes (Lamontagne et al. 2008).

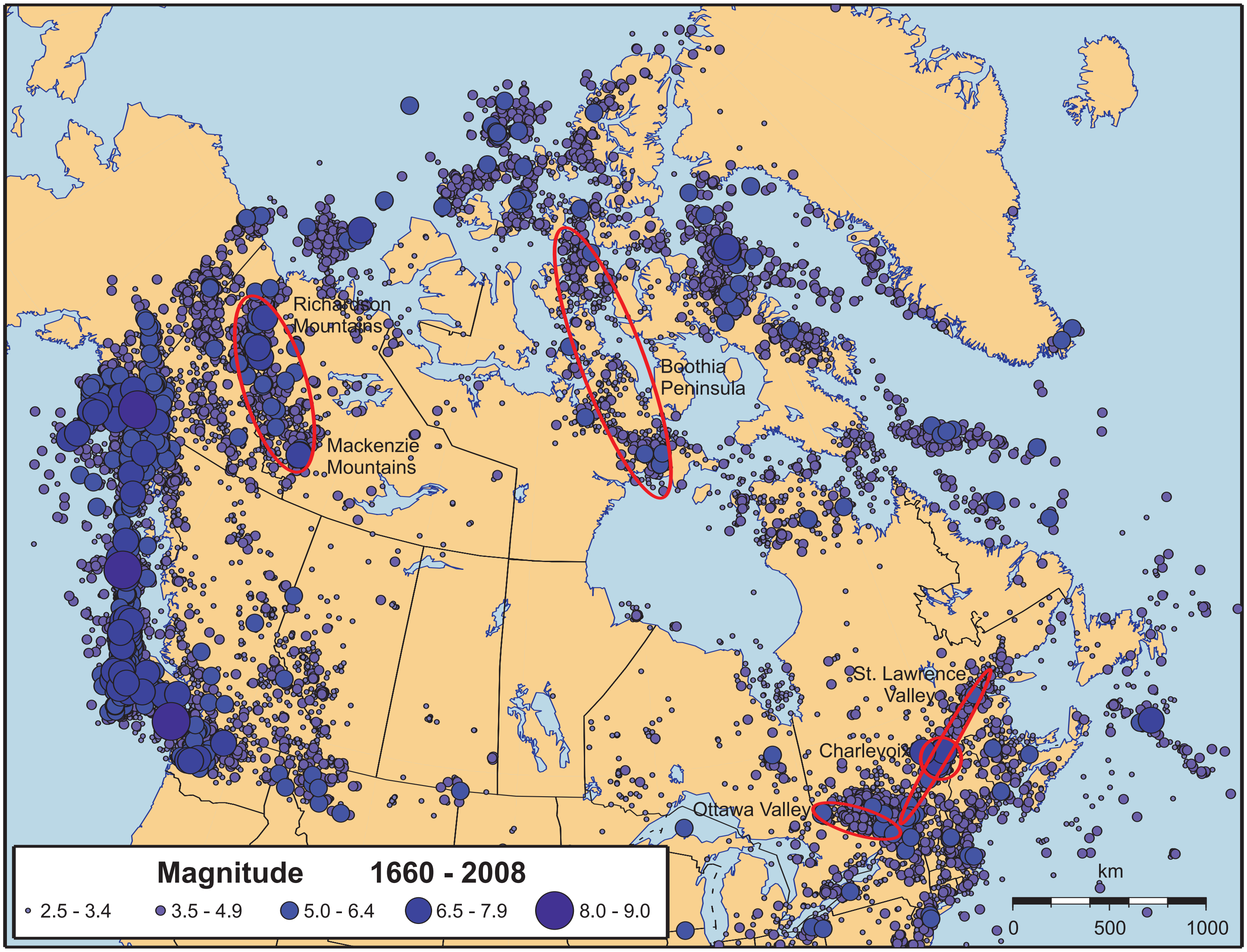


**Figure 1**. Map of earthquakes with magnitude ≥2.5 in Canada (1660–2009). The red ellipses and article highlight some of the areas discussed in the text.

## CAUSES OF EARTHQUAKES IN CANADA

Each year in Canada, approximately 4000 earthquakes are detected by seismologists at Natural Resources Canada. The earthquake distribution (Fig. 1) can largely be explained by tectonic setting (Fig. 2); for example, most of the earthquakes occur along the active plate boundaries off the west coast. However, there is also significant activity throughout the Cordillera (particularly in the Yukon and Northwest Territories), along the Arctic margin, in the Ottawa and St. Lawrence river valleys, in the northern Appalachians, and along the eastern offshore margin. The fewest earthquakes occur within the stable craton (including the plains of Saskatchewan and Manitoba; Fig. 2). An average of approximately 50 earthquakes are felt across Canada each year.

The largest and most frequent earthquakes occur along the west coast, and most are associated with plate motions and active faults (Fig. 2). In southwestern British Columbia (BC), the oceanic Juan de Fuca and Explorer plates are subducting beneath the North American Plate at a rate of 2–4 cm/yr (Riddihough and Hyndman 1991). This subduction process produces three types of earthquakes: those within the subducting plate (typically at 30–60 km depth), those within the North American Plate (down to 30 km depth), and giant subduction earthquakes along the interface between the latter two plates. The last of the three types are sometimes also referred to as megathrust, or great earthquakes. Just to the north of Vancouver Island, the Pacific and North America plates slide past one another along the Queen Charlotte Fault (Canada's 'San Andreas'). This seismically active fault zone produced Canada's largest historic earthquake – a M 8.1 event just west of the Queen Charlotte Islands in 1949. This fault extends north to the Yakutat region of Alaska, where collisional tectonics (including a subduction zone to the west that generated a M 9.2 earthquake in 1964) again dominates.

The seismicity in the Richardson and Mackenzie mountains of the Yukon and Northwest Territories (Fig. 1) results from crustal stress being

