Yakutat collision and strain transfer across the northern Canadian Cordillera

Stéphane Mazzotti
Roy D. Hyndman
Pacific Geoscience Centre, Geological Survey of Canada, 9860 West Saanich Road, Sidney, British Columbia V8L 4B2, Canada,
and School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia V8W 3P6, Canada

ABSTRACT

The collision of the Yakutat block in the corner of the Gulf of Alaska has resulted in large deformation in the adjacent Chugach–Saint Elias Mountains. This collision is inferred to produce the strong seismicity in the Mackenzie and Richardson Mountains of the northern Canadian Cordillera foreland belt, 800 km to the northeast. Strain is transmitted from the Yakutat collision across the northern Cordillera with little intervening deformation, in spite of high heat flow and thin mechanical lithosphere. Global Positioning System results and seismic deformation rates indicate a northeastward motion of the northern Cordillera at ~5 mm/yr, relative to the craton to the east, that is mostly accommodated in the foreland belt. This quasi-rigid displacement of the Cordilleran upper crust requires a decoupling level in the weak lower crust that rises to join the basal detachment of thrusting in the foreland. Based on a two-dimensional mechanical model, we show that the strain transfer and the lower crust detachment are made possible by the high temperature (~900 °C) at the base of the Cordilleran crust. The northern Cordillera presents a type example of an orogenic float associated with large-scale décollement in weak lower crust.

Keywords: collision, crustal shortening, intraplate tectonics, northern Cordillera, rheology, Yakutat.

INTRODUCTION

The Yakutat block is a small composite oceanic-continental terrane that has migrated northwestward with the Pacific plate along the North America western margin and has been colliding obliquely with the continent in the corner of the Gulf of Alaska since the Miocene (e.g., Lahr and Plafker, 1980; Bruns, 1983; Plafker et al., 1994). The block acts as an indenter, resulting in crustal thickening, rapid uplift, and intense seismicity in the adjacent Saint Elias and Chugach Mountains (Fig. 1). The Yakutat block is being forced to the west around the corner of the Gulf of Alaska along a series of strike-slip and thrust faults.

In the northern Canadian Cordillera foreland belt, the Mackenzie and Richardson Mountains region is affected by strong seismicity, 600–800 km northeast of the Yakutat collision (Fig. 1). We propose that deformation along the Mackenzie and Richardson Mountains results from a transfer of strain from the Yakutat collision across the northern Cordillera, associated with a quasi-rigid displacement of the Cordilleran upper crust over a lower crust detachment. Using Global Positioning System (GPS) results, we determine the rate of northeastward migration of the Cordillera relative to the craton to the east. We show from earthquake focal mechanisms and seismicity statistics that most of this motion is accommodated by shortening across thrust faults in the Mackenzie Mountains, and along right-lateral strike-slip faults in the Richardson Mountains. We present a two-dimensional thermomechanical model that illustrates how strain transfer can be accounted for by the presence of a decoupling level in the weak lower crust, associated with a very high temperature at the Moho.

YAKUTAT COLLISION

The Yakutat block is composed of a thick Cretaceous continental margin succession in the east (Yakutat Group) and Eocene oceanic crust in the northwest. Both parts are overlain by Cenozoic clastic sedimentary rocks (Plafker et al., 1994, and references therein). It is bounded on the southwest by the Transition fault system, a transpressive right-lateral fault zone. To the east, the transcurrent Fairweather fault marks the boundary of the Yakutat terrane with older accreted blocks and accommodates most of the Pacific–North America motion

