Seismicity in the vicinity of the SNORCLE corridors of the northern Canadian Cordillera[1, 2]

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Abstract: The Slave – Northern Cordillera Lithospheric Evolution (SNORCLE) corridors of the northern Cordillera sample some of the most, and least, seismically active regions of Canada. The earthquake history of this region is short. Precise determination of earthquake locations and depths is not possible even today. Nonetheless, significant gains in our knowledge of the seismicity of this region have been made in recent years from studies of historic earthquakes, microseismicity studies, and advances in waveform modelling techniques combined with broadband data that allow for determination of focal mechanisms and depths for moderate earthquakes. This article summarizes our current knowledge of the seismicity and seismic hazards across the region. These detailed analyses have shown that (*i*) the largest historical earthquakes have occurred in regions of ongoing microseismicity; (*ii*) the largest earthquakes have occurred in pairs or in swarms, suggesting that stress triggering is important in this region; (*iii*) the active faults are concentrated in the offshore region; (*iv*) there is a concentration of seismicity in the Fold and Thrust belt, several hundred kilometres from the active plate margin; and (*v*) there is no seismicity associated with the Quaternary volcanic zone in northern British Columbia. Potentially damaging (magnitude $M \geq 5$) earthquakes can be expected every few years in the vicinity of the northern Cordillera. The $M_w = 7.9$ Denali, Alaska, earthquake (where M_w is the moment magnitude) was a good reminder that the effects of a large earthquake can be substantial, even hundreds of kilometres from the epicentre. Detailed studies of seismicity, earth structure, and tectonics, with the latter made possible in large part by the SNORCLE transect, will allow for informed decision-making for resource development and the design of safe structures and infrastructure in the northern Canadian Cordillera.

Résumé : Les corridors du projet SNORCLE de la Cordillère septentrionale permettent d'échantillonner quelques-unes des régions sismiques les plus et les moins actives du Canada. L'histoire des séismes de cette région est brève. Même de nos jours, il est impossible de déterminer avec précision les endroits et les profondeurs des séismes. Néanmoins, au cours des dernières années, nous avons grandement amélioré notre compréhension de la séismicité de cette région à partir de l'histoire des tremblements de terre, des études de microsismicité et des avances dans les techniques de modélisation des types d'ondes, combinés aux données à large bande qui permettent de déterminer les mécanismes focaux et les profondeurs de séismes à intensité modérée. Le présent article résume nos connaissances actuelles de la séismicité et des dangers sismiques à travers la région. Ces analyses détaillées ont démontré que : (*i*) les plus grands séismes historiques ont eu lieu dans des régions de microsismicité active; (*ii*) les plus grands séismes ont eu lieu par paires ou par groupes, suggérant que le déclenchement des contraintes est important dans cette région; (*iii*) les failles actives sont concentrées dans la région au large des côtes; (*iv*) la sismicité est concentrée dans la ceinture de plis et de chevauchements, à plusieurs centaines de kilomètres de la bordure de la plaque active et (*v*) il n'y a pas de sismicité associée à la zone volcanique quaternaire du nord de la Colombie-Britannique. L'on peut s'attendre à des séismes ($M \geq 5$) causant potentiellement des dommages régulièrement à quelques années d'intervalle à proximité de la Cordillère septentrionale. Le séisme de Denali, en Alaska, $M_W = 7{,}9$, est un bon rappel que les effets d'un gros séisme peuvent être substantiels, même à des centaines de kilomètres de l'épicentre. Des études détaillées de la sismicité, de la structure de la Terre et de la tectonique, cette dernière étant rendue possible en grande partie par le transect SNORCLE, permettront de prendre des décisions informées dans le développement des ressources et la conception de structures et d'infrastructures sécuritaires dans la Cordillère canadienne septentrionale.

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Introduction

The Slave – Northern Cordillera Lithospheric Evolution (SNORCLE) corridors extend from the active plate tectonic boundaries along western North America, over the accreted terranes of the northern Cordillera, to the stable North American craton (Fig. 1). Not coincidentally, the SNORCLE transects also span a range of seismic hazard, from the highest in Canada (near the western ends of corridors 2 and 3) to the lowest in Canada (corridor 1). Although the region is sparsely populated, the seismicity and seismic hazard are nonetheless of great interest, notably for decision-making and design considerations for proposed gas pipelines in the northern Cordillera and for possible oil and gas development in the Beaufort Sea. The interest in seismic hazard in this area is especially relevant given the recent (November 2002) $M_w = 7.9$ earthquake along the Denali fault in Alaska, just to the west of the Yukon Territory (where M_W is the moment magnitude).

The purpose of this article is to provide an overview of the seismicity (including studies of the largest earthquakes and microseismicity studies), the history of earthquake monitoring, the accuracy of epicentral locations and focal depths, focal mechanisms, and the correlation with mapped surface features. Although not in the immediate SNORCLE transect area, we include a summary of the effects of the $M_w = 7.9$ Denali, Alaska, earthquake of November 2002 to illustrate the impact (and signature) of large earthquakes in remote areas of the northern Cordillera. Combining these seismicity observations with the new results from analyses of the SNORCLE data (presented in this volume) will allow for better estimates of the earthquake hazard and an improved understanding of the active tectonics of the northern Canadian Cordillera.

Tectonics

Just to the west of the SNORCLE transects, the active tectonics is dominated by the ~6 cm/year northwestward motion of the Pacific Plate relative to the North America Plate. Along the west coast, this motion is largely accommodated by dextral transcurrent motion along the Queen Charlotte and Fairweather faults (Fig. 1*a*). In Alaska, this motion is accommodated by subduction of the Pacific Plate beneath North America. In southeast Alaska, the transition from strike-slip to subduction is denoted by the oblique collision of the Yakutat block (Plafker 1987; Mazzotti and Hyndman 2002) (Fig. 1*a*). This collision results in significant crustal shortening and uplift in the St. Elias and Chugach Mountains region (Fig. 1*b*) of the southwest Yukon Territory and northwest British Columbia. Just inboard of the major plate boundaries is a series of fault zones, the most notable of which is the Denali fault zone (Fig. 1*a*). Other faults in this region (to be discussed in more detail in the following sections) include the Totschunda fault; the Shakwak, Duke River, and Dalton faults (which make up the Denali fault system in Canada); the Chugach – St. Elias fault zone; and the Chatham Strait fault. To the east of the coastal fault zones is a series of accreted terranes (Snyder et al. 2002; Wheeler and McFeely 1991). The Tintina fault zone (Fig. 1*a*) is a prominent feature that extends across the northern Cordillera (Wheeler and McFeely 1991) and has been interpreted as a major intracontinental transform fault (Roddick 1967). Estimates for right-lateral displacement along this fault zone range from 450 km to more than 1000 km since the middle to Late Cretaceous (based on geological evidence, e.g., Gabrielse 1985, and palaeomagnetic evidence, e.g., Irving et al. 1996). To the east of the Tintina fault zone, SNORCLE lines 2 and 3 cross ancestral North America and terminate in the vicinity of the Fold and Thrust belt (see Welford et al. 2001). Farther to the east, SNORCLE line 1 extends from the eastern limit of cordilleran deformation, crossing Proterozoic strata (Snyder et al. 2002) to the Archean cratonic shield, containing the oldest known rocks on Earth.