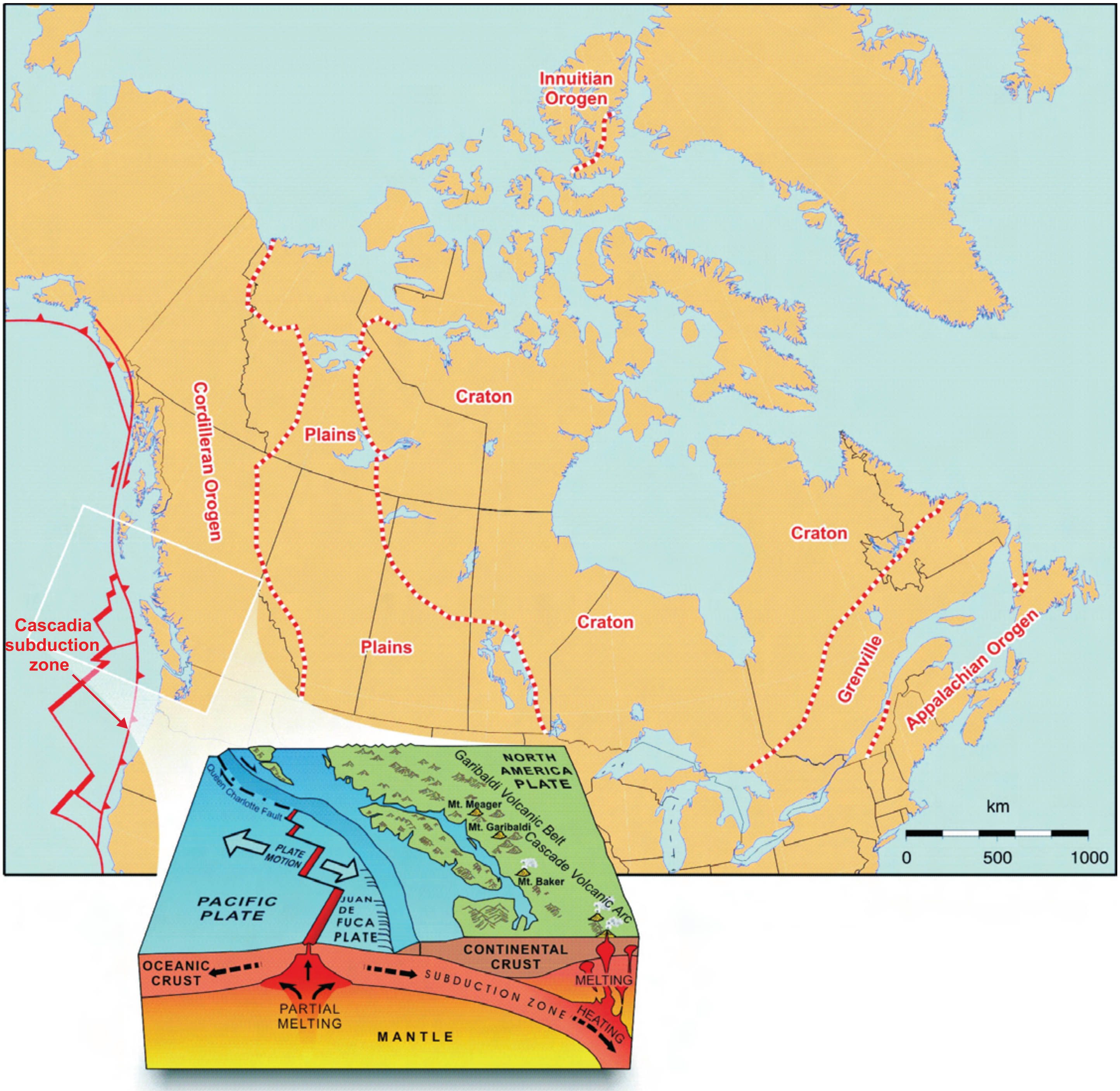


**Figure 2**. Major tectonic features of Canada. Inset shows the active tectonics along Canada's west coast, including the Queen Charlotte Fault and the subduction zone.

transferred from the Yakutat collisional zone to reactivate shallow thrust faults within the foreland fold and thrust belt of the Mackenzie Mountains (Mazzotti et al. 2008) and strike-slip faults within the Richardson Mountains (Cassidy and Bent 1993). The seismic zones along the eastern Arctic margin (including a M 7.2 earthquake in Baffin Bay in 1933) are situated at the ocean–continent transition, and may be related to the reactivation of Mesozoic rift faults. Seismicity within the Labrador Sea is concentrated on the extinct spreading ridge and associated transform faults associated with the breakup of Pangea. Concentrations of seismicity near Baffin Island and across the Boothia and Ungava peninsulas may be caused by postglacial rebound (Adams and Basham 1991).

In eastern Canada, earthquakes are believed to be primarily caused by a northeast-to-east oriented compressive stress field reactivating zones of crustal weakness – either failed rifts or old fault zones (Kumarapelli and Saull 1966; Adams and Basham 1991). The most active zones are located at the mouth of the St.

Lawrence River, near La Malbaie in Charlevoix County, in western Québec/eastern Ontario, and in the northern Appalachians. Charlevoix (Fig. 1) is the site of five large earthquakes (M >6) since 1663, the most recent being in 1925. The offshore Atlantic margin (southeast of Newfoundland) experienced a magnitude 7.2 earthquake in 1929.

## EARTHQUAKE MONITORING IN CANADA

Earthquake monitoring began in Canada in the late 1800s. The first known, instrumentally detected earthquake in Canada was the March 23, 1897 M~5 Montreal-area event, recorded on a 3-component seismograph at McGill University in Montreal, Québec (QC). The first continuously operating seismographs in Canada were located in Toronto, Ontario (ON) (installed September, 1897) and Victoria, BC (starting September 3, 1898). These were low-gain Milne seismographs (most sensitive to large, distant earthquakes), which were a part of the global network established by the British Association for the Advancement of Science. Additional low-gain seismographs were deployed across Canada (e.g. Ottawa, Halifax, St. Boniface and Saskatoon) during the first two decades of the 1900s. For a detailed description of the early history of earthquake recording in Canada, see Stevens (1980), Rogers (1992), and Basham and Newitt (1993).

Significant upgrades in earthquake monitoring capacity in Canada occurred in the 1960s, 1970s, 1990s, and most recently in the early 2000s. In the early 1960s, 24 'standard' seismic stations (similar to the 'World Wide Standard Seismic Network') were deployed across Canada. These stations contained 'short-period' as well as 'long-period' seismographs (using photographic recording) and recorded both local and global earthquakes. With this network, any earthquake larger than about M 3.5 beneath the Canadian landmass could be recorded. Starting in the mid 1970s and into the 1980s, digital telemetered networks with short-period seismometers were installed in both southwestern BC and southeastern Canada. These networks provided, for the first time in Canada, real-time access to seismic data. Beginning in 1991, the Canadian National Seismograph Network (CNSN) was completely modernized (North and Beverley 1994), with digital data from approximately 80 sites being continuously transmitted in real-time (via satellite links, dedicated phone lines, and UHF radio links) to data processing centres in Sidney, BC and Ottawa, ON. Nearly half of the stations included state-of-the-art three-component broadband seismometers. This network lowered the magnitude threshold in most areas of Canada (except the far north) to about M 3. In 2000, the POLARIS seismic network – a partnership of government agencies, Canadian universities, and industry – began to be deployed across Canada. POLARIS deployed more than 90 three-component broadband, digital seismic stations across the country, targeting specific research areas (including seismic hazard, mapping earth structure for the diamond industry, etc.). As of 2009, there are more than 120 seismic stations operating within the CNSN, and more than 100 POLARIS sites in operation (Fig. 3).

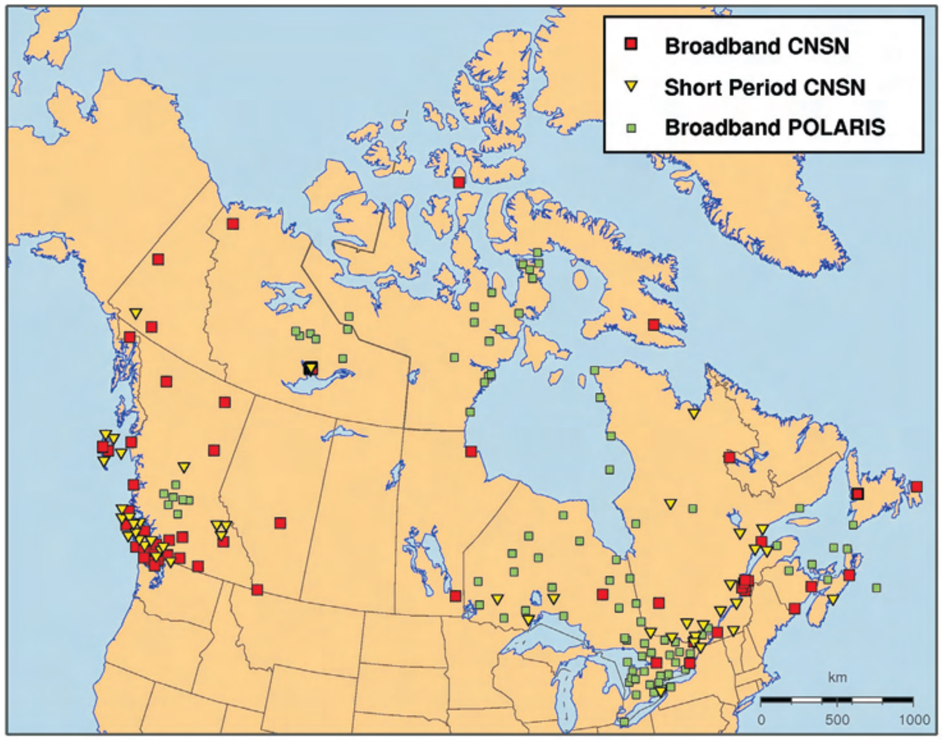


**Figure 3**. The CNSN and POLARIS seismic stations operating in Canada in 2009.

In addition to the CNSN and POLARIS networks, the Geological Survey of Canada (GSC) operates a 'strong motion seismograph network'. These instruments are designed specifically to record the very strong shaking associated with large earthquakes (when the 'standard' seismographs may be off-scale), thereby providing information critical for engineering purposes. As of 2009, the GSC operates 123 strong-motion instruments in Canada (Cassidy et al. 2007; Fig. 4a, b). Most of these instruments are modern 'Internet Accelerometers' located in the urban centres of southwestern BC (Fig. 4c, d). These low-cost instruments, designed at the Natural Resources Canada (NRCan) office in Sidney (Rosenberger et al. 2007), transmit data in real-time via the Internet. In addition, when triggered by strong shaking, they send information on the shaking level via e-mail to key clients.