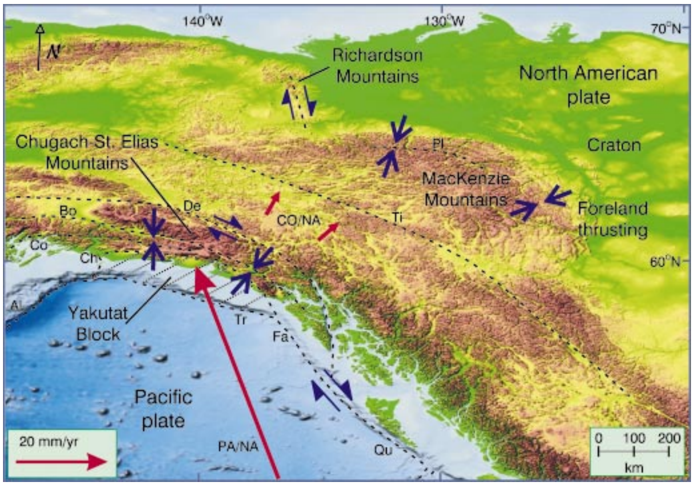

Figure 1. Tectonics of northwestern Canada and eastern Alaska. Red arrows show Pacific–North America (PA/NA) and northern Cordillera–North America (CO/NA) motions. Dashed lines are main fault systems: Al—Aleutian trench, Bo—Border Range fault, Ch—Chugach–Saint Elias thrust, Co—Contact thrust, De—Denali fault, Fa—Fairweather fault, Pl—Plateau thrust, Qu—Queen Charlotte fault, Ti—Tintina fault, Tr—Transition fault.

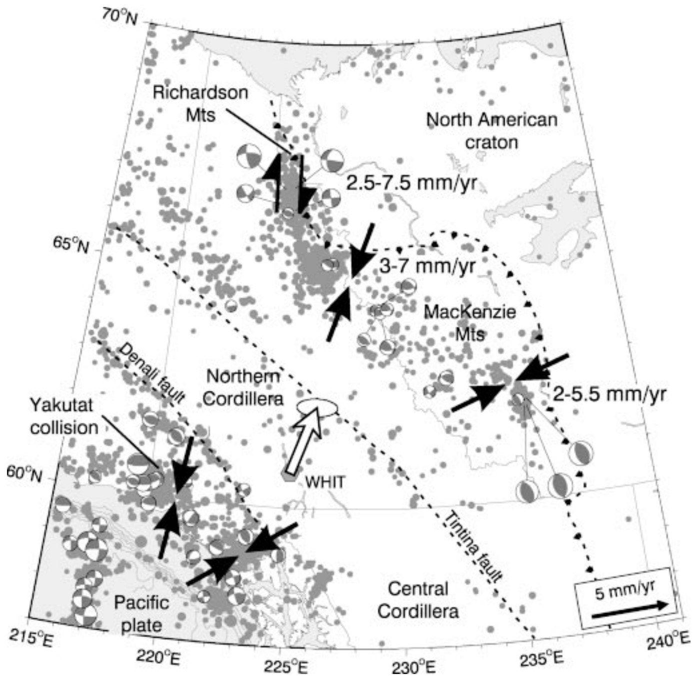

Figure 2. Crustal seismicity. Shaded circles are shallow earthquakes (depth < 30 km, M > 2, 1980–2000). Focal mechanisms after Harvard moment tensor solution and Ristau et al. (2001). Deformation rates in Cordillera foreland belt are derived from earthquake statistics. Large open arrow shows Whitehorse (WHIT) Global Positioning System velocity relative to craton to east. Dashed line is Cordillera eastern deformation front.

(Plafker et al., 1978; Fletcher and Freymueller, 1999). To the north, underthrusting and accretion of the Yakutat oceanic crust and its cover assemblage is accommodated along a series of northeastward- to northward-dipping thrust faults, including the Chugach–Saint Elias, Contact, and Border Ranges fault systems (Fig. 1).

The Saint Elias and Chugach Mountains, on the northeastern border of the Yakutat block, compose a region of high elevation and steep topography (Fig. 1). The mountains rise rapidly from sea level to peaks nearly 6000 m high. The average topography is ~2500 m, in contrast to most of the Canadian Cordillera, which rises to ~1000 m. These ranges are inferred to result from the collision and underthrusting of the Yakutat block beneath adjacent terranes. Uplift of the Saint Elias Mountains started in the Miocene (e.g., Gabrielse, 1991) at an average rate of ~0.3 mm/yr.

SEISMICITY

The region adjacent to the Yakutat block has intense seismicity (Fig. 2). Large historical earthquakes include a series of strike-slip events (M = 7–7.6) that ruptured the entire length of the Fairweather fault, and three major thrust earthquakes (M = 7.4–8) along the northeastern edge of the Yakutat block (e.g., Doser and Lomas, 2000). Smaller (M = 5–7) earthquakes along the eastern and northern edges indicate a compression direction that rotates northward from approximately east-west to approximately north-south around the corner of the Gulf of Alaska (Fig. 2; Doser and Lomas, 2000).

The seismic activity decreases rapidly east of the collision zone. The main concentration of crustal earthquakes is along the Denali fault (Fig. 2), a transpressive right-lateral strike-slip fault subparallel to the Fairweather fault. Farther east, the central part of the northern Cordillera is affected by little seismicity. A slight concentration of earthquakes (to M ~ 4.5) suggests a small activity of the right-lateral Tintina strike-slip fault zone (Fig. 2).