Seismicity

Earthquake monitoring

The following entry in the diary of a Hudson's Bay trader at Fort Selkirk, Yukon, on 27 December 1850 represents the first written report of an earthquake in the Yukon Territory (Jackson 1990): "… 33 min after 3 Oclock (sic) an earthquake was felt here for the space of one minute. It was very severe and the houses were visibly affected."

Instrumental earthquake recording in western Canada began in 1899 when a seismograph was deployed at Victoria, British Columbia. The first seismograph station in the vicinity of the northern Cordillera began operating at Sitka, Alaska (SIT), in 1904. It was not until 1935 that another station began operating at College, Alaska (COL). These were low-gain instruments, however, and it was not until the late-1950s to mid-1960s when short-period, high-gain seismographs in Alaska and the Canadian National Seismograph Network were deployed that smaller (to about local magnitude $M_L \approx 5$) earthquakes could be located in the Yukon and Northwest Territories. Local seismographs were deployed in the immediate area during the late 1960s to early 1970s (Inuvik (INK) in 1969 and Whitehorse (WHY) in 1971). As of 2003 (Fig. 2), there are additional seismic stations in the region (Haines Junction, Yukon (HYT); Dease Lake, B.C. (DLBC); and Fort Nelson, B.C. (FNBC)), but this still represents a sparse network with limited epicentral resolution and little to no control on focal depth. In terms of "completeness," i.e., the level at which all earthquakes of a certain magnitude have been recorded, the values estimated (Adams and Halchuk 2003) for seismic source zones in the vicinity of the SNORCLE transects are given in Table 1. What is apparent from Table 1 is that there is a relatively short time period (20–30 years) for which all minor earthquakes ($M_L > 3$) in the region have been recorded.

As of 2003, the magnitude completeness level across the region ranges from 2.7 to 3.0. With the exception of earthquakes near the Alaska–Yukon border (which can be located using both Canadian and Alaska data due to real-time data exchange), only three or four stations are available for locating most earthquakes in the northern Cordillera. As a result, the location errors are on the order of ±5–10 km horizontally, and focal depths cannot be routinely determined. Uncertainties this large, combined with the lack of depth control, make it very difficult to associate earthquake activity with specific surface faults or structures. There have been a few detailed studies (summarized later in this paper), however,

Fig. 1. (*a*) Simplified tectonic map of the SNORCLE transect region. The small Yakutat block (YAK) is caught between the Pacific (PAC) and North America (NA) plates. The arrows indicate the motion of the Pacific Plate and Yakutat block relative to North America. The SNORCLE corridors are indicated by thick, numbered lines. Major fault systems are labelled, including the Denali (Den), Tintina (Tin), Fairweather (Fai), Queen Charlotte (Qci), Chugach – St. Elias (Chu), Pamplona (Pam), Chatham Strait (CS), and Transition (Tra) faults. (*b*) Topographic map of the northern Canadian Cordillera, showing the locations of the major mountain ranges discussed in the text, the Beaufort Sea, the accreted terranes, and the stable North American craton.

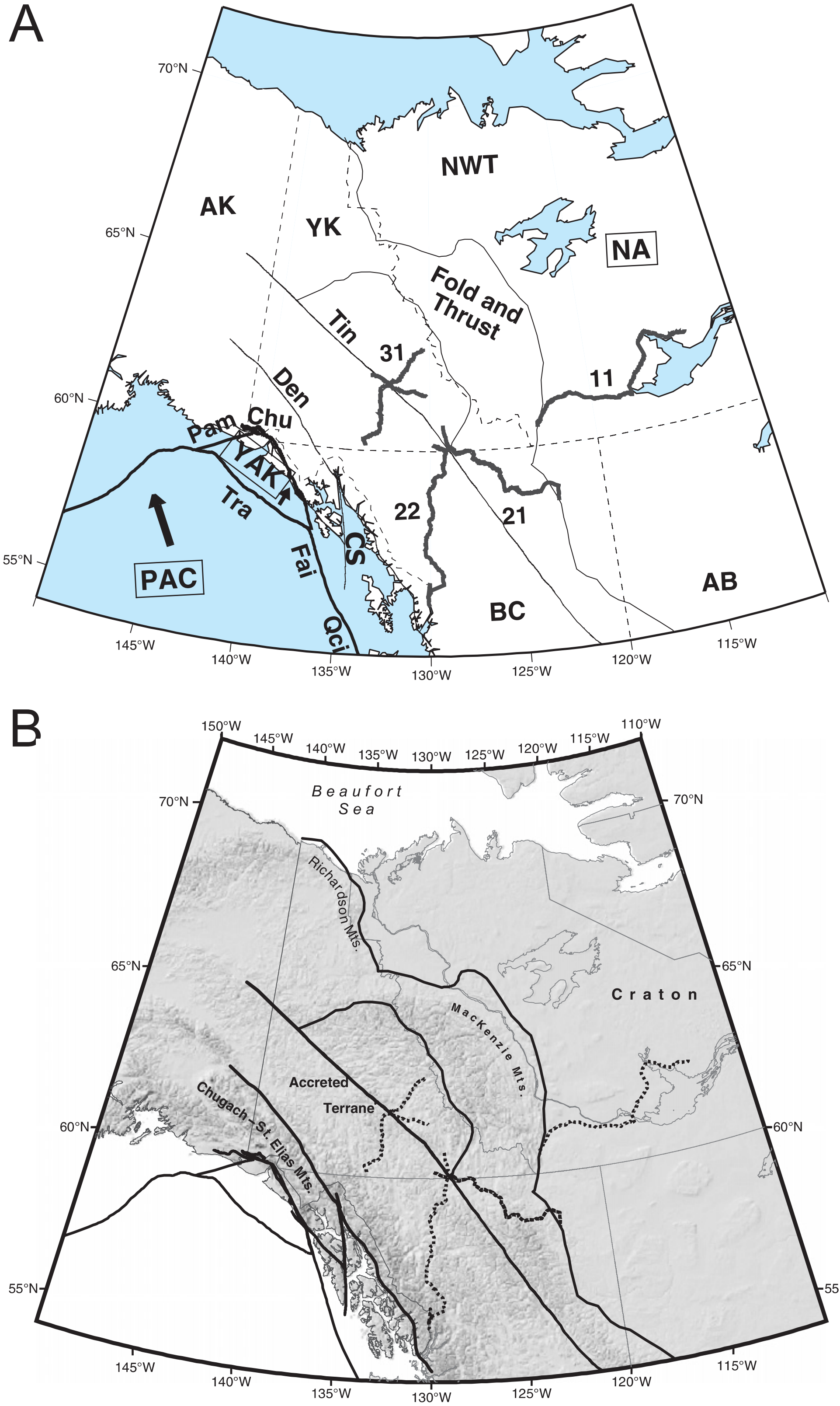


Fig. 2. Seismic stations of the northern Canadian Cordillera and adjacent regions as of January 2003. ■, three-component broadband stations of the Canadian National Seismograph Network (CNSN); ▲, single-component short-period stations of the CNSN; ●, seismic stations (primarily single-component short-period) in Alaska. Also shown is the distribution of seismic stations across the region in 1951 and 1971. BMBC, Bull Mountain; COL, College; DAWY, Dawson; DLBC, Dease Lake; FNBC, Fort Nelson; FSB and FSJ, Fort St. John; HYT, Haines Junction; INK, Inuvik; RUB, Prince Rupert; SIT, Sitka; WHY, Whitehorse; YKA and YKW, Yellowknife.