## CANADA'S EARTHQUAKE HISTORY

The known earthquake history of Canada varies significantly across the country, largely because of the time lag associated with European exploration (and hence written records); this history begins in the early-mid 1500s in eastern Canada, but not until the late 1700s along the BC coast. Canada's first reported earthquake is based largely on Huron oral tradition and describes an earth tremor felt at the

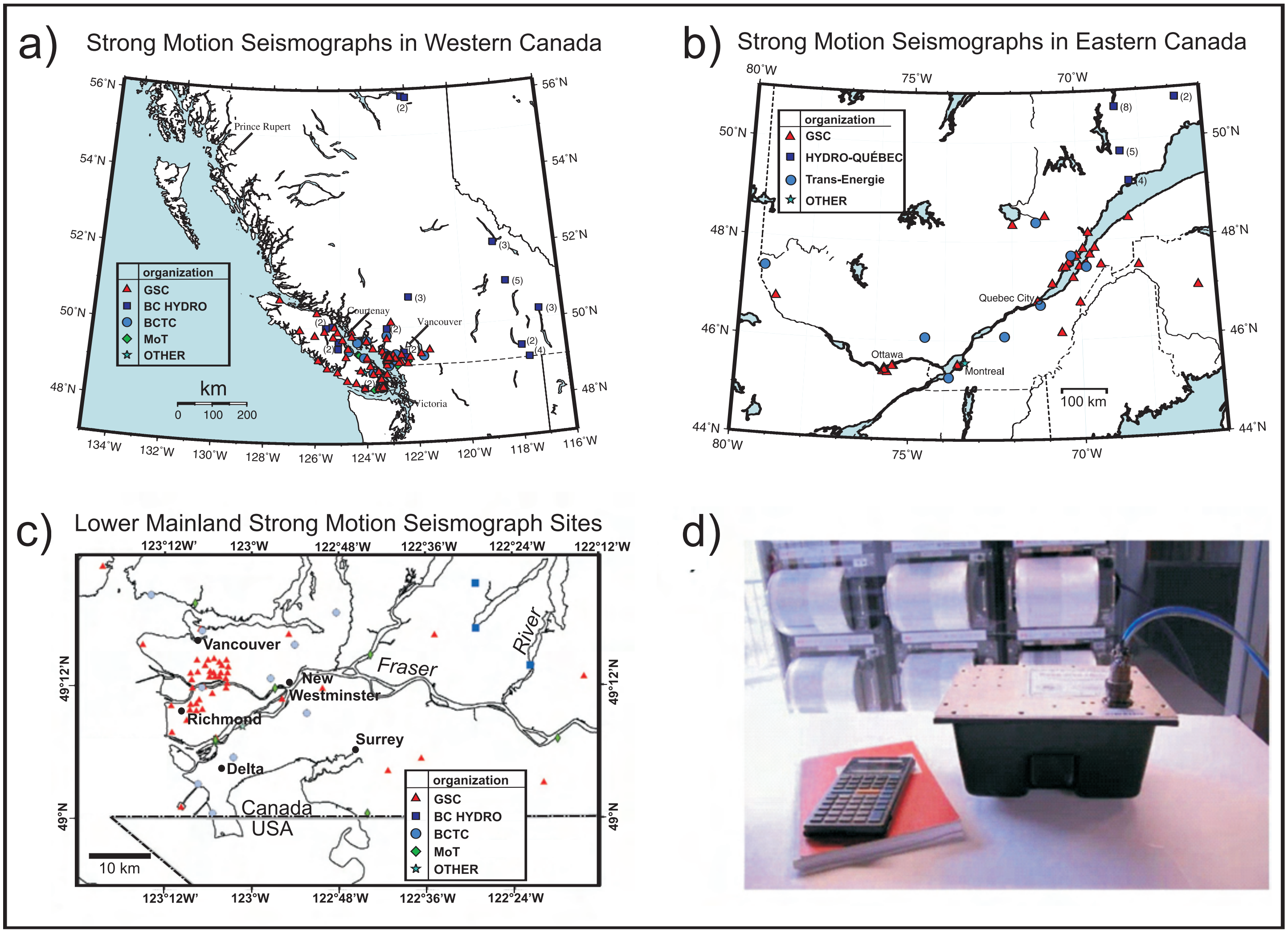


**Figure 4**. Maps of strong-motion seismographs in a) western Canada, b) eastern Canada, and c) the dense network in greater Vancouver; d) a photograph of a strong motion 'Internet Accelerometer'.

southeastern end of Georgian Bay, ON, "prior to 1637" (Gouin 1994). The first reported earthquake in western Canada is described in Captain George Vancouver's journal. He wrote that, "on February 17, 1793, a very severe shock of an earthquake had been felt" at the Spanish settlement at Nootka on the west coast of Vancouver Island (Rogers 1992). There are also numerous first nations' oral traditions associated with earthquakes, described later in this article. In northern Canada, the first reported earthquake in the Yukon Territory was described in the journal of Robert Campbell of the Hudson's Bay Company. He wrote that at Fort Selkirk (west-central Yukon) on December 27, 1850 "an earthquake was felt here for the space of one minute. It was very severe and the houses were visibly affected…" (Jackson 1990).

During historic time (1660–2009), more than 621 earthquakes of M >5 (i.e. earthquakes capable of causing damage in populated areas) have occurred in, and adjacent, to Canada. Some of these are described in more detail in the following sections. In many cases, additional information (including damage photographs) on the earthquakes listed below can be found on the 'Earthquakes Canada' website [http://earthquakescanada.nrcan.gc.ca] under the heading of 'Historic Events'. Note that throughout this document the generic term 'magnitude' is used. There are many different types of 'magnitude' scales; however, all define the size of an earthquake, and are related to the amount of energy released. We use the preferred magnitude from the Canadian Earthquake Epicentre File database. In most cases, this is either a 'moment magnitude' (Mw) or 'surface wave magnitude' (Ms) which are the best magnitude scales to use for large (M >5) earthquakes.

