Significant Canadian Earthquakes of the Period 1600–2006

M. Lamontagne[1], S. Halchuk[2], J. F. Cassidy[3], and G. C. Rogers[3]

INTRODUCTION

Raising earthquake awareness is an important goal of seismological research. In this respect, the effect of past local earthquakes is an excellent means to raise the local population's awareness. For this reason, Natural Resources Canada has put numerous photographic examples of impacts of local earthquakes on its Web sites (see, for example, http://www.earthquakescanada.ca). The information the site contains is used in the production of various publications and Web pages and is an important source of information for the public.

Another much-used public awareness tool is the Atlas of Canada, formerly on paper but now online, which provides authoritative, current, and accessible geographic information products. The atlas facilitates the integration and analysis of diverse data in order to increase overall knowledge about Canada. One much-consulted component of the Web-based atlas (http://www.atlas.gc.ca) is the natural hazards maps (floods, forest fires, landslides, volcanoes, avalanches, hurricanes, tornadoes, tsunamis, and earthquakes). The information is used by the public as well as by emergency organizations that seek information on the threats faced by their communities.

Before 2007, the Atlas of Canada provided very limited information on earthquake activity in Canada. Thirty earthquakes were briefly described in a nonsystematic manner that did not truly reflect the distribution of earthquakes across the territory or the recent advances in descriptions of historical earthquakes. To update the Atlas of Canada pages on earthquakes, the authors decided to create a list that would include up-to-date information on significant earthquakes in Canada. The authors also decided to publish the results and methodology in a Geological Survey of Canada Open File Report (Lamontagne *et al.* 2007) as a means of properly documenting each earthquake and ensuring peer review by Geological Survey of Canada seismologists. The new list could also update other existing sites including the EarthquakesCanada Web site.

This paper details how the information on significant Canadian earthquakes was gathered and the results and interpretation of this new view of Canada's earthquake activity. A subset of significant Canadian earthquakes (and the impact of those earthquakes) is presented herein (see Lamontagne *et al.* [2007] for the complete list of 160 events). The paper is of obvious interest to people wishing to learn more about Canadian earthquakes and to researchers interested in methods used in earthquake compilations.

1. Natural Resources Canada, Ottawa
2. Geological Survey of Canada, Ottawa
3. Geological Survey of Canada, Sidney, B.C.

SELECTION OF EARTHQUAKES

To decide whether an earthquake is "significant," criteria such as number of deaths, damage, magnitude, or maximum intensity could be used. Each category sets limits on the number of events and on the completeness of the list. Since the list was aimed at enhancing the awareness of the Canadian public about earthquake hazards, the authors decided to choose events that caused some minimum level of damage (such as cracked chimneys), or could have caused damage had they occurred close to inhabited regions. For this reason, the authors selected historically or instrumentally recorded earthquakes larger than magnitude 6, as well as some smaller ones felt by many Canadians.

Each earthquake on the list met one or more of the following criteria.

1. The preferred magnitude (either instrumental magnitude or estimated magnitude from damage or felt-area information) is 6.0 or greater. See the discussion below on the choice of the preferred magnitude
2. The earthquake had some impact on the built environment (starting from light damage such as broken pipes or chimneys, *i.e.*, Modified Mercalli Intensity VI) or on the natural environment (liquefaction, landslides, rock falls, tsunamis).
3. The earthquake was felt by a significant number of Canadians. This characteristic brought about the inclusion of some earthquakes within U.S. territory that were felt on the Canadian side of the border.
4. The earthquake occurrence is supported by paleoseismological evidence (only the 1700 Cascadia earthquake met this criterion, since other paleoearthquakes are too uncertain in location, origin time, and magnitude).

In addition to these criteria, we subjectively qualified the significance of the earthquake from damage information and magnitude. We rated them from major (14 events), very significant (14 events), significant (23 events), or weakly significant (109 events generally remote from inhabited areas, weakly or not felt). Table 1 provides the list of events that were in the first two categories (major and very significant).

doi: 10.1785/gssrl.79.2.211

TABLE 1

List of major and very significant earthquakes. Depth of the focus (hypocenter) is given in kilometers below sea level. If the exact focal depth cannot be determined, it is fixed to a value representative of events in the area and given with (F). An "x" means that the exact value is unknown.