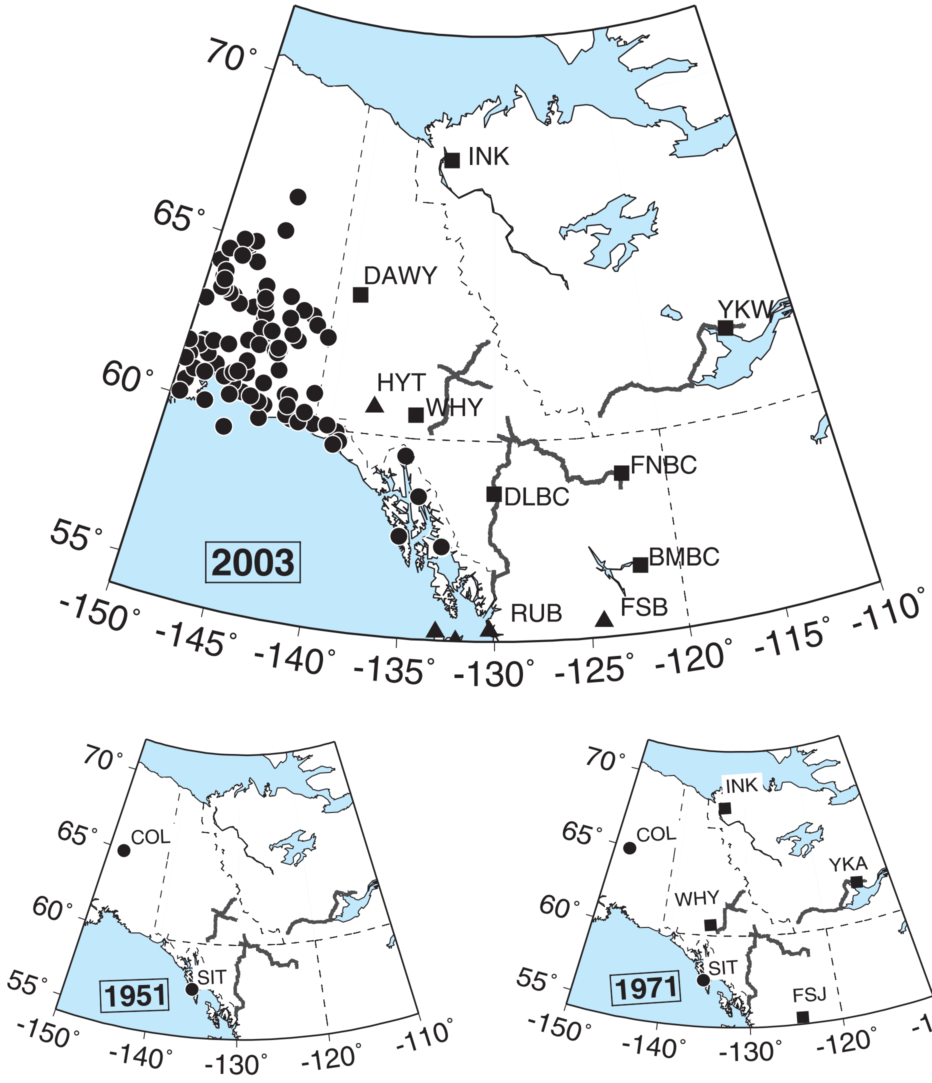


Table 1. Magnitude completeness as a function of time in the vicinity of the SNORCLE transects.

Year	Magnitude, M
1899	7.2
1917	6.3
1951	5.3
1972	3.8
1979	3.0

that provide some constraints on earthquake depths and faulting style in specific areas.

Seismicity patterns

Seismicity recorded across the SNORCLE transect region is illustrated in Fig. 3. It is clear that the most seismically active region is along the plate boundaries in the coastal and offshore area. This is where the largest earthquakes, and the vast majority of the earthquakes, occur. Eight earthquakes of magnitude > 7 have struck this region since 1899 (Fig. 4). The most significant inland seismicity occurs along segments of the Denali fault zone system (Fig. 3), where the seismicity rate is an order of magnitude lower than that in the coastal region. The largest known earthquake to have occurred in the vicinity of the Canadian portion of this fault system is an $M_S = 6.5$ (where M_S is the surface wave magnitude) in 1944 (Fig. 4). In November 2002, an $M_w = 7.9$ earthquake occurred along the Alaska segment of the Denali fault. This earthquake is described in more detail later in the paper. The region between the Denali and Tintina systems (sampled by SNORCLE lines 31 and 22) is relatively aseismic, with relatively few (and small) earthquakes (Figs. 3, 4). There appears to be an alignment of epicentres along the Tintina fault

Fig. 3. Seismicity of northwestern Canada and adjacent parts of Alaska during the period 1899–2002. The smallest dots represent earthquakes of local magnitude $M_L = 3–4.4$, the mid-sized dots $M_L = 4.5–6.4$, and the largest dots $M_L > 6.4$. The thick grey lines denote the SNORCLE corridors. Thin black lines denote faults and structures that are labelled in Fig. 1. Seismicity shown in Alaska to the west of 145° is not complete. Faults: Den, Denali; Tin, Tintina.

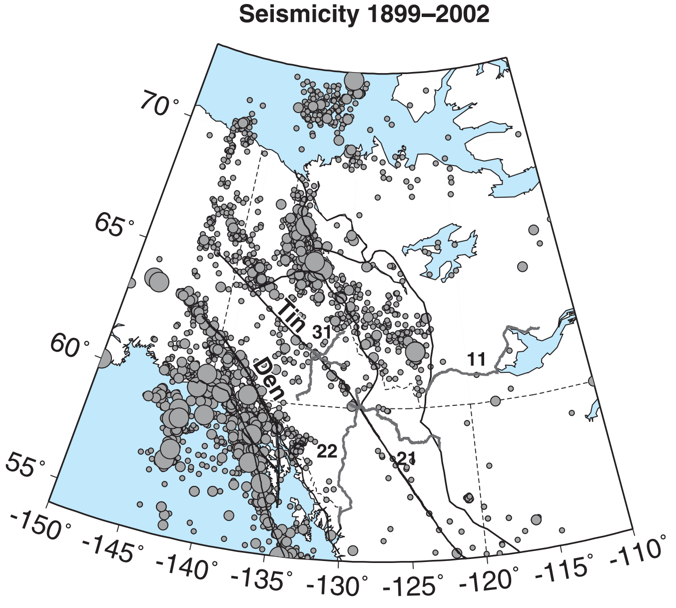

Seismicity 1899–2002

Fig. 5. Locations of temporary seismograph stations operated for microseismicity studies (described in text). ◆, study of Leblanc and Wetmiller (1974); ●, stations operated near the Denali fault zone by Horner (1983); ■, Windy Craggy station operated by Horner (1989); ▲, stations operated by Rogers (1976); ★, stations operated by BC Hydro and the GSC during the 1980s. Focal mechanisms determined from these studies are shown. Letters correspond to the microseismicity surveys described in the text.