## Potentially Damaging (M 5.0–6.4) Earthquakes ('The Good')

For the purposes of this article, 'good' earthquakes are defined as those that were widely felt (thereby providing a 'friendly reminder' to people that earthquakes occur, and often prompting them to become better prepared for future earthquakes), and scientifically useful for understanding and better assessing hazards associated with future, potentially larger earthquakes. However, these earthquakes are not 'good' in the generally accepted sense, as, in some cases, they seriously fright-

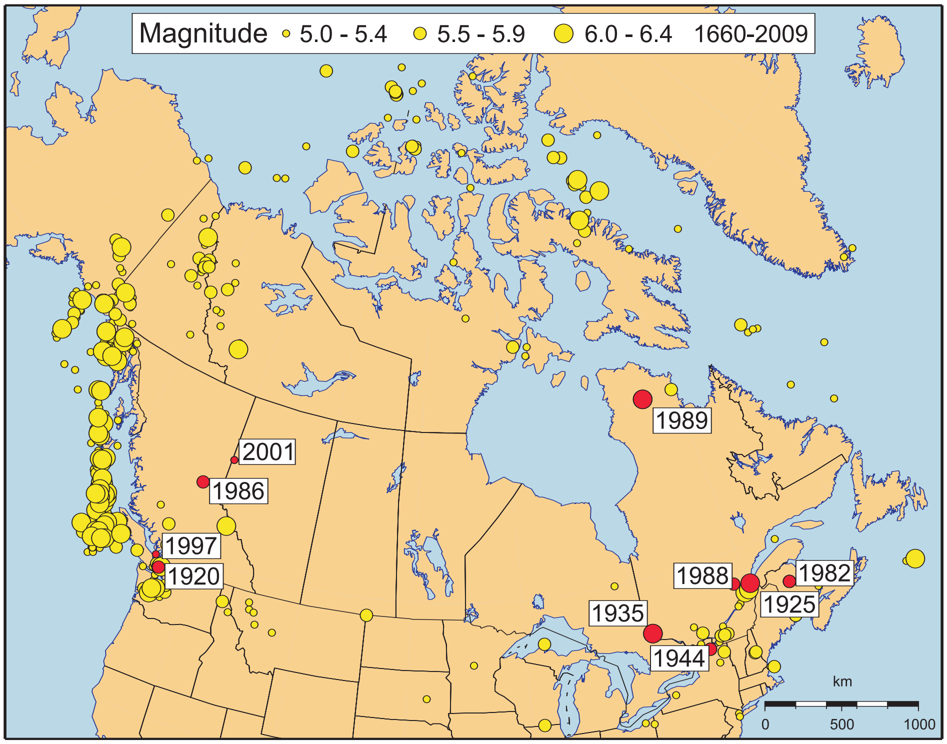


**Figure 5**. Location of all 'good' (M 5.0–6.4) earthquakes in Canada (1660–2009). Those highlighted in red are discussed in the text.

ened people and caused millions of dollars in damage. Typically, these earthquakes range in magnitude from about 5.0 to 6.4 (Fig. 5). In total, 561 earthquakes within this magnitude range have occurred within or adjacent to Canada between 1660 and 2009 (Fig. 5). Details on ten 'good' earthquakes are provided below.

### *1920: M 5.5, Gulf Islands, British Columbia*

This earthquake struck at 11:10 p.m. local time on January 24. It was centred beneath the Gulf Islands and was felt across much of southwestern BC and northwestern Washington State to distances of at least 150 km. There were numerous reports of minor damage. At Bellingham and Anacortes, Washington, brick walls were cracked; in Vancouver, some bricks fell from chimneys; at Victoria, plaster cracked and dishes fell; at Brentwood, the concrete chimney and wall of an electric power plant were cracked; and on Mayne Island, the metal chimney at a lighthouse was damaged (Milne 1956).

### *1925: M 6.2, Charlevoix, Québec*

On February 28, 1925, at 9:19 p.m., a M 6.2 earthquake struck the Charlevoix–Kamouraska area (Fig. 5). Shaking from this earthquake was felt across much of eastern North America, to distances of 1000 km. This earthquake caused considerable damage near the epicentre along the St. Lawrence River. The cracked walls, fallen chimneys and broken windows reminded local inhabitants that they live in an active seismic zone that has experienced 5 major earthquakes since 1663. In addition to homes, some very important structures were damaged by the quake: the church in Saint-Urbain, the railway terminal (Gare du Palais) and port installations in Québec City, and a church as far away as Shawinigan (about 250 km from the epicentre). In the weeks that followed, dozens of aftershocks continued to shake the area, keeping the inhabitants living in fear. For additional details, see Bent (1992) and Bruneau and Lamontagne (1994).

### *1935: M 6.2, Témiscaming, Québec*

On November 1, 1935, just after 1 a.m. a M 6.2 earthquake struck about 10 km east of Témiscaming, QC. This earthquake was felt west to Thunder Bay, ON, east to the Bay of Fundy, across the northeastern United States, and south to Kentucky and Virginia (more than 1100 km from the epicentre). In Témiscaming, about 80% of all chimneys were damaged. In addition, cracks developed in some solid brick walls. In Mattawa and North Bay (both about 70 km from the epicentre), many chimneys were thrown down. In the epicentral region, minor rockfalls were observed as well as cracks in the gravel and sand at the edges of islands and borders of lakes. In the months that followed the earthquake, numerous aftershocks were felt in Témiscaming and Kipawa. The day following the earthquake, it was observed that the water of Tee Lake close to the epicentre was discoloured by shaking caused by the earthquake. Near Parent, QC (300 km away from the epicentre), 30 m of railroad embankment slid away. Témiscaming continues to be seismically active. Residents were reminded of this on New Year's Day, 2000, when a M 5.2 earthquake struck the region; this caused some minor damage in Témiscaming and was felt as far as Toronto. For additional details, see Hodgson (1936), Hodgson (1945), and Bruneau and Lamontagne (1994).

### *1944: M 5.6, Cornwall, Ontario*

This M 5.6 earthquake occurred just after midnight on September 5, 1944. It was felt from New York to Boston to Québec City and Toronto. It caused considerable damage (estimated at $2 million) in Cornwall, ON (where about 2000 chimneys were damaged), and Massena, New York (where 90% of the chimneys were damaged or destroyed). Most of the damage occurred in areas underlain by the Leda Clay (ancient glacial lake sediments) of the St. Lawrence River valley. For additional information on this earthquake, see Hodgson (1945) and Bruneau and Lamontagne (1994).

### *1982: M 5.7, Miramichi, New Brunswick*

Just before 9 a.m. on January 9, 1982, a M 5.7 earthquake struck near Miramichi, New Brunswick (NB). This event came as a shock to local residents who were unaccustomed to earthquakes, as did the M 5.1 aftershock that struck 3½ hours later. These earthquakes were felt across the Maritime provinces, eastern Québec and the New England states, to distances of about 350 km from the epicentre. People in highrises in Ottawa and New York City felt swaying from the surface waves generated by this earthquake. Fortunately, because the immediate epicentral area was unpopulated, damage was very slight: a few hairline cracks but no structural damage in buildings up to 100 km away. Although there was no evidence for rupture at the surface, high-quality digital data and monitoring of aftershocks showed a very clear 'image' of a west-dipping rupture zone (fault) just below the surface. For more information, see Basham et al. (1982) and Basham and Adams (1984).

#### *1986: M 5.4, Prince George, British Columbia*

On March 21, 1986 at 3:56 p.m. a widely felt M 5.4 earthquake occurred in an area of low historic seismicity just west of the Rocky Mountains in east-central BC (Fig. 5). The epicentral region is sparsely populated and only minor damage (mainly to older masonry chimneys) occurred, although the earthquake was felt strongly in Prince George, 70 km to the west. Within 48 hours of the main shock, portable short-period seismographs were deployed in the epicentral region and operated for eight days. The few aftershocks that were recorded were confined to a depth range of 9 to 16 km, and the largest was M 2.5. No foreshocks were detected by the CNSN. The occurrence of this earthquake and several other moderate-to-large earthquakes in the northern and central parts of the eastern Cordillera raises the question of the level of seismic hazard in the more populated southern section of the eastern Cordillera. For additional details on this earthquake see Rogers et al. (1990).