Date	Time (U.T.)	Region	Lat	Lon	Mag	Landslide	Tsunami	Damage	Deaths	Description
1663-02-05	22:30	Charlevoix-Kamouraska, Quebec	47.6	–70.1	7	Yes	No	Yes	0	Epicenter most likely in the Charlevoix-Kamouraska seismic zone, Quebec; felt in most of New France (Quebec City, Trois-Rivières, Montreal) and parts of New England (Boston) and New Amsterdam (New York City). Some damage to masonry in Quebec City, Trois-Rivières, and Montreal. Landslides reported in the Charlevoix region and along the St. Lawrence, Shipshaw, Betsiamites, Pentecôte, Batiscan, and Saint-Maurice rivers. Numerous aftershocks felt in Quebec City during the following months.
1700-01-27	05:00	Cascadia Subduction Zone, British Columbia	48.5	–125	9	Yes	Yes	Yes (in Japan from tsunami)	Unknown; native villages destroyed according to oral traditions	Cascadia subduction zone, offshore of Vancouver Island, Washington, and Oregon. Recorded widely in oral native accounts and by geological evidence for subsidence and a tsunami along the outer coast; confirmed by a tsunami record in Japan. Extent of damage unknown.
1732-09-16	16:00	Near Montreal, Quebec	45.5	–73.6	5.8	No	No	Yes	0	Probable epicenter near Montreal, Quebec. Felt in New France from Louisbourg to the James Bay. Considerable damage in the city of Montreal where hundreds of chimneys were damaged and walls cracked. No injuries documented. Aftershocks felt in Montreal.
1791-12-06	20:00	Charlevoix-Kamouraska, Quebec	47.4	–70.5	6	No	No	Yes	0	Felt strongly in Charlevoix, Quebec, and in Quebec City. Damage to houses and churches in Baie-Saint-Paul, Les Éboulements, and on Île aux Coudres.
1855-02-08	18:00	Moncton, New Brunswick	46.0	–64.5	5.2	No	No	Yes	0	Minor damage was reported for this earthquake. Chimney damage reported in Moncton, New Brunswick. In Hopewell, near the epicenter, the shock cracked the plastering of walls.
1860-10-17	11:15	Charlevoix-Kamouraska, Quebec	47.5	–70.1	6	No	No	Yes	0	Widely felt in Quebec and felt as far as New Brunswick, eastern Ontario, and New England. Damage in the epicentral region on both shores of the St. Lawrence River: North shore: Baie-Saint-Paul; La Malbaie; South shore: Rivière-Ouelle. Also felt strongly in Quebec City.

(continued)

TABLE 1 (continued)

Date	Time (U.T.)	Region	Lat	Lon	Mag	Landslide	Tsunami	Damage	Deaths	Description
1870-10-20	16:30	Charlevoix-Kamouraska, Quebec	47.4	–70.5	6½	Yes	No	Yes	Possibly 2 in Les Éboulements	Felt over most of the Province of Quebec, in Ontario, New Brunswick, and in New England. Considerable damage to houses in Charlevoix, especially in Baie-Saint-Paul, Les Éboulements, and along the south shore of the St. Lawrence River. Damage to chimneys reported in lower town in Quebec City. Possible rock slide along the Saguenay River.
1872-12-15	05:37	Washington-British Columbia border	47.76	–119.90	6.8	No	Yes (USA)	Yes	0	Lake Chelan, Washington. Strong shaking felt in southern British Columbia. The shaking was strong enough to frighten people and cause them to run out of buildings in Victoria, New Westminster, and Yale, British Columbia, and in Seattle, Washington. The earthquake was reported felt from central British Columbia in the north (Quesnel) to central Oregon in the south (Salem) and east into present-day Alberta and Montana.
1899-09-10	21:41	Yukon-Alaska border	59.39	–139.5	8.0	Yes	Yes	Yes (USA)	0	Yukon-Alaska border. First of three great earthquakes in this region in the space of eight days. Strong effects experienced in many parts of northern British Columbia and southern Yukon Territory. Followed by a series of strong aftershocks the following days. Phenomena observed included surface faulting, avalanches, fissures, spouting from sand craterlets, and slight damage to buildings. A destructive tsunami 10.6 meters in height occurred in Yakutat Bay, and tsunamis also were observed at other places along the Alaskan coast.
1904-03-21	06:04	Passamaquoddy Bay, New Brunswick	45.0	–67.2	5.9	No	No	Yes	0	Strong earthquake felt throughout the Maritime provinces, the St. Lawrence lowlands, and the New England states. Minor damage to buildings was reported from several communities along the coasts of New Brunswick and Maine, and chimneys were thrown down at St. Stephen in southwestern New Brunswick and Eastport in southeastern Maine.

(continued)

TABLE 1 (continued)

Date	Time (U.T.)	Region	Lat	Lon	Mag	Landslide	Tsunami	Damage	Deaths	Description
1918-12-06	08:41	Vancouver Island, British Columbia	49.44	–126.22	6.9	No	No	Yes	0	The exact epicenter is uncertain, but 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 some damage to the Estevan Point lighthouse and to a wharf at Ucluelet. This earthquake awakened people all over Vancouver Island and in the greater Vancouver area. It was felt in northern Washington State and as far east as Kelowna, in the interior of British Columbia.
1920-01-24	07:10	Gulf Islands, British Columbia	48.6	–123	5.5	No	No	Yes	0	In Victoria, British Columbia: fallen plaster, broken china. In Brentwood, 20 km north of Victoria, the concrete chimney and wall of an electric power station were cracked. In Vancouver: a few bricks fell from the tops of chimneys. Minor damage also in several Washington State communities. No reported aftershocks.
1925-03-01	02:19	Charlevoix-Kamouraska, Quebec	47.8	–69.8	6.2	Yes	No	Yes	6 (heart attacks)	Charlevoix-Kamouraska seismic zone, Quebec, near Île aux Lièvres. The earthquake was felt over most of eastern Canada and northeastern U.S. It caused damage to unreinforced masonry (chimneys, walls) in the epicentral region on both shores of the St. Lawrence, and in Quebec City (including damage to port facilities), Trois-Rivières, and Shawinigan. Possible liquefaction near Saint-Urbain, Quebec. Numerous felt aftershocks followed.