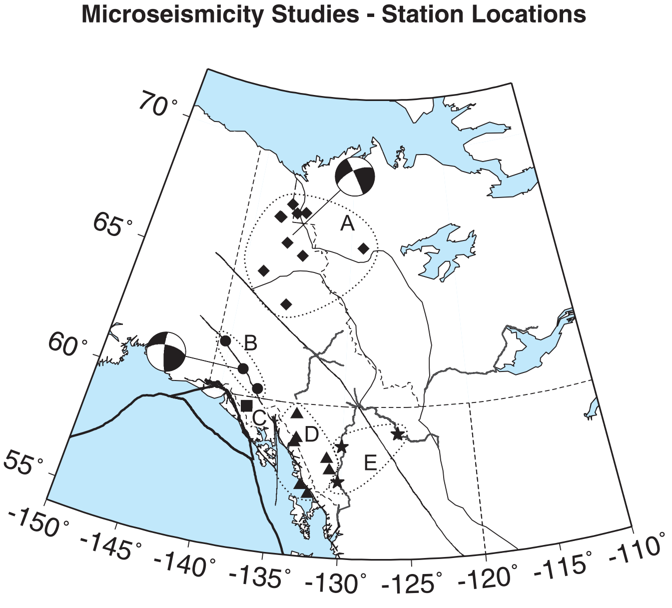
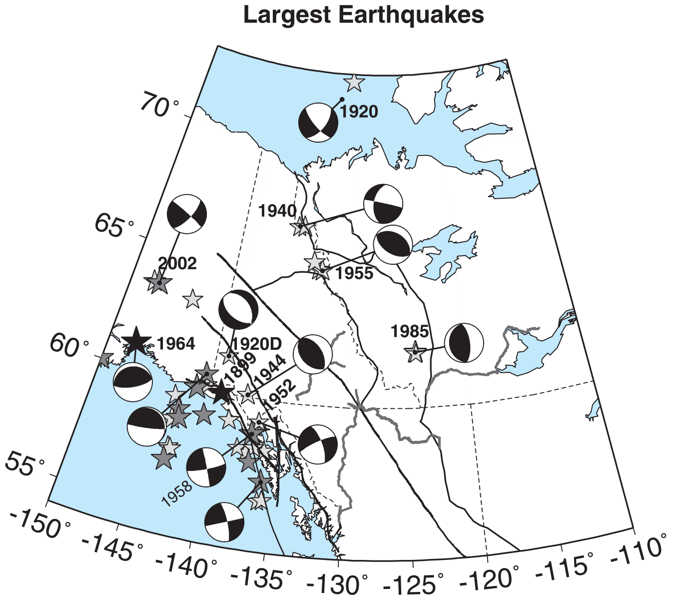

Microseismicity Studies - Station Locations

Fig. 4. Locations of the largest (M ≥ 6) earthquakes in the northern Canadian Cordillera. Focal mechanisms are shown for select events. Key earthquakes discussed in the text are labelled with their year of occurrence.


Largest Earthquakes

(Fig. 3), however, these are all very small earthquakes (M_L < 3) and most of the activity is at the northern end, close to the Alaska border.

Farther inland, the only significant seismicity is along the eastern edge of the Cordillera, more than 600 km from the active plate boundary. This fold and thrust belt seismicity is concentrated in two areas: the MacKenzie–Ogilvie mountains region and the Richardson Mountains region (Fig. 3). The largest known earthquakes in the Canadian Cordillera have occurred in these regions. The M_S = 6.6 and 6.9 Nahanni earthquakes (Horner et al. 1990; Wetmiller et al. 1988) of 1985 (see Fig. 4) are located not far from the western end of SNORCLE line 1 and the eastern end of line 21. In the northern McKenzie Mountains a series of M_S = 6.0–6.5 earthquakes occurred in the mid-1950s (Cassidy et al. 2002), and earthquakes of M_S = 6.0–6.5 have occurred in the Richardson Mountains (Cassidy and Bent 1993). It is noteworthy that these large earthquakes are not located at the deformation front, but rather 50–150 km to the west (Fig. 4).

Another cluster of earthquake activity, significantly to the north of the SNORCLE corridors and hence not dealt with in detail here, is located in the Beaufort Sea. Seismicity in this area is of interest for potential oil and gas exploration. The largest earthquake recorded in the Beaufort Sea is an M_S = 6.5 (Fig. 4) in 1920 (Basham et al. 1977). There is some evidence that earthquakes here occur at a depth of about 40 km (see Hasegawa et al. 1979; Rogers and Horner 1991).

To the east of the Fold and Thrust belt, very few earthquakes have been recorded on the stable craton of the Northwest Territories.

Detailed studies and faulting styles

Five detailed microseismicity studies have been conducted in northern British Columbia, the Yukon, and the Northwest Territories during the past 30 years (see Fig. 5). Each of these studies utilized short-period vertical component seismometers with analogue recording instruments. None applied modern analysis or location techniques. Nonetheless, they provided far more detailed images of seismicity patterns than is available using a sparse regional network. In addition, there have been detailed studies of the largest earthquakes in the region (some of Canada's largest earthquakes). Here, we summarize the results of those studies. Faulting styles for this region are inferred from earthquake focal mechanisms and the rupture characteristics of the largest earthquakes. Until very recently, however, focal mechanisms could only be determined for those earthquakes large enough to be recorded across North America and Europe (typically $M_L > 5$). For these events, focal mechanisms could be determined using the polarity of first motions (*P*-nodal technique), or by modelling body waves and surface waves (e.g., see Cassidy and Bent 1993). These studies were time-consuming in that they required digitizing analogue records prior to modelling. Only a small number of earthquakes (described here) could be analysed using these methods. As described later in the paper, it is now possible to obtain many more focal mechanisms from earthquakes as small as $M_w \approx 4$ by modelling high-quality digital waveforms at regional (up to about 1000 km) seismic stations.

Microseismicity studies

(A) Richardson Mountains region, Yukon and Northwest Territories

Six seismograph stations were operated in this region for a 6 week period during the summer of 1972. Details are provided in Leblanc and Wetmiller (1974). This experiment covered the northern Yukon and parts of the Northwest Territories (Fig. 5). During this experiment, 27 earthquakes of $M_L \geq 1.2$ were located, and many more (too small to locate) were recorded. Fortuitously, an $M_b = 4.8$ (where M_b is the body wave magnitude) earthquake (large enough to be recorded at seismic stations across North America and Europe) was recorded in the Richardson Mountains during this experiment. This study demonstrated the presence of two clusters of earthquakes; one in the southern part of the Richardson Mountains and the other in the northern Mackenzie Mountains. Both areas have a concentration of mapped surface faults and have experienced large (M > 6) historical earthquakes (described later in the textr). Two other key observations for this study (based on the $M_b = 4.8$ earthquake and its aftershocks) are that (*i*) earthquakes in the Richardson Mountains are in the lower crust (at about 20–30 km depth), and (*ii*) the interpreted focal mechanism (the first determined for the region) suggested right-lateral strike-slip motion along a near-vertical north-northwest-striking nodal plane (Fig. 5).