#### *1988: M 5.9, Saguenay, Québec*

On Friday, November 25, 1988 at 6:46 p.m. the largest earthquake in eastern North America in 53 years occurred 35 km south of Chicoutimi, QC and about 150 km north of Québec City (North et al. 1989). The epicentre was located in a relatively 'seismically quiet' area, and had a deep focus (29 km beneath the surface). Few aftershocks were recorded, but it was preceded by a foreshock of M 4.7 on November 23, 1988. It was felt as far away as Detroit, Boston, Halifax, and southern Labrador. Damage in the sparsely populated epicentral area was modest, limited to cracked or fallen un-reinforced masonry walls; however, eleven landslides were attributed to the earthquake. Damage outside the epicentral area was correlated with underlying unconsolidated sediments; for example, nearly 350 km from the epicentre, the former Montréal Est City Hall (built on 17 m of clay) suffered severe damage to its masonry cladding. Detailed analysis of seismic data from this earthquake by a large number of researchers (e.g. Hough et al. 1989; Boore and Atkinson 1992; Boatwright and Choy 1992; Somerville et al. 1990) has provided valuable insight into the nature of moderate earthquakes in eastern North America. For example, the strong ground motion recordings exceeded predicted levels, which Haddon (1992) attributed to the direction and focusing of seismic energy, whereas other researchers (Boore and Atkinson 1992) related it to the earthquake source properties and directional differences in how seismic waves attenuate.

#### *1989: M 6.3, Ungava, Québec*

On December 25, 1989 a M 6.3 earthquake occurred in the remote area of Ungava, in northern Québec. Only weakly felt at distant villages along Ungava Bay, this was one of the most significant earthquakes of the century, as it provided the first historical evidence for surface faulting in eastern North America (Adams et al. 1991). It also allowed, for the first time in eastern North America, an opportunity to compare the extent and magnitude of surface faulting and regional deformation with waveform modelling of the rupture process (Bent 1994) and aftershock distribution. The surface effects also indicate the type of evidence to be sought from prehistoric ruptures. The observation of surface faulting, and comparison with modelling from the seismic observations, was a major leap forward in constraining seismic hazard in eastern North America.

#### *1997: M 4.7, Georgia Strait, British Columbia*

At 7:40 a.m. on June 24, 1997, a M 4.7 earthquake struck southwestern BC. This earthquake, located beneath the Strait of Georgia midway between the population centres of Vancouver (30 km to the east) and Nanaimo (30 km to the west), was felt across most of Vancouver Island and east as far as Abbotsford (100 km away). Minor damage included broken glass in Vancouver and a broken water pipe in North Vancouver. This earthquake triggered a rush on purchases of earthquake preparedness kits in the region. Detailed analysis of this earthquake and its aftershock sequence (Cassidy et al. 2000) provided the first 'image' of an active fault in southwestern BC. For details, see Cassidy et al. (2000) and Mosher et al. (2000).

#### *2001: M 5.3, Near Dawson Creek, British Columbia*

At 8:20 p.m. on Friday, April 13, 2001, residents of northwestern Alberta (AB) and northeastern BC were surprised by a M 5.4 earthquake, the largest ever recorded in that 'seismically quiet' region; the epicentre was located 40 km to the northeast of Dawson Creek, BC. This earthquake was felt in Edmonton, AB (500 km to the east), Prince George, BC (300 km to the southwest) and Fort Nelson, BC (340 km to the northwest). Although there were no reports of structural damage, items were knocked from shelves, and, like the 1986 Prince George earthquake, it served as a 'friendly reminder' of earthquake hazards in the Cordillera.

### Damaging (M 6.5–7.9) Earthquakes ('The Bad')

A total of 57 'bad' earthquakes in the M 6.5–7.9 range have occurred across (or near) Canada since 1660 (Fig. 6). Most of these were either off the west coast or in remote areas. Here we highlight (in chronological order) the top 10 of the 'bad' events, mainly those that caused significant damage (highlighted in red in Figure 6).

#### *1663: M~7.0, Charlevoix, Québec*

This earthquake, with a magnitude estimated at M ~7.0, most probably occurred in the Charlevoix region of

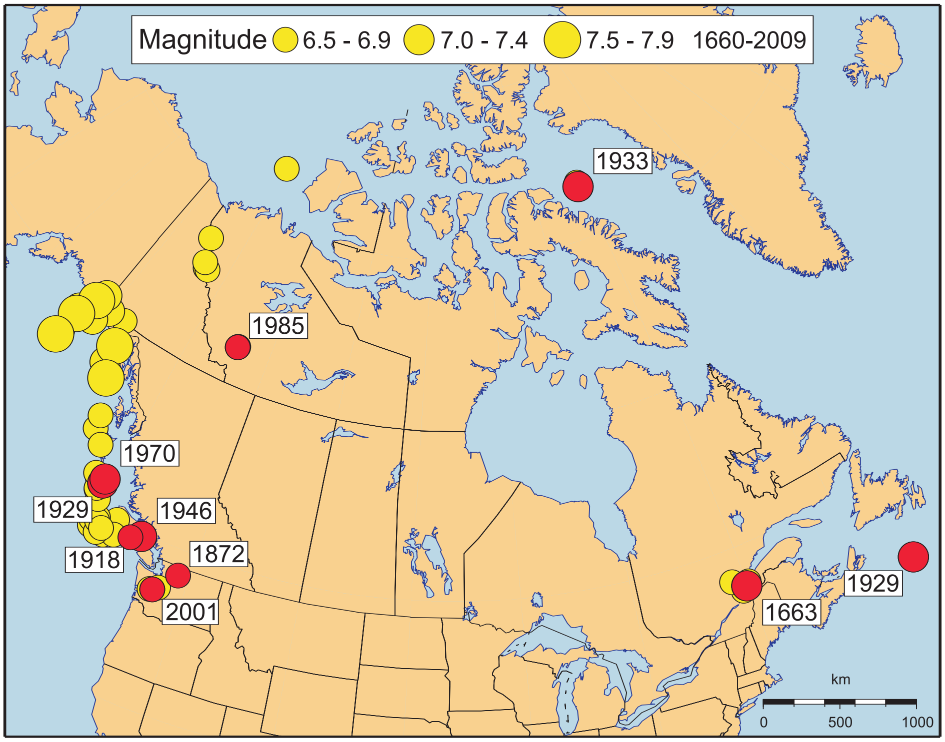


**Figure 6**. Location of all 'bad' (M 6.5–7.9) earthquakes in Canada (1660–2009). Those highlighted in red are discussed in the text.

Québec (Fig. 6). It was felt over the entire eastern part of North America (an area of about 2 million km$^2$; Gouin 2001). At the time, most of the population of New France lived in Québec City, Trois-Rivières and Montreal (all more than 100 km away from the epicentre), which may explain why no loss of life was reported and damage was confined to a few cracked and broken chimneys and items being tossed from shelves. The earthquake triggered large landslides over a vast area, including the Charlevoix region and along the St. Lawrence, Shipshaw, Betsiamites, Pentecôte, Batiscan, and Saint-Maurice rivers.

### *1872: M 6.8, Northern Washington State, USA*

This M 6.8 earthquake (Bakun et al. 2002) was located about 250 km southeast of Vancouver, BC. It occurred within the North American Plate, and was felt from Quesnel (nearly 600 km to the north) to Eugene, Oregon (500 km to the south). Strong shaking was reported in Victoria, where items were knocked from shelves and people ran out into the streets (Milne 1956). Numerous aftershocks were felt for more than a year following this earthquake (Bakun et al. 2002).

### *1918: M 6.9, Vancouver Island, British Columbia*

This large, M 6.9, earthquake occurred just after midnight local time on Friday, December 6, 1918. It occurred near the west coast of Vancouver Island, and was felt very strongly at Estevan Point lighthouse and at Nootka lighthouse on the southern tip of Nootka Island. There was damage to the Estevan Point lighthouse (rendering it inoperable) and to a wharf at Ucluelet. This earthquake awakened and frightened people all over Vancouver Island and in the greater Vancouver area. It was felt in northern Washington State and at Kelowna, more than 500 km to the east in the interior of BC. The earthquake occurred within the North American plate, and was followed by at least 14 aftershocks (including one as large as M 5.6). For more details see Cassidy et al. (1988).