Earthquake activity increases in the Mackenzie and Richardson Mountains, 600–800 km to the northeast of the Yakutat collision zone (Fig. 2). The high seismic concentration in the northern section of the Cordillera foreland thrust belt is in contrast to low seismic activity in the central section. In the Mackenzie Mountains, seismicity is concentrated 50–150 km west of the deformation front. In this region, an imbricate stack of thin thrust sheets is detached above deep low-angle thrusts (e.g., Plateau fault; Gabrielse, 1991). Two M ~ 7 and several M = 5–6 thrust earthquakes in the southern Mackenzie Mountains indicate east-northeast compression, with a rotation to northeast compression in the northern Mackenzie Mountains (Fig. 2). In the Richardson Mountains, seismicity extends along a north-south band to the Beaufort Sea. The largest historical events are two M ~ 6.5 right-lateral strike-slip earthquakes along a north-south fault system (Cassidy and Bent, 1993). The earthquake mechanisms indicate a northeast compression, similar to that in the northern Mackenzie Mountains.

CORDILLERA KINEMATICS

Very long baseline interferometry (VLBI) measurements provided the first indirect data on the motion of the northern Canadian Cordillera and the associated deformation in the northeastern foreland belt. On the basis of VLBI and fault-slip data, Lundgren et al. (1995) proposed a thin-shell mechanical model, where the northern Cordillera moves northeastward at ~10 mm/yr, most of this motion being accommodated in the Mackenzie Mountains but almost no deformation occurring in the Richardson Mountains. Based on campaign-style GPS measurements over 3 yr, Fletcher and Freymueller (1999) obtained a smaller motion of Whitehorse relative to stable North America of ~5 mm/yr eastward.

We use the analysis of a permanent network of 16 GPS stations over North America (James et al., 2001) to derive the velocity of Whitehorse relative to Yellowknife on the craton to the east. Continuous GPS data spanning ~5 yr (1996–2001) were analyzed using double differencing, leading to a daily horizontal repeatability of 2–3 mm. Linear trends in the time series were estimated simultaneously with an annual term and potential offsets. The relative rates were adjusted to the global ITRF97 solution and corrected for the rigid rotation of North America (James et al., 2001). The velocity of Whitehorse relative to Yellowknife is 4.5 ± 1 mm/yr toward N20° ± 10° E (Fig. 2), similar in rate but more northward than the campaign results by Fletcher and Freymueller (1999).

SEISMIC DEFORMATION RATES

In order to obtain quantitative constraints on where the 5 mm/yr northeastward motion of the northern Cordillera is accommodated, we estimate the rate of seismic moment release and the associated rate of crustal deformation in the Mackenzie and Richardson Mountains. We derive the total moment rate using the frequency of occurrence for each magnitude increment assuming a Gutenberg-Richter recurrence relation (e.g., Anderson, 1979). The contribution for each magnitude increment is integrated to an estimated maximum magnitude. The moment rate can then be used to estimate the deformation rate, assuming a regional fault style, an effective seismic thickness, and that within this seismic thickness most of the deformation occurs by earthquakes[1]. This method has been used to determine long-term seismic deformation rates in southern California (e.g., Field et al., 1999) and in northern Cascadia (Hyndman et al., 2000).

We choose a fault type that corresponds to a 30° dipping thrust

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[1] GSA Data Repository item 2002052, Estimation of deformation rates from earthquake statistics, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