(B) Southwest corner of the Yukon

Three seismograph stations operated in the southwest corner of the Yukon from September 1978 to March 1981. Seismic monitoring over this 2.5 year period (for details, see Horner 1983; Horner et al. 1982) provided the most detailed image of the seismicity, accurate focal depths, and possible association with surface faults in this area to date. This study revealed two principal zones of seismicity that are consistent with historical patterns. The most active region was along the plate boundary along the southeast coast of Alaska. The second active zone was an ~15–20 km-wide band centred on the Duke River and Dalton segments of the Denali fault system (see Horner 1983). All focal depths were shallow (<~15 km). A composite focal mechanism revealed a predominantly strike-slip faulting pattern (Fig. 5), along either a north–south- or an east–west-striking nodal plane. It is noteworthy that neither of these aligns with the mapped surface faults in the area.

(C) Windy Craggy area, northwest British Columbia

One seismograph station operated 30 June to 3 August 1987 and June 1988 to August 1990 in the northwest corner of British Columbia to monitor seismic activity near the Windy Craggy copper deposit and proposed mine (Fig. 5). During this deployment, earthquakes as small as $M_L = 1$ could be recorded, although focal depth could not be resolved with this single station. This study (see Horner 1989) demonstrated the high rate of seismic activity in the St. Elias region (about one earthquake per day). The pattern of seismicity located during this survey was similar to that obtained from the historical record.

(D) Northwest British Columbia and southeast Alaska

For 80 days in the summer of 1968, for 81 days in the summer of 1969, and from September 1971 to December 1972 seismographs were operated within and around the Quaternary volcanic zone (Fig. 5) in northern British Columbia (Milne et al. 1970; Rogers 1976). The main conclusion of these studies was that there was not any significant seismic activity associated with the volcanic zone (including Mt. Edziza). Other seismic activity was detected throughout the region, however. In 1969, 140 microearthquakes (the largest about $M_L \approx 2.5$) were detected and 77 could be located (as described in Rogers 1976). The most common seismic event observed during all these studies (about 8000 in 1968 and 7000 in 1969) was small, low-frequency events that had a pronounced seasonal cycle, with high rates of activity in the summer and fall and almost no activity in the winter and early spring. Their locations were concentrated in a few source zones in the vicinity of large glaciers in southeast Alaska, and they were interpreted as having a glacial origin (Rogers 1976). These studies also showed a concentration of seismic activity in the Glacier Bay region, some activity along the Queen Charlotte and Fairweather faults, some activity in the vicinity of the Denali fault zone, scattered seismicity in the archipelago of southeast Alaska and the Coast batholith (the latter is a different pattern than that exhibited by seismicity from regional networks), and a distinct lack of seismic activity along the Chatham Strait fault.

(E) Northern British Columbia

During the 1980s, BC Hydro and the Geological Survey of Canada (GSC) operated three seismograph stations (Bob Quinn Mine, Dease Lake, and Muncho Lake) in northern British Columbia (Fig. 5) to better assess seismic hazard in the vicinity of proposed hydroelectric developments in the region. Data from these stations were analyzed with data from other seismographs operated by the GSC, effectively lowering the detection threshold of earthquakes in northern British Columbia to about $M_L = 2.5$ (e.g., see Drysdale and

Horner 1986). This monitoring revealed for the first time a weak band of seismicity associated with the Rocky Mountain Trench, a southward extension of the Tintina fault. It also reconfirmed that there was no significant seismicity associated with the volcanic zone, and that the most numerous seismic events recorded were the seasonal events emanating from the region of large glaciers in southeast Alaska.

Largest earthquakes

The largest earthquakes in the area (Fig. 4) have occurred offshore, along the active plate boundaries. The most significant earthquakes are the 1899 sequence (including M_w = 7.8, 8.2, and 8.6 events) at Yakutat Bay, an M_S = 7.9 event in 1958 along the Fairweather fault (Fig. 4), an M_w = 7.6 event in 1972 at the northern end of the Queen Charlotte fault, an M_w = 7.5 event in 1979 along the Chugach – St. Elias fault zone, and a series of events (including two of M_S = 7.6) within the Pacific Plate. In the onshore region, the largest earthquakes include the 2002 M_w = 7.9 Denali, Alaska, earthquake, the 1944 M_S = 6.5 earthquake near the Dalton fault in the southern Yukon (Fig. 4), the 1920 M_S = 6 earthquake near the Denali fault in the Yukon, and the 1952 M_S = 6 event near the northern end of the Fairweather fault in the Yukon.

The 3 November 2002 M_w = 7.9 Denali fault (Alaska) earthquake was one of the largest strike-slip earthquakes ever recorded in North America. It was felt strongly across the Yukon and Northwest Territories (causing some minor damage) and caused buildings to sway and generated seiches up to 2400 km from the epicentre (Cassidy and Rogers 2004). It was located ~300 km to the west of the Alaska–Yukon border and produced surface rupture over a distance of ~340 km (Eberhart-Phillips et al. 2003). This earthquake sequence began as a thrust event (40 km of surface rupture) on a previously unrecognized fault (the Susitna Glacier fault) and then ruptured 218 km as right-lateral strike slip down the Denali fault towards Canada (see fig. 2 in Eberhart-Phillips et al. 2003). It is noteworthy that rupture did not continue along the Denali fault into Canada, but rather stepped to the right through a 14 km-wide series of fault segments and continued as right-lateral slip along the Totschunda fault system (fig. 2 in Eberhart-Phillips et al. 2003) for another 76 km. This earthquake produced up to 3.3 m of dip slip on the Susitna Glacier fault, up to 8.8 m of right-lateral slip along the Denali fault, and up to 2.1 m of horizontal slip along the Totschunda fault. This earthquake triggered thousands of landslides (some as large as 30 million m^3 of rock and ice), most within about 30 km of the surface rupture. There were also liquefaction features observed over a large area (Eberhart-Phillips et al. 2003). The 3 November 2002 earthquake occurred only 11 days after an M_w = 6.7 earthquake that occurred on the Denali fault about 55 km to the west. This earthquake and its aftershock sequence, which extended to within 10 km of the 3 November event, increased the Coulomb stress (and therefore the chance of an earthquake) along both the Susitna Glacier fault and the Denali fault. The M_w = 7.9 earthquake has, in turn, increased the Coulomb stress along both the Denali fault in the vicinity of the Alaska–Yukon border and the Totschunda fault. An initial overview of this earthquake sequence and its effects is presented in Eberhart-Phillips et al. (2003). Numerous detailed studies of all aspects of this earthquake sequence will be published over the next few years.

In the interior of the northern Cordillera, as described earlier, the largest earthquakes have occurred several hundred kilometres to the east of the plate margin, in the Fold and Thrust belt. A pair of large earthquakes (M_S = 6.2 and 6.5) occurred in the Richardson Mountains of the northern Yukon Territory (about 450 km north of SNORCLE line 31) in May and June of 1940. A detailed analysis of these earthquakes (Cassidy and Bent 1993) showed that they represented strike-slip faulting along either a north–south-striking fault or an east–west-striking fault. The earthquakes occurred at depths of 7–14 km and had no detected (or felt) aftershocks. It is likely that these earthquakes are associated with the predominant north–south-striking Richardson Fault system.