### *1929: M 7.0, Queen Charlotte Islands, British Columbia*

This M 7.0 earthquake occurred on May 26, 1929, along the Queen Charlotte Fault, about 50 km south of the Queen Charlotte Islands. The earthquake was felt from Ketchikan, Alaska, 450 km to the north, to Terrace and Skeena, BC, nearly 400 km to the east. The strongest shaking was reported on the Queen Charlottes: at Masset (300 km distance), houses shook violently; at Queen Charlotte City and Skidegate, dishes were broken and a 1 m local tsunami was reported; at Sandspit, 500 feet of beach was reported to have disappeared into the sea; and at Rose Harbour, chimneys toppled. For more details, see Milne (1956), and Rogers (1986).

### *1929: M 7.2, Grand Banks, Newfoundland*

This M 7.2 earthquake struck at 5:02 p.m. on November 18, 1929. It was located about 250 km south of Newfoundland, along the southern edge of the Grand Banks and was felt as far away as New York (nearly 1500 km to the southwest) and Ottawa (nearly 1500 km to the west). On land, damage caused by shaking was limited to Cape Breton Island, where chimneys were overthrown or cracked and where some highways were blocked by minor landslides. This earthquake is most notable for the devastating tsunami that was generated by a large submarine slump (estimated at 200 km$^3$ of material) triggered by the earthquake shaking (Fig. 7). The tsunami killed 28 people in Newfoundland, and was recorded along the Atlantic seaboard of the US and across the Atlantic in Portugal. The underwater slump also ruptured 12 transatlantic cables in multiple locations. For more details on this earthquake, see Bent (1995) and Ruffman and Hann (2006).

### *1933: M 7.3, Baffin Bay, Nunavut*

This earthquake is the largest instrumentally recorded earthquake to have occurred along the passive margin of North America and is also the largest known earthquake north of the Arctic Circle. In spite of its intensity, the 1933 earthquake did not result in any damage because of its offshore location and the sparse population of the adjacent onshore regions (the closest communities were more than 200 km away). For more information see Bent (2002).

### *1946: M 7.3, Vancouver Island, British Columbia*

This earthquake, Canada's largest recorded onshore earthquake to date, was a M 7.3 event that occurred at 10:15 a.m. on Sunday, June 23, 1946. The epicentre was on central Vancouver Island, just to the west of Courtenay and Campbell River. This earthquake caused considerable damage on Vancouver Island (Fig. 8), and was felt as far away as Portland, Oregon (about 500 km to the south), and Prince Rupert, BC (about 600 km to the north). The earthquake knocked down 75% of the chimneys in the closest communities, Cumberland, Union Bay, and Courtenay (including the Courtenay School; fortunately, the earthquake occurred on a Sunday morning so no children were at their desks) and did considerable damage in Comox, Port Alberni, and Powell River on the eastern side of Georgia Strait. A number of chimneys were shaken down in Victoria and people in Victoria and Vancouver were frightened, many running into the streets. More than 300 landslides were triggered by the earthquake (Mathews 1979), and there were numerous instances of liquefaction, particularly along the east coast of central Vancouver Island (Rogers 1980). Two deaths resulted, one from drowning when a small boat capsized in an earthquake-generated wave, and the other from a heart attack in Seattle. For additional information see Hodgson (1946) and Rogers and Hasegawa (1978).

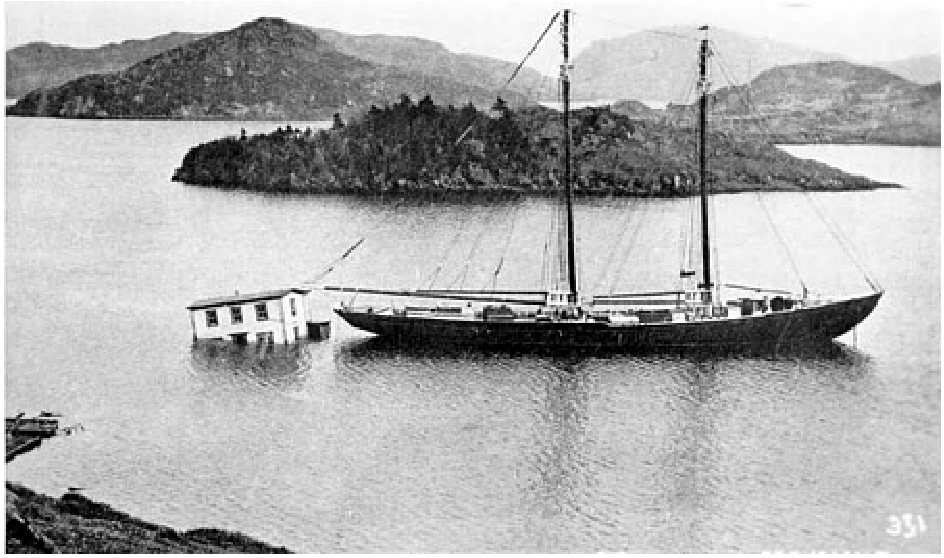

**Figure 7**. Photograph of a house that was washed 1–2 km out to sea by the tsunami resulting from the 1929 Grand Banks earthquake. Photograph courtesy of the Provincial Archives, Government of Newfoundland and Labrador.


**Figure 8**. Damage to the Bank of Montreal building in Port Alberni, BC, resulting from the M 7.3 earthquake of 1946.

### *1970: M 7.4, Queen Charlotte Islands, British Columbia*

This M 7.4 earthquake occurred on June 24, 1970, at 6:09 a.m. It was felt with Modified Mercalli Intensity IV (i.e. rattling dishes, windows and doors) throughout the Queen Charlotte Islands and was felt to a distance of about 350 km on the adjacent mainland and on northern Vancouver Island (Horner et al. 1975). The epicentre was beneath the ocean about 30 km south of the southernmost point of the Queen Charlotte Islands. Observed aftershocks indicate it ruptured the Queen Charlotte Fault in a southerly direction for about 35 km. The faulting mainly involved right lateral strike-slip motion; however, analysis of seismic data revealed that this was the first earthquake in the region to show a significant component of thrusting, which is consistent with the convergent motion between the Pacific and North American plates. A slight swell was observed in Tasu Harbour, 100 km north of the epicentre and about 10 minutes after the earthquake, but no tsunami was observed on tide gauges. The position of the earthquake relative to the great 1949 earthquake to the north (see next section on 'Destructive Earthquakes') reveals the existence of a 'seismic gap' along the Queen Charlotte Fault that has not ruptured in the past century (Rogers 1986).

### *1985: M 6.9, Nahanni, Northwest Territories*

The M 6.9 Nahanni earthquake of

**Figure 9**. Rock avalanche triggered by the October 5, 1985 Nahanni earthquake (Horner et al. 1987). Photograph by R. Horner.

December 23, 1985, is not just a single earthquake, but part of a remarkable series of earthquakes that struck the northern Canadian Cordillera over a three-year period (1985-1988). The sequence began with a surprising M 6.6 event on October 23, 1985 (surprising because the largest known earthquake in the immediate area prior to this was about M 5), and continued for several years after, including a M 6 event in 1988. The 1985 earthquakes were felt to distances of about 1500 km. Because no community is closer than 100 km to the epicentres, no major structural damage was reported. At Wrigley, about 115 km north of the epicentre, residents reported seeing the ground roll. Vehicles bounced on the road and trees and power lines whipped back and forth. Sections of the banks of the Mackenzie River slumped into the water. Inside homes, furniture moved, dishes fell from cupboards, doors swung open and shut, and walls flexed. One of the largest rock avalanches ever recorded in Canada (Fig. 9) was triggered by the October 5 earthquake. A 70-m scarp resulted from the landslide, which was estimated to displace 5 to 7 million $m^3$ of rock. Recordings of shaking for this earthquake were the strongest ever recorded in Canada and provided important information on ground motion processes and earthquake hazards (Choy and Boatwright 1988; Boore and Atkinson 1989). Deployment of seismographs to record the hundreds of aftershocks revealed that the earthquake sequence involved thrusting along a shallow, 50 km-long by 15-km wide, west-dipping fault (Wetmiller et al. 1988).