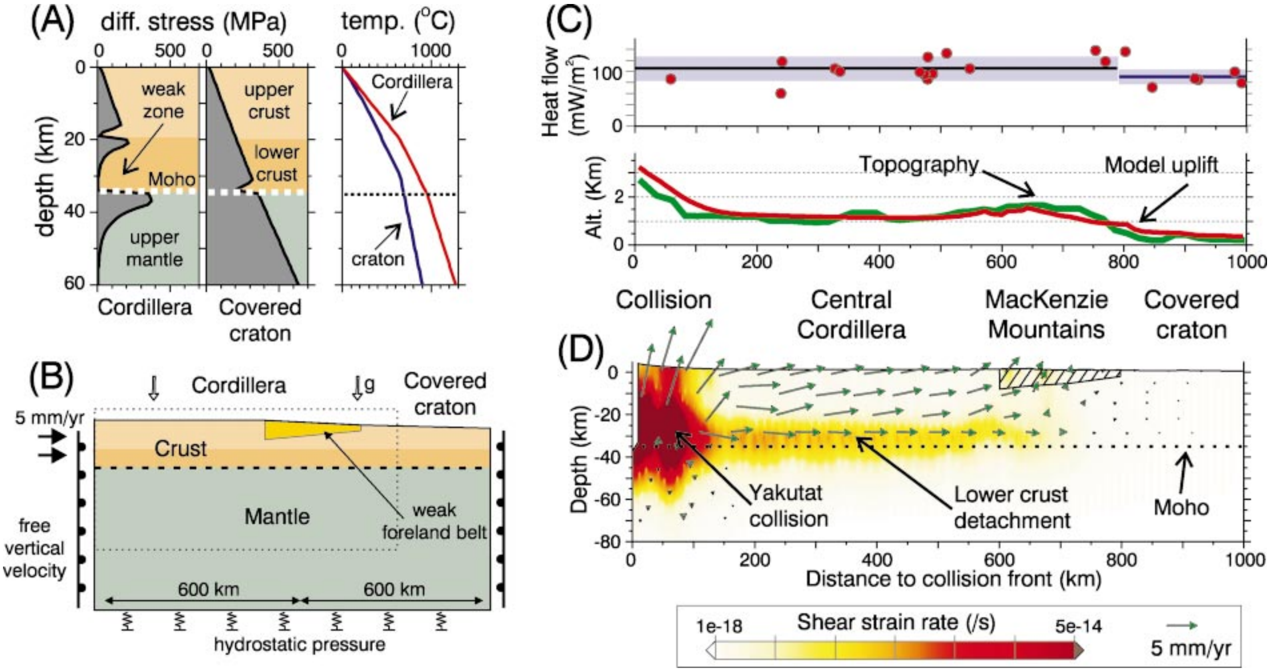

Figure 3. Rheology and strain transfer. A: Rheology and temperature profiles of Cordillera and covered craton. B: Description and boundary conditions of finite element model. C: Heat-flow data points; Cordillera topography versus predicted uplift after 2 Ma. D: Model shear strain rate and velocity fields after 2 Ma. Vertical exaggeration ~3.5.

for the Mackenzie Mountains and to a vertical strike-slip fault for the Richardson Mountains, in agreement with the structural style in each belt. The seismic thickness in both regions is determined to be 10–15 km, on the basis of local studies of earthquake depth distribution (Wetmiller et al., 1988; Cassidy and Bent, 1993). The maximum magnitude of integration is determined using the length of the largest fault in each region, the seismic thickness, and an empirical relation between magnitude and fault area (Wells and Coppersmith, 1994). In the Mackenzie Mountains, the largest earthquake along the ~250-km-long Plateau thrust (Gabrielse, 1991) would correspond to a magnitude M = 7.8 (range 7.5–8). In the Richardson Mountains, a length of 200 km for the main strike-slip fault, based on the seismicity extent, would lead to a maximum magnitude M = 7.5 (range 7.2–7.8).

With those parameters, we estimate a shortening rate of 4.5 ± 2.5 mm/yr across the Mackenzie Mountains and a right-lateral strike-slip rate of 5 ± 2.5 mm/yr in the Richardson Mountains (Fig. 2). The uncertainties are based on the statistical error and on the range of seismic thickness and maximum magnitudes. These results strongly depend on the maximum magnitude of integration. A change of 0.5 in magnitude results in a change in the deformation rate by a factor of ~2. Using the largest historical earthquake to define the maximum magnitude in both regions (cf. discussion of seismicity herein), we obtain a lower bound deformation rate of ~1 mm/yr.

STRAIN TRANSFER

The inferred deformation rates in the Mackenzie and Richardson Mountains suggest that most of the northern Cordillera motion is accommodated in the foreland belt. Most information about the structure and properties of the lithosphere along this transect comes from a series of geophysical experiments between 58° and 63°N. The crust thickness, as shown by seismic reflection profiles, is fairly consistent at ~35 km in the Cordillera and the craton (Cook et al., 1999; Erdmer et al., 2001).

Heat flow is very high in the Cordillera (~105 mW/m^2) and in the covered craton to the east (~90 mW/m^2) (Fig. 3C; Lewis and Hyndman, 2001). Because of higher heat generation in the craton upper crust, modeled thermal profiles are quite different in these two regions and indicate a temperature at the base of the crust of ~950 °C and ~650 °C, respectively (Fig. 3A; Lewis and Hyndman, 2001). This difference in temperature is supported by isostatic considerations. Because the crustal thickness does not vary significantly between the Cordillera and the covered craton, the difference of elevation (1–1.5 km versus ~0.3 km) must be supported by a light hot lithosphere in the Cordillera.