(continued)

TABLE 1 (continued)

Date	Time (U.T.)	Region	Lat	Lon	Mag	Landslide	Tsunami	Damage	Deaths	Description
1929-05-26	22:39	Queen Charlotte Islands, British Columbia	51.51	–130.74	7.0	Yes	Yes	Yes	0	The epicenter of this tremor was in a region that was not heavily populated. The earthquake was felt as far north as Ketchikan, Alaska, and Anyox, British Columbia, and to the east as far as Terrace, Skeena, and Lakelse. Prince Rupert does not appear to have been in the area of maximum damage, but at Haysport, a short distance southeast of Prince Rupert, goods were knocked off shelves. Centers on the Queen Charlotte Islands suffered greatly. At Massett, water was splashed out of tanks, trees were reported to have swayed, and houses shook violently. The Prince Rupert paper stated that people were thrown to the ground. At Queen Charlotte City dishes were broken, clocks were stopped, and a foot-high (30 cm) tsunami wave was reported. Nearby at Skidgate there was a tsunami wave, and there were fissures on the beach. At Sandspit 500 feet (160 m) of the beach was reported to have disappeared into the sea. Further south at Lockeport the crest of a hill was dislodged, and close by at Rose Harbour chimneys were toppled. From these reports it would appear that the major damage was along the east shore of the Queen Charlotte Islands, but this is probably because that was the only settled portion of the region.
1929-11-18	20:38	Laurentian slope, offshore Newfoundland and Nova Scotia	44.69	–56	7.2	Yes	Yes	Yes	28 (27 drowned by the tsunami, one child succumbed to her injuries a few years later)	Laurentian Slope south of Newfoundland; offshore earthquake felt over most of the Maritimes, eastern Quebec and New England. On land, damage due to earthquake vibrations was limited to Cape Breton Island where chimneys were overthrown or cracked and where some highways were blocked by minor landslides. One chimney also fell in Fredericton, New Brunswick. The earthquake generated a massive submarine slump (landslide) and a large ocean wave (tsunami) which killed 27 people when it struck the Burin Peninsula. Total property losses were estimated at more than $1 million 1929 dollars (estimated as nearly $20 million 2004 dollars).

(continued)

TABLE 1 (continued)

Date	Time (U.T.)	Region	Lat	Lon	Mag	Landslide	Tsunami	Damage	Deaths	Description
1933-11-20	23:21	Baffin Bay, Nunavut Territory	73	–70.75	7.3	No	No	No	0	As of 2006, the largest earthquake ever recorded inside the Arctic Circle. No damage because of its offshore location and the sparse population of the adjacent onshore regions.
1935-11-01	06:03	Region of Témiscaming, Quebec	46.78	–79.07	6.1	Yes	No	Yes	0	The earthquake occurred approximately 10 km east of Témiscaming, Quebec. This earthquake was felt west to Thunder Bay, Ontario (then named Fort William), east to the Bay of Fundy, and south to Kentucky and Virginia. Damaged chimneys were reported in Témiscaming, Quebec, and North Bay and Mattawa, Ontario. In the epicentral region, small rock falls were observed as well as cracks in the gravel and sand at the edges of islands and borders of lakes. Some 300 km away from the epicenter, near Parent, Quebec, earthquake vibrations triggered a 30 meter slide of railroad embankment. Numerous aftershocks were felt in Témiscaming and Kipawa during following months.
1936-03-28	09:15	Vernon, British Columbia	50.5	–119.5	4.5	Yes	No	Yes	0	Dishes broken in Vernon, plaster was cracked. In Owama, rockslides were heard. In Mara, south of Sicamous, bricks were dislodged from chimneys. Notch Hill residents reported four chimneys down.
1944-09-05	04:38	Cornwall, Ontario-Massena New York	44.96	–74.77	5.6	No	No	Yes	0	Cornwall, Ontario, region–New York border. Felt over most of eastern Ontario, southern Quebec, and New England. Considerable damage to unreinforced masonry in both Cornwall, Ontario, and Massena, New York. About 2,000 chimneys were damaged in Cornwall, Massena, and several adjacent communities.

(continued)

TABLE 1 (continued)

Date	Time (U.T.)	Region	Lat	Lon	Mag	Landslide	Tsunami	Damage	Deaths	Description
1946-06-23	17:13	Vancouver Island, British Columbia	49.76	–125.34	7.3	Yes	No	Yes	1 from drowning	Vancouver Island's largest historic earthquake (and Canada's largest historic onshore earthquake). The epicenter was in the Forbidden Plateau area of central Vancouver Island, just to the west of the communities of Courtenay and Campbell River. This earthquake caused considerable damage on Vancouver Island and was felt as far away as Portland, Oregon, and Prince Rupert, British Columbia. The earthquake knocked down 75% of the chimneys in the closest communities, Cumberland, Union Bay, and Courtenay, 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. Two deaths resulted from this earthquake, one due to drowning when a small boat capsized in an earthquake-generated wave, and the other from a heart attack in Seattle.
1949-08-22	04:01	Offshore Queen Charlotte Islands, British Columbia	53.62	–133.27	8.1	No	Yes	Yes	0	Widely felt over a large area of western North America; this was Canada's largest and one of the world's greatest earthquakes. There was some damage on the Queen Charlotte Islands; chandeliers in Jasper, Alberta, were observed to sway. The shaking was so severe on the Queen Charlotte Islands that cows were knocked off their feet, and a geologist 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, British Columbia, windows were shattered and buildings swayed.
1964-03-28	03:36	Prince William Sound, Alaska	61.04	–147.73	9.2	Yes (USA)	Yes	Yes (from tsunami)	0	Widespread damage in Alaska from strong shaking, landslides, and a large tsunami. Felt strongly in Snag and White River, Yukon Territory. Tsunami left serious damage at Alberni and Port Alberni, British Columbia.