### *2001: M 6.8, Nisqually, Washington State, USA*

On February 28, 2001, a M 6.8 earthquake occurred between Seattle and Olympia in the state of Washington, about 150 km southeast of Victoria, BC. This earthquake, like the similar-sized events in the same area in 1949 and 1965, was centred within the Juan de Fuca plate about 60 km beneath the surface. It resulted in widespread damage (more than $2B U.S. in Washington State), including structural damage to buildings (especially to unreinforced masonry) and bridges, and liquefaction and landslides that impacted transportation routes. In Canada, the earthquake was felt all across southwestern BC, from northern Vancouver Island to the Okanagan Valley. There was some minor damage (including broken windows, pipes and chimney damage) in Victoria and greater Vancouver, BC (Molnar et al. 2004). Studies of the earthquake provided important new information on the hazards associated with these deep, oceanic plate earthquakes (Frankel et al. 2002; Atkinson and Boore 2003; Kao et al. 2008).

## Destructive (M >8) Earthquakes ('The Ugly')

Some of the world's largest earthquakes have occurred in, or adjacent to, Canada. All have occurred along the active plate boundaries off the west coast (Fig. 10).

### *1700: M 9.0, Offshore Vancouver Island, British Columbia*

At 9 p.m. on January 26, 1700, a massive 'megathrust' earthquake struck off the west coast of Vancouver Island. It ruptured the Cascadia subduction fault from northern Vancouver Island to northern California (Fig. 10), causing very strong ground shaking for several minutes and spawning a tsunami that travelled across the Pacific. This earthquake was likely similar, in many ways, to the 2004 Sumatra M 9.2 subduction earthquake (Cassidy et al. 2005). The Cascadia earthquake of 1700 occurred prior to European exploration and settlement of the area, although the event was recorded in the oral traditions of First Nations peoples on Vancouver Island. These oral reports describe the collapse of houses (because of landslides) in the Cowichan area, shaking that was so severe that people could not stand, and so prolonged that it made them sick. They also describe the destruction of a winter village on the west coast of Vancouver Island near present-day Pachena Bay (Rogers 1992). Numerous other First Nations oral histories in Washington and Oregon are likely related to this event (Ludwin and Smits 2007). Japanese records of the tsunami triggered by the earthquake (Satake et al. 1996) indicate that it struck at about 9 p.m. and had a magnitude of 9. Geological evidence from Vancouver Island to California demonstrates that M 9 earthquakes occur, on average, about every 500 years along the Cascadia fault, and that the interval between earthquakes varies from 250 to 850 years). In addition to large tsunami and liquefaction, they can also cause sudden coastal subsidence (Atwater et al. 1995).

### *1899: M 8.2, Alaska Panhandle Region*

During September of 1899, the Yakutat Bay region of Alaska, near the Yukon/BC border, was shaken by a series of major earthquakes. The


**Figure 10**. Location of all M >8 earthquakes near Canada's borders. For each earthquake (see text) the rupture zone is shown in red.

sequence began on September 4, with a M 8.1 earthquake, followed by M 7.4 and M 8.2 events on September 10. Significant topographic changes resulted from this earthquake – a maximum uplift of 14.5 m occurred on the west coast of Disenchantment Bay, and changes of 5 m or more affected a large area. Subsidence of as much as 2 m was observed in a few areas. Other documented phenomena included surface faulting, avalanches, fissures, spouting from sand craterlets, and slight damage to buildings. A destructive tsunami 11 m in height occurred in Yakutat Bay, and localized tsunamis were observed at other places along the Alaskan coast.

The first earthquake was strong enough to throw people off their feet at Disenchantment Bay (nearly 100 km from the epicentre). The largest event on September 10 shook a mostly unsettled region, so the total affected area is unknown. The event was felt strongly in northwestern BC and southern Yukon, including Whitehorse. Prospectors camped on Disenchantment Bay felt over 50 shocks on September 10, two of which were strong. Two of the many shocks felt that day were also described as severe by residents at Yakutat village. Ten or more earthquakes were felt at the Coast and Geodetic Survey camp near the Copper River delta in Alaska, and several of them were violent. Several shocks were also felt on September 10 in the Chugach Mountains near Prince William Sound; five were reported about 300 km to the northeast on the Yukon River; and several were felt to the southeast at Juneau and Skagway. Details on this earthquake sequence are provided by Plafker and Thatcher (2009).

### *1949: M 8.1, Queen Charlotte Islands, British Columbia*

On August 22, 1949, a M 8.1 earthquake occurred on the Queen Charlotte Fault, the boundary between the Pacific and North American plates that follows the west coast of the Queen Charlotte Islands off the west coast of BC (Fig. 2). The shaking was so severe on the Queen Charlotte Islands that cows were knocked off their feet, and a geologist working on the north end of Graham Island could not stand up. Chimneys toppled, and an oil tank at Cumshewa Inlet collapsed. In Terrace, on the adjacent mainland, cars were bounced around, and standing on the street was described as "like being on the heaving deck of a ship at sea". In Prince Rupert, windows were shattered and buildings swayed. The earthquake was felt from the Yukon Territory to Washington State. Based largely on the distribution of hundreds of aftershocks that occurred in the months after the earthquake, the rupture zone is estimated to have extended along a 500-km long section of the fault (Fig. 10), and average displacement was about 5 m (Bostwick 1984).

## EARTHQUAKE RESEARCH AND ADVANCES IN MITIGATION

The best way to reduce future earthquake-related losses is to have robust seismic codes and standards in place to ensure that buildings and critical infrastructure will withstand future earthquakes. Structures designed according to code provisions can resist moderate earthquakes without significant damage, and major earthquakes without collapse. Earthquake research provides the fundamental building blocks that are used to develop and improve seismic-hazard models, which are then included in seismic codes and standards.

The first seismic provisions in the National Building Code of Canada (NBCC) were put in place in 1953. These early seismic-hazard maps included four 'zones', based on qualitative assessment of historic earthquake activity. Significant updates to these seismic-hazard maps were made in 1970, 1985, and 2005, and some changes will be made in the 2010 code. The 1970 map (Milne and Davenport 1969) was the first national-scale probabilistic seismic hazard map. It defined four zones based on peak acceleration at a 1% annual probability of exceedance (i.e. a 1-in 100-year event). The 1985 maps (Basham et al. 1985) included 7 zones, with both 'acceleration' maps (for small buildings) and 'velocity' maps (for taller buildings) based on a 10% probability of exceedance in 50 years (a 1 in 475-year event). Most recently, the 2005 maps (Adams and Atkinson 2003; Adams and Halchuk 2003; Heidebrecht 2003) provide location-specific uniform hazard spectral acceleration levels at the 2% in 50-year probability level (a 1 in 2475-year event). A simplified seismic-