A sequence of strong earthquakes (M_S = 6–6.5) occurred in the northern Mackenzie Mountains (about 300 km north of SNORCLE line 31) between 1953 and 1957. A detailed study of these earthquakes (Cassidy et al. 2002) showed that they were very different from those in the Richardson Mountains. These earthquakes had a well-defined aftershock sequence, occurred at a depth range of 7–15 km, and were associated with thrust faulting along a shallow-dipping plane dipping to the north-northeast.

The largest earthquake recorded in the northern Cordillera, an M_S = 6.9 event, occurred in the southern Mackenzie Mountains (near the western end of SNORCLE line 11) in December 1985 (Fig. 4). This earthquake was part of a sequence that included an M_S = 6.6 earthquake in October 1985 and an M_S = 6 event in March 1988. These earthquakes were a surprise in that they were nearly two magnitude units larger than any previous earthquakes in the southern Mackenzie Mountains. They were also significantly larger than any previous earthquakes recorded (maximum M_S = 6.5) within the entire northern Canadian Cordillera. Detailed analyses of these earthquakes are presented in Horner et al. (1990), Wetmiller et al. (1988), and Weichert et al. (1986). Due to the large number of stations around the world recording these earthquakes, and because portable instruments were deployed in the area to record aftershocks, these are the best studied earthquakes in the region to date. The focal depths for these earthquakes and their hundreds of aftershocks (Horner et al. 1990) are 4–10 km. Despite the relatively shallow depth, no surface break was found. Focal mechanisms for each of these events show thrust faulting on north-striking, shallow, west-dipping planes. It is noteworthy that the main shocks or aftershocks did not fall on any of the mapped Laramide faults in the area (Wetmiller et al. 1988). This earthquake sequence was interpreted (Horner et al. 1990) as having occurred along a buried Laramide-age fault that extends through the Proterozoic and Paleozoic rocks above the crystalline basement. These earthquakes were likely caused by the regional compressive stress field activating optimally aligned faults. This suggested the possibility that large earthquakes may occur anywhere within the Fold and Thrust belt of the Canadian Cordillera, with clear implications for earthquake hazards. A number of other earthquake-related studies were conducted in the Nahanni region following this earthquake sequence. These include (*i*) mapping earthquake-induced landslides (Evans et al. 1987), and (*ii*) remote sensing methods, including optical, synthetic aperture radar (SAR), and SAR interferometry (InSAR). Both the optical and SAR images revealed north–south- and east–west-trending tectonic features that had not previously been mapped (Moon et al. 1991, 1998) and demonstrated the applications of these techniques to hazard studies in remote areas.

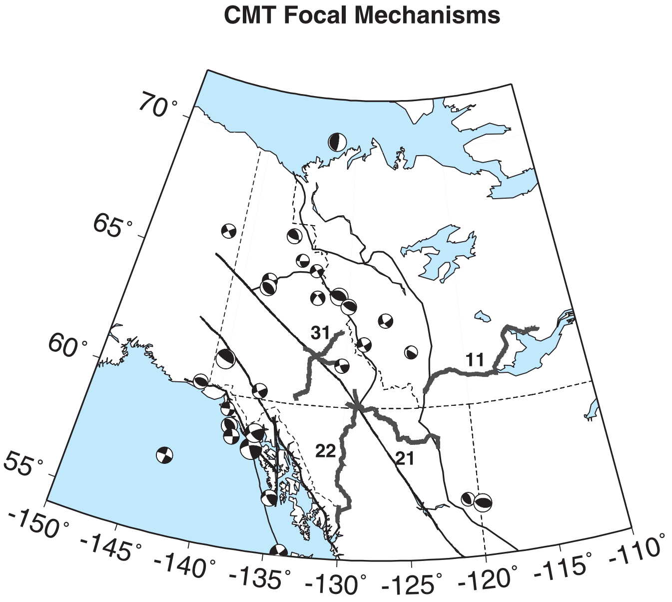
It is noteworthy that the largest earthquakes within the northern Cordillera have occurred either in pairs (1940 Richardson Mountains earthquakes, 2002 Denali Alaska earthquakes) or in swarms (1953–1957 northern Mackenzie Mountains, 1985–1988 Nahanni). This suggests that Coulomb stress triggering plays an important role in this region.

Faulting styles and relationship with surface faults

Faulting styles in the study area can be inferred from earthquake focal mechanisms. These have been determined for the largest historic earthquakes (as described earlier in the paper) and more recently (see Ristau et al. 2003) using a moment tensor routine (Ammon 2001) for smaller events ($M_L > 4$; see Fig. 6). This is now possible because of high-quality digital data. The regional moment tensor routine (Ristau et al. 2003) uses region-specific Earth models and regional waveforms (to distances of about 1000 km). This modelling provides the earthquake mechanism, seismic moment, and focal depth. By extending the magnitude threshold down to about M = 4, it is possible to calculate nearly 10 times as many moment tensor solutions compared with teleseismic methods.

In the offshore region, focal mechanisms (Fig. 4) are consistent with the relative plate motions of the Pacific and North America plates. A detailed study of earthquakes in this area (Doser and Lomas 2000) yields focal mechanisms consistent with right-lateral motion along the strike-slip Queen Charlotte and Fairweather fault systems, and collision between the Yakutat terrane and the North America plate (Fig. 1). All slip vectors are parallel to predicted Pacific – North America plate motions in the vicinity of the Fairweather and Queen Charlotte faults (Doser and Lomas 2000). Large earthquakes in 1927 ($M_S = 7.1$), 1958 ($M_S = 7.9$), and 1972 ($M_w = 7.6$) have ruptured the entire length of the Fairweather fault (Doser and Lomas 2000). Near the Yakutat block, mechanisms show thrust faulting. Here, the slip vectors are rotated clockwise relative to the predicted plate motions, and a slip rate of ~3 mm/year has been estimated along the Transition fault zone during the past 100 years (Doser and Lomas 2000). In this region, most of the Pacific – North America plate motion appears to be concentrated along the Chugach – St. Elias and Pamplona fault zones (Horner 1983), resulting in significant uplift in the St. Elias Mountains. Doser and Lomas (2000) conclude that most moderate events in the St. Elias region occur along thrust faults at depths of about 13–18 km and therefore represent deformation within the North America plate and the Yakutat block.

Fig. 6. Select CMT focal mechanisms for recent $M_w > 4.5$ earthquakes in the northern Canadian Cordillera obtained using the centroid moment tensor method and regional waveforms (see text). Location of the major faults and the SNORCLE corridors are shown.