(continued)

TABLE 1 (continued)

Date	Time (U.T.)	Region	Lat	Lon	Mag	Landslide	Tsunami	Damage	Deaths	Description
1982-01-09	12:53	Miramichi Highlands, New Brunswick	47.0	–66.6	5.8	No	No	Yes	0	First of two moderate earthquakes, Miramichi Highlands, New Brunswick. Because the epicentral area is unpopulated, damage was very slight: a few hairline cracks but no structural damage in buildings up to 100 km away. Followed by hundreds of aftershocks over the following months.
1985-10-05	15:24	North Nahanni River, Northwest Territories	62.21	–124.22	6.6	Yes	No	No	0	Felt in the western Northwest Territories, southeastern Yukon, and northern Alberta and British Columbia. The earthquake caused large landslides, rock falls, and a major rock avalanche in the epicentral region. An estimated 5 million to 7 million cubic meters of rocks crashed 1.6 km down from the crest to the toe of the slide. Felt strongly with slight damage at Wrigley, Fort Simpson, and Fort Liard. Hundreds of aftershocks recorded in the following months.
1985-12-23	05:16	North Nahanni River, Northwest Territories	62.19	–124.23	6.9	Yes	No	No	0	Felt in the western Northwest Territories, southeastern Yukon, northern Alberta, and British Columbia. Hundreds of aftershocks recorded in the following months.
1988-11-25	23:46	Saguenay Region, Quebec	48.12	–71.18	5.9	Yes	No	Yes	2 (heart attacks)	Laurentides Fauna Reserve, south of Saguenay (Chicoutimi), Quebec. Preceded by a foreshock 2½ days before. Damage caused to unreinforced masonry at Jonquière, Chicoutimi, La Baie, Charlevoix region, Montmagny, Quebec City, Sorel, and Montreal-East. Liquefaction of soft soils in the Ferland-et-Boilleau area. Eleven cases of soil movements reported. Only one felt aftershock.
1989-12-25	14:24	Ungava Peninsula, Quebec	60.12	–73.6	6.3	No	No	No	0	The first earthquake in eastern North America to have produced surface faulting. No damage due to remoteness of epicenter from inhabited communities. Weakly felt in some northern Quebec communities.
1990-10-19	07:01	Mont-Laurier, Quebec	46.47	–75.59	5.0	No	No	No	0	Some minor damage in Mont-Laurier (cracked chimneys, water pipes broken). Widely felt up to distances of 500 km.
2001-02-28	18:54	Southern Puget Sound, Washington	47.15	–122.71	6.8	Yes	No	Yes (USA)	0	Felt strongly throughout Puget Sound, Seattle, and vicinity. Felt as far away as Portland, Oregon, Kelowna, British Columbia, and possibly Salt Lake City, Utah. Major structural damage in Olympia, Tacoma, and Seattle, Washington. Very low-level damage in Victoria, British Columbia.

COMPLETENESS AND PRECISION OF SOURCE INFORMATION

This list of significant Canadian earthquakes was as complete as possible at the time of writing (June 2007). However, the list is not and cannot be complete for the whole of the Canadian territory for the entire period 1600–2006. This is primarily due to the time lag of written records (corresponding to European exploration and settlements) across Canada from east to west. In the east, there are written records from the 1600s on; in the west from the 1850s in settled areas. It is possible that future studies will reveal hitherto unknown events or will modify our knowledge of some of these events. Due to the nature of documenting earthquakes, such modifications to the list are more probable for pre-instrumental data.

Before the introduction of seismographs in the late 19th century, earthquake occurrences were known only through historical accounts. If an earthquake was sufficiently large or sufficiently close to inhabited regions, it could be reported in personal accounts, diaries, or newspapers. This implies that pre-instrumental earthquakes are only known only if they had been felt by people who reported them in documents that were preserved and indexed. Consequently, our knowledge of pre-instrumental earthquakes depends entirely on how the population with written history (as opposed to oral traditions) was distributed as a function of geography and time. This explains the more numerous pre-1850s earthquake occurrences in eastern Canada versus western and northern Canada.

Toward the end of the 19th century, seismographs were progressively installed in Canada (Stevens 1980). These early instruments were not very well adapted to recording local events and could only detect large, distant earthquakes (teleseisms). They were insensitive to earthquakes of magnitude less than about 5. More sensitive, short-period seismographs only began regular operations at the beginning of 1928 (Smith 1962). Slowly, the number of stations increased, and the ability to record local earthquakes improved. It is only after 1950 that all earthquakes of magnitude 6.0 or larger could be detected over the whole Canadian territory (Basham *et al.* 1982). The magnitude completeness dates for each seismic zone used in the seismic hazard maps of Canada can be found in Adams and Halchuk (2003).

SOURCE PARAMETERS

As the completeness of earthquake reporting has improved over the years, the precision of source parameters has heightened. The sections below examine in more detail the uncertainty of the source parameters: origin time, location (latitude and longitude, depth), and magnitude.

Origin Time

The list provides both the origin time of earthquakes in local and in Coordinated Universal Time (UTC).