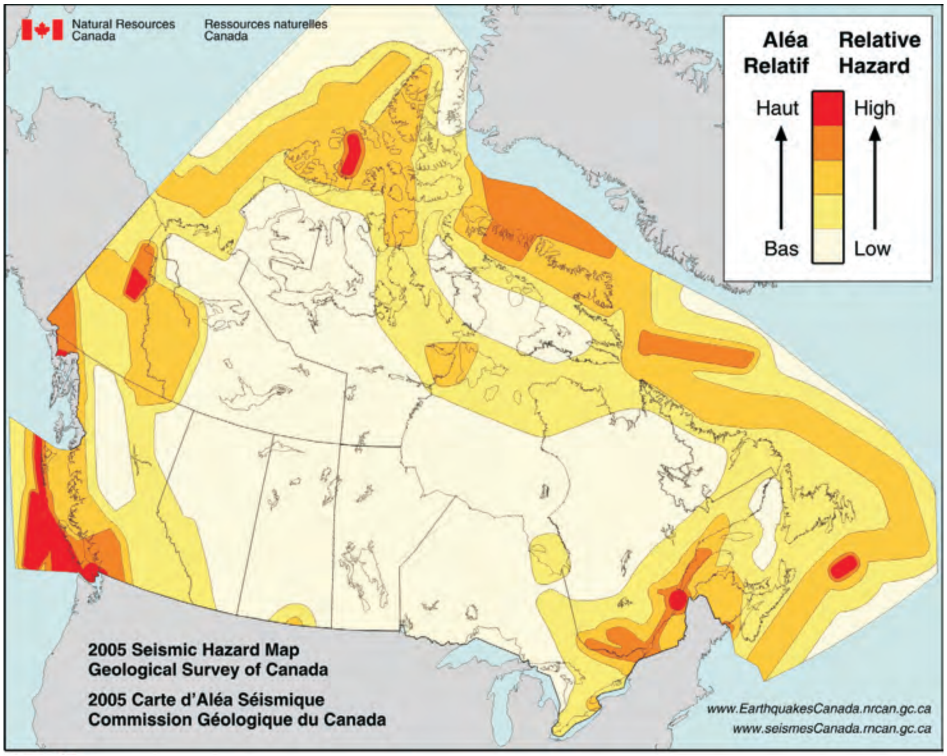


**Figure 11**. Simplified 2005 seismic hazard map for small (1–2 storey) structures.

hazard map from the 2005 NBCC is shown in Figure 11. These maps use 'firm-soil' as a reference shaking level (rather than 'bedrock' used in all previous maps). Another significant change in this map was incorporation of the hazard associated with the rare (every ~500 years) Cascadia megathrust earthquake on Canada's west coast. It was found that the megathrust event dominates the seismic hazard for communities along the west coast of Vancouver Island.

Updates to the seismic hazard maps, and ultimately to the seismic provisions in the NBCC, are driven by earthquake monitoring and research results (e.g. Adams and Atkinson 2003, and other papers in the special volume of the Canadian Journal of Civil Engineering, Vol. 30, No. 2).

Samples of recent important research activities (note that this list is only a small sample) include:

1. Subduction zone studies in BC, including GPS monitoring (e.g. Hyndman and Wang 1995; Mazzotti et al. 2003), and investigation of Episodic Tremor and Slip (e.g. Dragert et al. 2001; Rogers and Dragert 2003), marine mapping of the seafloor, paleoseismological studies (Adams 1990; Atwater et al. 1995; Clague 1997), searching for active faults using modern high-resolution techniques such as LiDAR, and precise location of earthquake epicentres (Cassidy et al. 2000);
2. Ground motion studies in both eastern and western Canada (e.g. Atkinson 2005; Atkinson and Boore 2006; Atkinson and Macias 2009);
3. Crustal deformation monitoring using Global Positioning Systems, which provides critical new information to identify zones of strain accumulation that indicate probable locations of future earthquakes (Mazzotti et al. 2003);
4. Better understanding of earthquakes in stable cratonic regions, particularly levels of activity and maximum magnitudes (Mazzotti and Adams 2005; Fenton et al. 2006; Atkinson and Martens 2007); and
5. Better crustal models, and improved understanding of wave propagation and variation in earthquake shaking with local geological conditions (e.g. Cassidy and Rogers 1999; Atkinson and Cassidy 2000).

As we learn more about earthquakes across Canada and around the world, hazard maps will continue to evolve and improve, providing for safer structures, and safer and more resilient communities.

## Sources of Seismic Risk

Here we briefly outline some of the key aspects of seismic risk in Canada, as illustrated by historic Canadian earthquakes. For additional details on the geological and human effects of large earthquakes in southwestern BC, see Clague (2002). For additional details on significant earthquakes in eastern Canada, see Lamontagne (2002).

### *Pre-Building Code Buildings*

As demonstrated by large, historic earthquakes in both eastern and western Canada, many older, un-reinforced masonry structures built prior to modern building codes are extremely vulnerable to earthquake shaking (Fig. 8). Some specific examples are provided in Bruneau and Lamontagne (1994) and a summary in Lamontagne (2009).

### *Seismically triggered Landslides*

Seismically triggered landslides pose a significant threat and can hamper recovery efforts after a major earthquake by blocking transportation links. In the mountainous areas of western Canada, strong ground shaking can trigger widespread landslide activity. The 1946 Vancouver Island earthquake (Mathews 1979; Rogers 1980) triggered more than 300 landslides at distances exceeding 100 km from the epicentre. The 1985 Nahanni earthquakes triggered massive landslides, as illustrated in Figure 9. In eastern Ontario and southern Québec, landslides triggered by earthquakes have been observed in the marine clays of the St. Lawrence and Ottawa river valleys (Aylsworth 2007).

### *Liquefaction*

Liquefaction caused by historic and prehistoric earthquakes in Canada has been observed on the Fraser River delta of Vancouver (Clague et al. 1997; Clague 2002), and, in the case of the M 7.3 Vancouver Island earthquake of 1946, to a distance of about 100 km (primarily along the east coast of Vancouver Island). Rogers (1980) reports that liquefaction resulting from the

1946 earthquake, caused extensive damage to the wharf and cannery buildings at Kildonan, as well as 'spectacular downdrops and fountains of blue clay that caked trees at Reid Island'. Liquefaction effects have also been observed for some earthquakes in eastern Canada (*see* Lamontagne 2002), including the deep (29 km beneath the surface) 1988 Saguenay earthquake, which caused extensive liquefaction-related damage to local houses (Lefebvre et al. 1991).

### *Tsunamis and Seiches*

Tsunamis triggered by both distant and local earthquakes have affected Canada, as demonstrated by the 1929 Newfoundland tsunami, the 1964 tsunami in Alberni Inlet on Vancouver Island (generated by the M 9.2 Alaska earthquake) and the 1700 tsunami on Vancouver Island generated by a M 9.0 Cascadia earthquake. For details, see Clague (2002). Seiches (standing waves set up in bodies of water such as lakes, rivers, bays, or even swimming pools) can be generated when seismic waves from an earthquake (including waves from a very distant earthquake that cannot be felt) pass through a region. Several good examples of seiches generated in western Canada by the M 6.9 Denali, Alaska earthquake of 2002 are described in Cassidy and Rogers (2004).

### *Variation in Ground Shaking*

Soft soils and deep sedimentary basins such as the Fraser River delta near Vancouver can significantly alter ground shaking. Examples of clear variations in ground shaking across greater Vancouver are described in Cassidy and Rogers (1999) and Atkinson and Cassidy (2000). Similarly, in eastern Canada, amplification of ground shaking associated with thicknesses of soft Leda Clay has resulted in enhanced damage during past earthquakes (Hodgson 1945; Lamontagne 2009). Research on variations in earthquake ground shaking is currently underway in a number of urban centres in eastern Canada, including Ottawa (e.g. Motazedian and Hunter 2008). For a summary of some recent site response studies across Canada see Cassidy and Molnar (2009).

## CONCLUSION

Large and damaging earthquakes have struck Canada in the past, and will again in the future. We cannot predict earthquakes at this time, and therefore our best defense against earthquakes is to have modern earthquake codes and standards, based on the latest earthquake research. In addition, scientists need to continue to work with emergency response organizations, planners, and the public to maintain and raise awareness of earthquake hazards and their potential impacts in Canada, and help prepare for future earthquakes through improved monitoring, mitigation of effects, and emergency plans.

One of the primary goals of this article is to provide a reminder of Canada's past earthquakes—the 'good', the 'bad', and the 'ugly'—so that we can be better prepared for future earthquakes.

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