To examine the possibility of a lower crust detachment, we estimate the strength profiles for the Cordillera and the covered craton using these thermal parameters. The upper crust, lower crust, and upper mantle follow quartz diorite-, diabase-, and olivine-controlled rheologies, respectively. The rheology parameters used to define the elastoplastic behavior of the materials are derived from a compilation of laboratory experiments (Ranalli, 1995). Under these conditions, only the upper 15–20 km of the Cordilleran crust show significant strength, in contrast to the craton, which shows no substantial crustal weak zone (Fig. 3A). The weak Cordilleran lower crust thus can act as a detachment, allowing motion of the upper crust over the uppermost mantle. The depth of the decoupling layer is a function of the crustal composition and fluid content. An amphibolite facies mid-lower crust would be weaker than dry mafic granulite at the base of the crust and would give rise to a mid-crustal detachment zone.

We propose that a small part of the Yakutat–North America motion is transmitted to the northern Cordillera upper crust, which is then pushed as a quasi-rigid block over a weak lower crust decoupling level and thrust over the craton, 800 km to the east. To illustrate this process, we use a two-dimensional thermo-mechanical model to reproduce the observed kinematics and deformation pattern along a cross section from the Yakutat collision to the craton. Our finite element model is based on the ADELI software (Chéry and Hassani, 2001). The crust and mantle rheologies follow those defined previously. The thermal structure corresponds to a smooth two-dimensional extrapolation of the temperature profiles shown in Figure 3A. The model boundary conditions are shown in Figure 3B and replicate the indentation of the northern Cordillera by the Yakutat block at 5 mm/yr.

In our preferred model (Fig. 3D), a clear decoupling level establishes in the lower crust of the Cordillera, allowing for a translation of the upper crust with little intervening deformation. In the foreland belt, the lower crust detachment rises, allowing the overthrusting of the Cordilleran upper crust over the craton. The foreland belt sedimentary prism is represented by a thin (5–10 km) preexisting weak layer (small internal friction angle). After 2 m.y. of convergence, the integrated uplift along the model cross section replicates the topography profile of the northern Cordillera (Fig. 3C).

Alternative models with colder thermal profiles in the Cordillera do not allow the development of a significant decoupling between the uppermost mantle and the upper crust. The threshold temperature is 700–800 °C at the base of the crust for a diabase lower crust. The presence of a weak foreland region is required for the translation and thrusting of the upper crust over the craton. Models with no weak layer produce a continuum of the deformation in the Cordillera, regardless of the temperature structure. This weakness of the foreland belt may be attributed to the presence of numerous sedimentary thrust sheets above deep (5–10 km), large-scale detachments underlying most of the Mackenzie Mountains (Gabrielse, 1991).

CONCLUSION

The northeastward motion of the northern Canadian Cordillera, ~5 mm/yr, corresponds to a quasi-rigid translation of the upper crust over a lower crust decoupling level. This motion is accommodated in the Cordillera foreland belt (Mackenzie and Richardson Mountains) by thrusting of Cordilleran upper crust over the craton to the east. We propose that this kinematic and deformation pattern is related to the collision of the Yakutat block in the corner of the Gulf of Alaska, ~800 km west of the foreland belt. A small part of the Yakutat–North America convergence propagates inland of the collision zone and is transferred across the entire northern Cordillera. This thick-skinned tectonics is made possible by the high temperature of the crust in the Cordillera (~900 °C at the Moho) that results in a very weak lower crust.

Our model provides a physical mechanism for the concept of orogenic float (e.g., Oldow et al., 1990), in which the faults within the orogen are linked to the plate boundary through a major deep crustal or upper mantle décollement system. This allows for coeval deformation along strike-slip and thrust faults that merge with a common detachment (e.g., in the northern Cordillera the Denali and Tintina right-lateral faults, and the Plateau thrust). The quasi-rigid displacement of the upper crust (the orogenic float) above a large-scale lower crust decoupling level may apply to other present or past orogens where significant deformation is accommodated in foreland regions far from the main collision front (e.g., Eocene shortening of the southern Canadian Cordillera; present-day convergence across the Tian Shan ~1000 km north of the Himalayan front).

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