Historical earthquakes of the 17th, 18th, and 19th centuries are reported with their approximate local times. In some cases, the best estimate of the origin time is the part of the day (day, morning, afternoon, evening, night). Burke (2007) discusses a method to calculate approximate UTC for earthquakes of the pre-standard time era. Later on, telegraphs associated with railroads improved the situation.

Events after the early 20th century were recorded by one or more seismographs and are reported according to UTC. Most dates (year/month/day) and times (hour:minute:second) are listed in UTC.

Location (Region, Area, Latitude, Longitude, Depth)

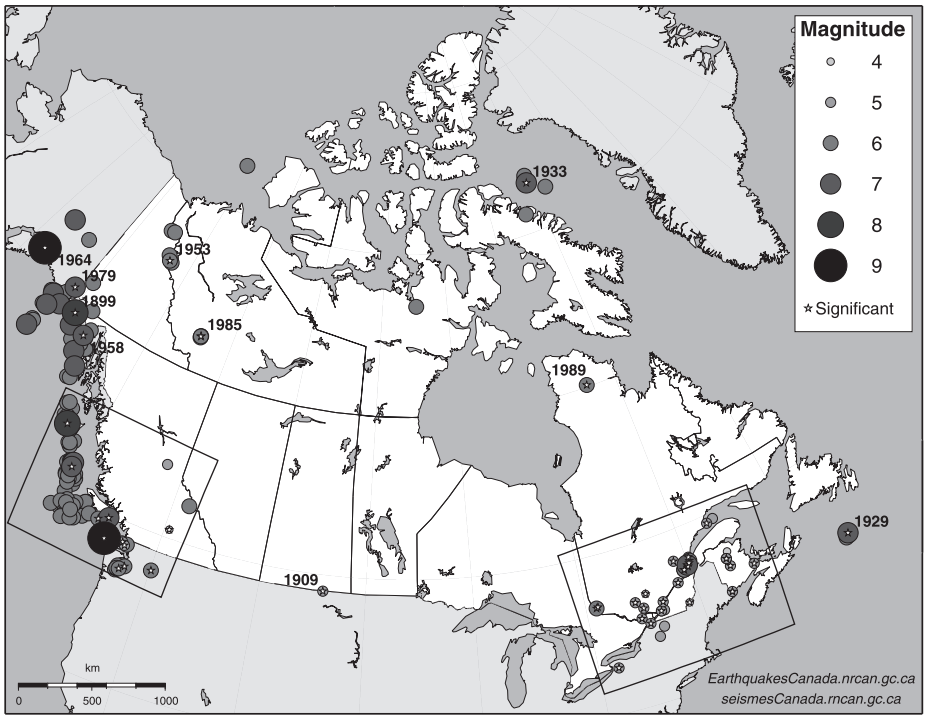
The location of an earthquake refers to the position of its epicenter (latitude and longitude). To give readers a quick reference to the location of the epicenter, we have defined, for each event, a region of Canada (E: East; N: North; W: West) and a geographic area. The regions of Canada are approximately: East: Ontario and provinces to the east; West: Manitoba and provinces to the west; North: the three territories. Since we included events with impact in Canada, some earthquakes have their epicenters on the U.S side of the border or in international waters. The epicenters of pre-20th century earthquakes are generally not as well-defined as more recent or instrumentally recorded earthquakes. For pre-instrumental earthquakes, locations are approximated from felt information (where the epicenter is the center of the felt area) or reports of damage (where the epicenter is generally the region of most significant damage).

Instrumentally recorded earthquakes are located using the arrival times of seismic waves. As the precision of these locations depends on the density and characteristics of the seismograph stations, more recent earthquakes are generally better located than older ones. In some cases, the location of aftershocks with a temporary network of seismographs provided an indirect means to locate the mainshock with increased precision. Figure 1 provides the location of the epicenters, and figures 2 and 3 provide more detailed views for southwestern and southeastern Canada, respectively.