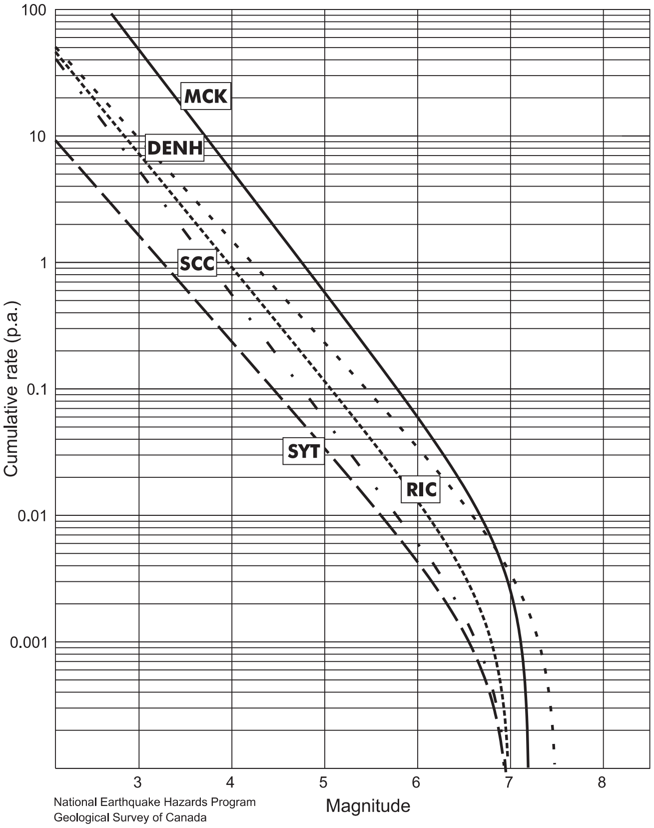
In the onshore region, extending from the coast through to the Canadian segments of the Denali fault system, there are very few focal mechanisms available. A composite mechanism of microseismicity (see Fig. 5) in the vicinity of the Denali fault (near the south end of Kluane Lake) showed a right-lateral strike-slip mechanism (Horner 1983) that is oriented north–south or east–west and not aligned with the fault system. A recent (3 August 2000) centroid moment tensor (CMT) solution for an $M_w = 4.5$ event in the vicinity of the fault system shows a right-lateral strike-slip mechanism with a nodal plane aligned with the fault (striking ~147°). The Canadian portion of the Denali fault system (comprising the Shakwak, Dalton, and Duke River faults) shows little evidence for active faulting. In historical times, two moderate earthquakes have been recorded near this system, namely an $M_S = 6.0$ event in 1920 and an $M_S = 6.5$ event in 1944 (Fig. 4). A recent relocation of these events (Doser and Lomas 2000) places them farther to the west, away from the Denali fault system. Focal mechanisms estimated in that study suggest normal faulting (1920 event) and thrust faulting (1944 event), which also indicates that they are not associated with the Denali system. Current seismicity rates and the lack of geological offsets along the Denali fault zone suggest about 1 mm/year or less along this zone through the Yukon Territory (Horner 1983). This is in contrast with the Denali fault system in Alaska which shows clear evidence for activity, including a slip rate of 8–13 mm/year based on Quaternary offsets (Eberhart-Phillips et al. 2003) and right-lateral motion from focal mechanisms of recent moderate to large earthquakes (Ratchkovski and Hansen 2002). To the east of the junction with the Totschunda fault, however, the estimated slip rate along the Denali fault in Alaska decreases to about 2–3 mm/year (Plafker et al. 1994*a*, 1994*b*). The Totschunda fault in Alaska (which experienced some rupture during the November 2002 Denali earthquake) shows Holocene displacements of 100–350 m (Richter and Matson 1971) and long-term slip rates of 5–10 mm/year, comparable with that of the Denali fault in Alaska (Plafker et al. 1977). This suggests that deformation is concentrated along the Denali (Alaska) and transferred to the Totschunda system, and not to the Denali fault in the Yukon.

Through the interior of the Yukon, there are only three focal mechanisms (based on CMT waveform modelling) from recent moderate ($M_w = 4$–5) earthquakes (Fig. 6) in the vicinity of the Tintina fault system. They are a mixture of right-lateral strike-slip and thrust earthquakes and do not align with the orientation of the Tintina fault system.

Throughout the Fold and Thrust belt of the northeastern Canadian Cordillera, focal mechanisms have been determined for the largest historic earthquakes, the Nahanni earthquakes of the 1980s, and, using the CMT method, several dozen modern moderate-sized earthquakes (Fig. 6). In the Mackenzie Mountains, the largest earthquakes all show thrust faulting. CMT solutions show mainly thrust faulting, but with some strike-slip mechanisms also (see Fig. 6). In the southern Mackenzie Mountains the nodal planes are oriented north–south, in agreement with local geological structures. In the northern Mackenzie Mountains, the nodal planes rotate to become northwest–southeast, again in agreement with the orientation of local surface structures. In the Richardson Mountains, focal mechanisms of the larger historic earthquakes show right-lateral strike-slip faulting, consistent with the Richardson fault system. The pressure axes for all of these earthquakes are in agreement with the regional stress field and have been interpreted as resulting from Yakutat collision and strain transfer across the rigid northern Canadian Cordillera (Mazzotti and Hyndman 2002; Hyndman et al. 2005).

Farther north, beneath the Beaufort Sea, only a few focal mechanisms are available (Fig. 4). They show (Hasegawa et al. 1979; Rogers and Horner 1991) normal faulting and a nearly horizontal tension axis (in contrast with the nearly horizontal pressure axes observed throughout the northern Cordillera). These earthquakes are interpreted to occur in the lower crust (Hasegawa et al. 1979) and cannot be associated with any surface faults.

Fig. 7. Normalized magnitude–recurrence curves for seismic source zones in the northern Canadian Cordillera. The zones proposed for use in the 2005 edition of the National Building Code of Canada seismic hazard maps are defined as follows: DENH, Denali zone; MCK, Mackenzie Mountains; RIC, Richardson Mountains; SCC, stable craton of North America; SYT, southern Yukon (interior). All curves have been normalized to an area of 100 000 km^2 to show the relative rate of seismicity across the region. Note that the offshore region (US) is not shown (but would be an order of magnitude higher than the highest curve plotted). Used with permission of the National Earthquake Hazard Program, Geological Survey of Canada.



* Note SCC curve is a weighted average of Worldwide (0.4), North American (0.4), and Canadian (0.2) curves that are used in the stable craton hazard model.