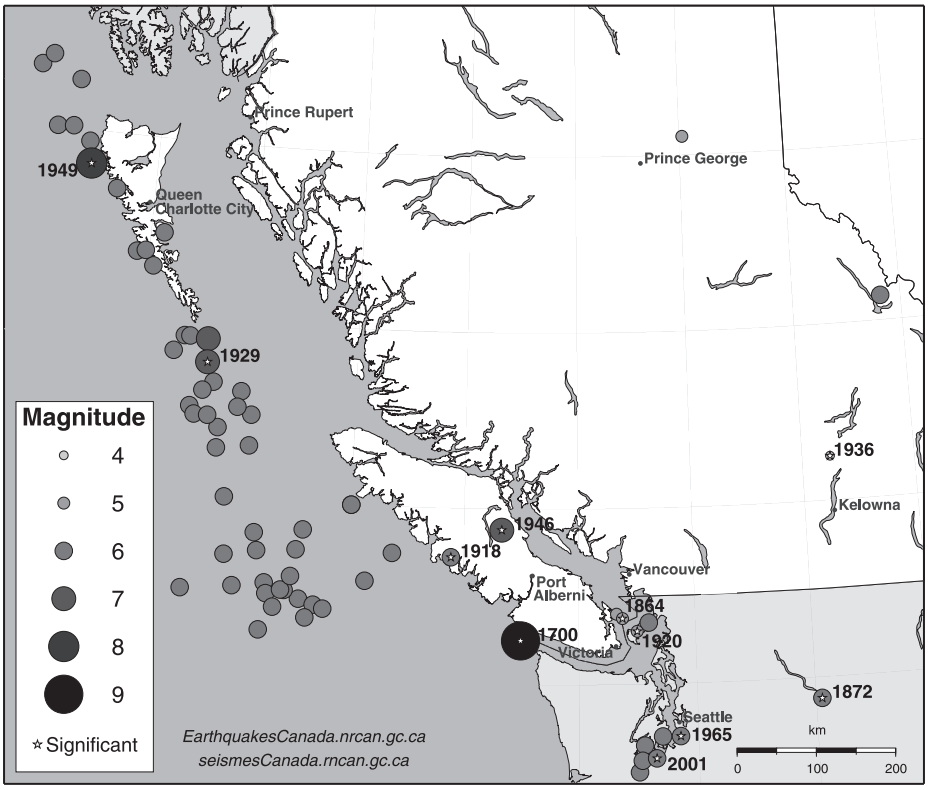
Focal depth can be estimated only from instrumental data and for this reason, only earthquakes recorded after the early 20th century have this information. Focal depths can be calculated from teleseismic recordings for larger events and from near-field records in areas of dense seismic coverage such as southwest British Columbia or the St. Lawrence Valley. In general, eastern and northern Canadian earthquakes occur in the upper 30 km of the Earth's crust. Beneath southwest British Columbia, earthquakes can occur within the continental crust as well as in the subducting ocean plate to depths of about 100 km.

Magnitude (Preferred Magnitude, Magnitude Type, Other Magnitudes)

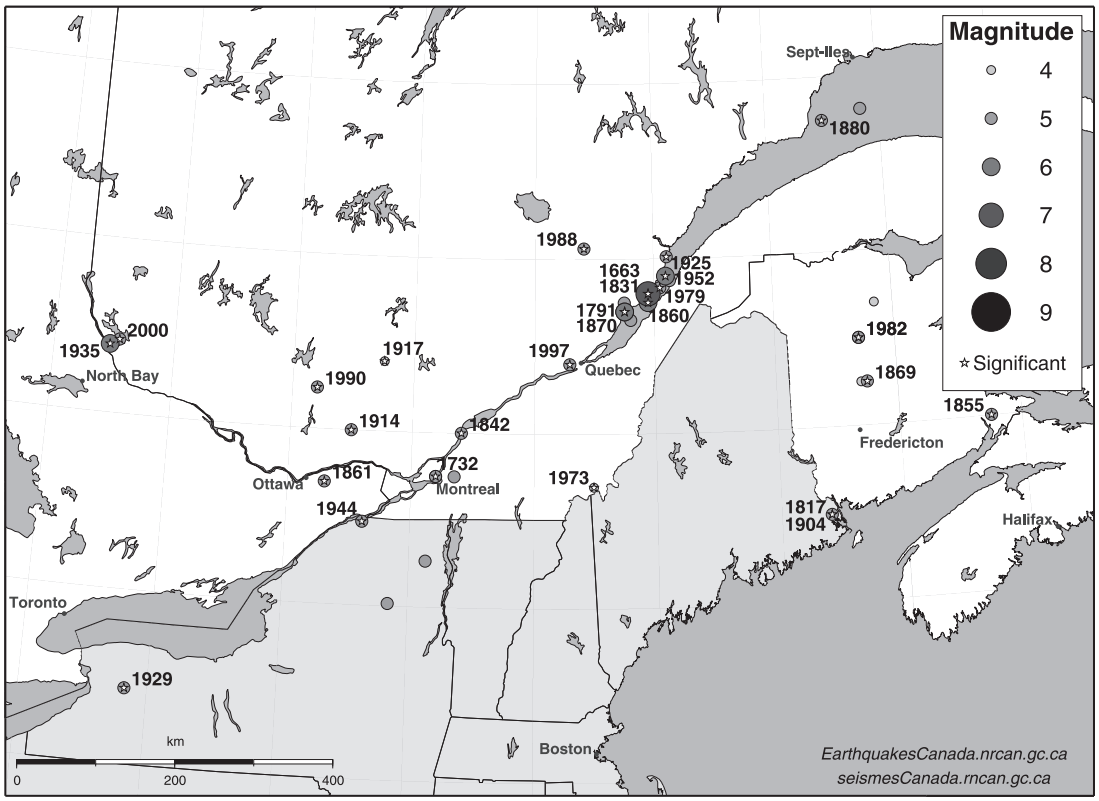
The magnitude of an earthquake is a convenient way of representing its size. There are many magnitude scales, and for this reason it is difficult to give the best magnitude rating for an event. The authors have chosen to use the moment magnitude rating as the primary magnitude when available. If the moment magnitude was unknown, for pre-instrumental events, for example, the magnitude chosen was the best estimate from the



▲ **Figure 1.** Significant earthquakes in or near Canada 1663–2006. Boxes show the extent of figures 2 (southern British Columbia) and 3 (southeastern Canada).



▲ **Figure 2.** Significant earthquakes in or near southwestern Canada 1850–2006, with dates of earthquakes with some impact. Note that only earthquakes from about 1850 on are recognized in the southwest part of British Columbia (with the exception of the 1700 Cascadia event). Note also that the fault ruptures of the **M** 9 1700 Cascadia earthquake and the **M** 8.1 1949 Queen Charlotte earthquake are not properly represented by a circle.



▲ **Figure 3.** Significant earthquakes in or near southeastern Canada 1663–2006, with dates of earthquakes with some impact.

information available. For some historical events, the authors chose not to use decimal units but rounded off the magnitude to the nearest one-half magnitude unit to reflect the very approximate magnitude value. For earthquakes before about 1955, earthquake magnitudes were not calculated on a routine basis, and only a few were studied in detail to determine their magnitude ratings. For most, the magnitude rating is approximate and is identified in this listing as other (OT). This includes some events for which the magnitude is estimated by comparing felt effects with more recent earthquakes in the same region.

Table 2 presents the distribution in magnitude ranges for the selected earthquakes. Approximately 25% of the selected earthquakes had magnitudes less than 6.0 and still had an impact on inhabited areas.

Area

The area descriptor is a general term that refers to the epicentral region of the earthquake. About 60% are located within British Columbia or in the offshore areas, where plate movements result in significant earthquake activity. The two other areas, considered intraplate tectonic environments, are less active: eastern Canada has approximately 25% of the total while northern Canada (north of 60°N) has about 15%, including some events in the Yukon Territory.

Impact

Three fields related to the impact of earthquakes are defined: landslides, tsunamis, and damage. Landslides include any mass movement triggered by earthquake-generated ground vibrations, such as earth flows, rock avalanches, rock falls, rotational landslides, slumps, etc. For convenience, liquefaction and sand expulsions are included in this group. A total of 18 events had associated mass movements in Canada. A noteworthy event is the 1663 Charlevoix earthquake that caused massive landslides, most of them in quick clay areas.

Tsunamis are sea waves generated by the motion of the sea floor through direct rupture or by mass movement induced by the ground vibrations or by coseismic rupture. A total of seven events had associated tsunamis, the most noteworthy being the 1700 Cascadia earthquake and the 1929 Grand Banks earthquake, which killed 28 people in Newfoundland.

Damage includes any type of damage ranging from light damage (cracks in the plaster of walls for example) through cracked chimneys up to the collapse of buildings. A total of 38 earthquakes caused some damage to buildings located on Canadian territory; the majority of these caused some chimney damage.

Deaths

There are no known documented cases of deaths directly caused by Canadian earthquakes. There were possibly two deaths caused by the 1870 Charlevoix-Kamouraska earthquake (Lamontagne forthcoming). There were, however, indirect deaths, such as those caused by the Grand Banks earthquake of 1929. The earthquake generated a massive submarine slump (landslide) that induced a large ocean wave (tsunami) that killed 27 people

TABLE 2
Number of events in the Significant Canadian Earthquake List per magnitude range

Magnitude range	Number of events
M < 5.0	6
5.0 ≤ **M** < 6.0	35
6.0 ≤ **M** < 7.0	98
7.0 ≤ **M** < 8.0	17
M ≥ 8.0	4

when it struck the Burin Peninsula of Newfoundland (plus one person who died from her injuries years later). Native oral traditions also tell of an entire village on Vancouver Island being destroyed by the tsunami caused by the year 1700 earthquake. The 1946 Vancouver Island earthquake caused one death in Canada: one person drowned when a small boat capsized when hit by a wave generated by a submarine slump (Hodgson 1946). Other indirect casualties include people who die of heart attacks but these numbers are very approximate. A total of six earthquakes might have caused direct or indirect casualties.

Maximum Intensity on the Mercalli Scale

Although many intensity scales exist, the Modified Mercalli Intensity (MMI) scale is the most commonly used for North American earthquakes and is the one we chose to use in this project. The MMI scale and isoseismal maps are not ideal to describe all possible consequences of an earthquake. First, rating intensity can be subjective since any level covers a range of effects on humans, structures, and the natural environment. Some analysts look for many effects before assigning the level, whereas others consider the maximum level witnessed in a given area. Second, intensity reports come only from inhabited areas, leaving out many unpopulated areas. In the 20th century, questionnaires were mailed to town postmasters who could describe only what they knew of the local impact. Currently, anyone who feels an earthquake can fill out Internet-based questionnaires, providing a better sampling of the maximum local impact (http://earthquakescanada.nrcan.gc.ca/dyfi/index_e.php). The maximum intensity analyzed herein is that which was experienced on Canadian territory. Approximately 60% of the selected earthquakes had no intensity value assigned to them, the vast majority being events remote from inhabited areas. Only five events could be considered catastrophic (MMI IX and above): 1663 in Charlevoix; 1700 Cascadia; 1870 Charlevoix; and the two 1985 Nahanni earthquakes. The same earthquakes occurring today near major cities would have catastrophic consequences.

DIFFERENCES FROM EXISTING EARTHQUAKE CATALOGS

The list of significant earthquakes has some differences from previous earthquake catalogs. The rationale behind these changes is as follows.

False Event

There are a few instances of false or "ghost" events. A notorious one is the 1534 pseudo-earthquake that supposedly occurred between the two voyages of Jacques Cartier in Canada (1534–1535). Gouin (1994) discarded this possibility. We removed this "ghost" event from our list.

New Events and Modified Information on Events

Recent research on many pre-instrumental earthquakes has provided new information. For example, the works of Gouin (2001) for Quebec, Burke (2004) for New Brunswick, and Bakun *et al.* (2002) and Doser (2006) in the vicinity of western Canada have provided better locations, refined magnitudes, and more information on many pre-instrumental earthquakes. In our updated list of significant earthquakes, we modified numerous epicenters and origin times based on updated information.