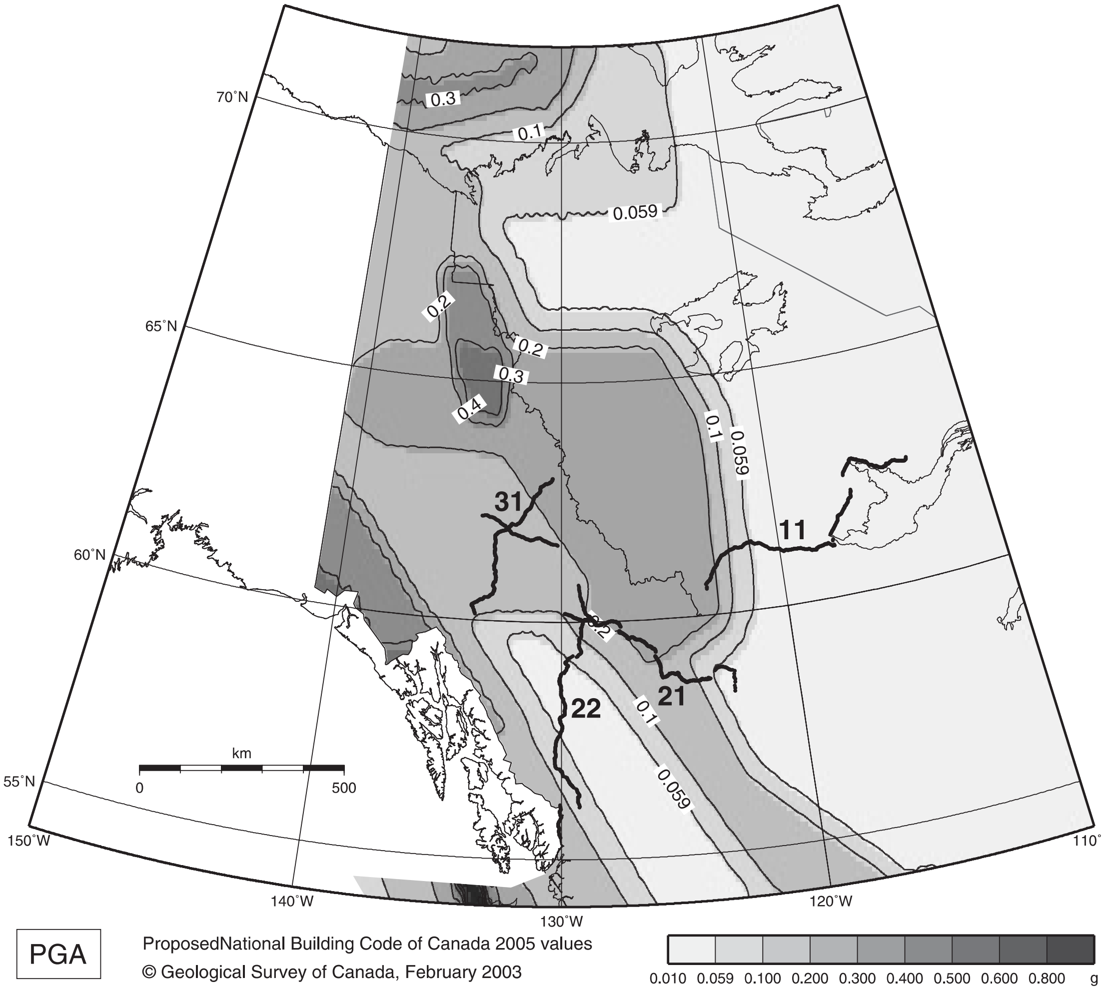
Rate of seismicity and seismic hazard

As is clearly evident in Figs. 3 and 4, there is a drastic variation in the rate of seismicity, the style of seismicity, and the associated level of seismic hazard across the SNORCLE transect region. Seismicity rates for the earthquake source zones across the region have recently been recomputed (Adams and Halchuk 2003) for use in proposed new seismic hazard maps for the 2005 edition of the National Building Code of Canada. The relative rate of seismicity for onshore source zones (all normalized to a uniform area) spanning the SNORCLE transect varies by more than a factor of 300 (Fig. 7). For the onshore regions, the most active area is the Richardson Mountains, and the least active is the stable craton. The estimated return period for an M ≥ 5 earthquake (capable of causing damage) varies from about one every 1.5 years along to the coast, to one every 3–5 years in the vicinity of the Denali fault system, to approximately one every 30 years in the interior of the Yukon (including near the Tintina system), and to about one every 2–3 years in the Richardson and Mackenzie mountains region. The derived peak acceleration values (proposed for the 2005 edition of the National Building Code of Canada) across the SNORCLE region are shown in Fig. 8. The highest hazard is in the offshore region and the southwestern corner of the Yukon Territory (Fig. 8), with the next highest zone being the Richardson and northern Mackenzie mountains of the Fold and Thrust belt, and the Beaufort Sea (Fig. 8). For details on the new proposed seismic hazard maps for Canada, see Adams and Halchuk (2003) and Adams and Atkinson (2003).

Summary

The SNORCLE corridors of the northern Canadian Cordillera sample some of the most (and least) seismically active regions of Canada. The detailed earthquake history of the region is relatively short. It has only been possible to locate earthquakes as small as $M_L = 3$ in the northern Cordillera since 1979. Even today, there are relatively few seismograph stations in the region, so it is not possible to determine precise earthquake locations and focal depths. This, in turn, makes it difficult to associate individual earthquakes with mapped surface features. Nonetheless, significant gains in our knowledge of the seismicity of the SNORCLE region have been made in recent years. This comes from (*i*) detailed

Fig. 8. Predicted peak ground acceleration (PGA) (2% in 50 years probability level) proposed for the 2005 edition of the National Building Code of Canada. Only values in Canadian territory are plotted. The frequency of shaking shown would affect small (one or two storeys) structures. Used with permission of the Geological Survey of Canada.



studies of historic earthquakes, (*ii*) microseismicity studies that have been conducted in the area, and (*iii*) recent advances in waveform modelling techniques combined with three-component broadband data, which now allow for routine estimation of focal mechanisms and depths for moderate earthquakes (as small as M_L = 4). This allows for a better understanding of faulting style and will yield improved estimates of the rate of seismic moment release as more data are collected. This article summarizes our current knowledge of the seismicity and seismic hazards across the region. This information, combined with the detailed structural and tectonic interpretations that have been made using SNORCLE data (this volume), will provide an improved understanding of seismic hazard and active tectonics of the northern Canadian Cordillera.

Detailed analyses of large historic earthquakes and results from microseismicity studies and waveform modelling of smaller, recent events have shown the following:

(1) The largest historical earthquakes have occurred in regions that exhibit ongoing microseismicity.
(2) The largest earthquakes have all occurred either in pairs (1940 Richardson Mountains earthquakes, 2002 Denali Alaska earthquakes) or in swarms (1953–1957 northern Mackenzie Mountains, 1985–1988 Nahanni). This suggests that stress triggering plays an important role in this region.
(3) There is no seismicity associated with the volcanic zones in northern British Columbia.
(4) The active faults (based on an alignment of epicentres and faulting style from focal mechanisms) are concentrated in the offshore region (e.g., Fairweather, Queen Charlotte, Transition zone, and Pampolona faults). In the onshore region, the only faults that appear to be seismically active are in Alaska (e.g., the Denali, Totschunda, and Chugach – St. Elias faults). There has been no evidence found for active faulting along the Tintina fault or the Canadian segments of the Denali fault system.
(5) There is a concentration of seismicity in the foreland Fold and Thrust belt, several hundred kilometres from the active plate margin. This seismicity appears to be concentrated along predominantly strike-slip faults in the Richardson Mountains and blind thrust faults in the Mackenzie Mountains. In both areas, the stress orientation

suggests that earthquakes are triggered by the regional stress field along optimally aligned faults (see Hyndman et al. 2005).

Although seismicity cannot be attributed to specific onshore faults in the northern Canadian Cordillera, the rate of activity is still very significant. On average, M ≥ 5 (potentially damaging) earthquakes can be expected every 2–3 years in the Richardson Mountains region and every 3–5 years in the southwest corner of the Yukon. The M_w = 7.9 Denali, Alaska, earthquake was a good reminder that the effects of a large earthquake can be very substantial, even at distances of hundreds of kilometres from the earthquake source. It is detailed studies of seismicity, earth structure, and tectonics, the latter made possible in large part by the SNORCLE transect, that will allow for informed decision-making for resource development and the design of safe structures and infrastructure in the northern Canadian Cordillera.

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