- An event previously listed as 14 July 1831 had a wrong date. The event occurred during the night of 7 July 1831 to 8 July 1831 (Gouin 2001).
- Gouin (2001) redefined the date of an earthquake from 9 November 1842 to 7 November 1842.
- An event on 22 October 1869, formerly located at Passamaquoddy Bay, New Brunswick (45.0N, 67.2W) was relocated to a more central New Brunswick location (Burke 2004).
- An earthquake on 29 November 1880 was previously falsely listed as 28 November 1880 (Gouin 2001).
- Revisiting of historical descriptions of damage or felt areas has refined the epicenter or the magnitude of some historical earthquakes including the 1872 British Columbia–Washington earthquake (Bakun *et al.* 2002).
- Reanalysis of seismograms for some earthquakes has modified the epicenter and magnitude (Doser 2006).

CONCLUSIONS

The list of earthquakes created in this project (Lamontagne *et al.* 2007) provides the most up-to-date compilation of significant Canadian earthquakes and their impacts. The list was used to update the earthquake pages contained in the Atlas of Canada Web site and related paper products.

Most significant Canadian earthquakes have occurred in recognized seismically active areas, a fact reflected in the seismic zoning maps used in the National Building Code of Canada. Consequently, modern buildings include earthquake resistance in their designs. To date, the damage caused to man-made structures has been limited, except for buildings constructed with unreinforced masonry. In general, Canadian homebuilders have used sturdy construction practices, even in pre-building-code times, partly to withstand strong winds.

Canadian earthquakes have caused very few direct casualties (possibly two), partly due to the remoteness from inhabited regions of most events, to the low population density on most of the Canadian territory, and to the wood-frame construction of most homes, which provides some earthquake resistance. Most indirect deaths were caused by tsunamis with potentially many

more in pre-historical times. In addition, landslides and mass movements triggered by earthquakes pose a hazard in many parts of the country, including the western Cordillera and on the quick clay deposits in the St. Lawrence lowland areas.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Kenneth Burke, Honorary Research Associate at the University of New Brunswick, for his valuable comments on a draft of the Open File Report. We also thank Janet Drysdale of Natural Resources Canada who supplied us with database information, Alison Bent for her comments, and Alison Bird for her review.

REFERENCES

Adams, J. and S. Halchuk (2003). *Fourth Generation Seismic Hazard Maps of Canada: Values for Over 650 Canadian Localities Intended for the 2005 National Building Code of Canada*. Geological Survey of Canada Open File Report 4459, Ottawa, Canada.

Bakun, W. H., R. A. Haugerud, M. G. Hopper, and R. Ludwin (2002). The December 1872 Washington State Earthquakes. *Bulletin of the Seismological Society of America* **92,** 3,239–3,258.

Basham, P. W., Weichert, D.H., Anglin, F.M., and Berry, M.J. 1982. *New probabilistic strong ground motion maps of Canada: a compilation of earthquake source zones, methods and results.* Publications of the Earth Physics Branch Open File Report 82-33, Energy, Mines and Resources, Canada.

Burke, K. B. S. (2004). Historical seismicity in the Central Highlands, Passamaquoddy Bay, and Moncton regions of New Brunswick, Canada, 1817–1961. *Seismological Research Letters* **75,** 419–431.

Burke, K. B. S. (2007). Determination of the times of historical earthquakes in the pre-standard time era. *Seismological Research Letters* **78,** 344–346.

Doser, D. I. (2006). Relocations of earthquakes (1899–1917) in south-central Alaska. *Pure and Applied Geophysics* **163**, 1,461–1,476.

Gouin, P. (1994). About the first earthquake reported in Canadian history. *Bulletin of the Seismological Society of America* **84** (2), 478–483.

Gouin, P. (2001). Tremblements de terre historiques au Québec: de 1534 à mars 1925, identifiés et interprétés à partir des textes originaux contemporains / Historical earthquakes felt in Quebec : From 1534 to March 1925, as revealed by the local contemporary literature. Montreal: Guérin, 1,491 pps.

Hodgson, E. A. (1946). British Columbia earthquake June 23, 1946. *The Journal of the Royal Astronomical Society of Canada* **40**, 285–319.

Lamontagne, M., S. Halchuk, J. F. Cassidy, and G. C. Rogers (2007). *Significant Canadian Earthquakes 1600–2006*. Geological Survey of Canada Open File Report 5539, 1 CD-ROM. The report is available at no charge at: http://geopub.nrcan.gc.ca/moreinfo_e.php?id=224164

Lamontagne, M. (forthcoming). The first documented direct losses of life from earthquake since European settlement: The Charlevoix, Quebec, earthquake of October 20, 1870. *Bulletin of the Seismological Society of America*.

Smith, W. E. T. (1962). *Earthquakes of Eastern Canada and Adjacent Areas 1534–1927*. Ottawa: Publications of the Dominion Observatory 26, no. 5.

Stevens, A. E. (1980). A history of some Canadian and adjacent American seismograph stations. *Bulletin of the Seismological Society of America* **70,** 1,381–1,393.

Natural Resources Canada
615 Booth Street, Room 216
Ottawa, Ontario K1A 0E9 Canada
maurice.lamontagne@nrcan.gc.ca