Structure, origin, and deformation of the lithosphere in the northern Canadian Cordillera from high-resolution, passive-source seismic velocity models

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Abstract

The recent deployment of temporary broadband seismic networks, notably the EarthScope USArray-Transportable Array (TA), has drastically improved the station coverage across northwestern Canada over the last ten years, enabling application of high-resolution passive-source seismic methods (i.e., seismic tomography, receiver functions and core phase shear wave splitting). This review highlights the main discoveries pertaining to the seismic velocity structure, origin and deformation of the lithosphere in the northern Canadian Cordillera (NCC). High-resolution seismic tomography models reveal that the lower crust in the NCC is marked by low velocity anomalies extending from the Gulf of Alaska to the Cordilleran deformation front, which are interpreted to reflect elevated temperatures that buoyantly support regional high elevations and potentially represent the seismic signature of strain transfer from the Yakutat collision zone to the Mackenzie Mountains. The Moho is relatively flat and shallow across the NCC, and is underlain by a thin layer of mantle lithosphere. Seismic velocity models further unveiled large-scale mantle structures associated with the unexposed Mackenzie craton in the north, and the Liard Transfer Zone in the south, which appear to buttress the NCC and further focus deformation in the eastern NCC. Seismic anisotropy and tomography provide evidence that the Tintina and Denali faults penetrate into the lithospheric mantle and played a first order role in shaping the present-day NCC. We propose that future studies should aim to: 1) resolve the shape of the Cordillera-craton boundary at upper mantle depths; 2) accurately estimate the lithosphere thickness in the NCC; and 3) improve coverage in the Beaufort Sea to understand the controls on convergent tectonics in the northern NCC.

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Abstract

The recent deployment of temporary broadband seismic networks, notably the EarthScope USArray-Transportable Array (TA), has drastically improved the station coverage across northwestern Canada over the last ten years, enabling application of high-resolution passive-source seismic methods (*i.e.,* seismic tomography, receiver functions and core phase shear wave splitting). This review highlights the main discoveries pertaining to the seismic velocity structure, origin and deformation of the lithosphere in the northern Canadian Cordillera (NCC). High-resolution seismic tomography models reveal that the lower crust in the NCC is marked by low velocity anomalies extending from the Gulf of Alaska to the Cordilleran deformation front, which is interpreted to reflect elevated temperatures that buoyantly support regional high elevations and potentially represent the seismic signature of strain transfer from the Yakutat collision zone to the Mackenzie Mountains. The Moho is relatively flat and shallow across the NCC, and is underlain by a thin layer of mantle lithosphere. Seismic velocity models further unveiled large-scale mantle structures associated with the unexposed Mackenzie craton in the north, and the Liard Transfer Zone in the south, which appear to buttress the NCC and further focus deformation in the eastern NCC. Seismic anisotropy and tomography provide evidence that the Tintina and Denali faults penetrate into the lithospheric mantle and played a first order role in shaping the present-day NCC. We propose that future studies should aim to: 1) resolve the shape of the Cordillera-craton boundary at upper mantle depths; 2) accurately estimate the lithosphere thickness in the NCC; and 3) improve coverage in the Beaufort Sea to understand the controls on convergent tectonics in the northern NCC.

1 Introduction

The geological history of western Canada spans 4 billion years, from juvenile terranes accreted along the Pacific Ocean margin to Archean rocks of the Canadian Shield (Gabrielse & Yorath, 1991). Recent reviews of the geology, structure and metallogeny of the Cordillera can be found in Colpron et al. (2007) and Nelson et al. (2013). Here we provide a brief review of the macro-scale features that can be targeted by passive-source broadband seismic networks. The Canadian Cordillera is a ∼500-800 km-wide Phanerozoic mountain belt that extends from the US border in the south to Alaska and the Beaufort Sea in the north. To the east, the Canadian

Cordillera is flanked by Proterozoic magmatic arcs and the Archean Canadian Shield. To the west, plate boundary interactions vary from south to north. In southwestern Canada, the oceanic Juan de Fuca plate subducts beneath the North American plate at the Cascadia Subduction Zone. Northward, the margin is characterized by transpressive to strike-slip motion between the Pacific and North American plates along the Queen Charlotte-Fairweather fault system. Further north, the Yakutat block is colliding obliquely with the North American margin in the Gulf of Alaska, producing the fastest rising and highest elevations in Canada within the St. Elias-Chugach mountain ranges.

The Canadian Cordillera can be broadly separated into northern (NCC) and southern (SCC) zones based on differences in surface geology, tectonics, and contemporary geodynamics. This separation approximately aligns with the Yukon-British Columbia border (latitude 60°N), and is demarcated by a clear change in seismicity (Fig. 1). Seismic activity is well observed to the north within the NCC, and is mainly focused at the plate boundary margin and at the Yakutat collision zone (Cassidy et al., 2005; Ristau et al., 2007). However, seismicity is also abundant within the Mackenzie Mountains and in the Richardson Mountains, $\sim$800 km away from the nearest plate boundary. In contrast, seismicity is almost absent in the SCC, with modest clusters of seismic activity located to the east within the foreland basin. This north-south transition roughly occurs at the Liard transfer zone (LTZ; Fig. 1), a tectonic structure inherited from the asymmetric Neoproterozoic rifted margins of Laurentia that separates a southern upper-plate margin from a northern lower-plate margin (Lund, 2008). The extension of the LTZ into the NCC coincides with the Liard Basin, located at the nexus of the NCC Tintina Fault and the SCC Rocky Mountain Trench. The Tintina fault is a margin-parallel right-lateral strike slip fault that accommodated $\sim$430 km of horizontal displacement between late Eocene and Early Cretaceous (Gabrielse et al., 2006) but displays low seismic activity. North of the NCC, earthquake focal mechanisms and sparse geodetic data (Leonard et al., 2007; Mazzotti et al., 2008) suggest that the Yukon crust is slowly converging ($\sim$2 mm yr^{-1}) with the Beaufort sea margin, which may lead to, or reflect, subduction initiation (Hyndman, et al., 2005).

Much of our knowledge of deep Cordilleran crust and mantle structure was gained from three deep magnetotelluric and controlled-source seismic profiles that were acquired as part of the Slave-Northern Cordillera Lithospheric Evolution transect (SNORCLE; Figure 1) from the

Lithoprobe project (Cook & Erdmer, 2005). Data collected by SNORCLE led to the discovery of several crustal-scale features in the NCC. First, the identification of a reflective westward tapering wedge within the Cordilleran crust west of the Tintina Fault was interpreted as the seismic signature of Proterozoic meta-sedimentary strata in the middle and lower crust beneath the Cordillera. This led to the hypothesis that the deep tapered wedge originated as sediments deposited in a passive margin setting. Under this scenario, most of the Cordilleran terranes are thin sheets thrust over older ancient North American basement. Second, seismic profiles showed a nearly flat and shallow Moho, indicating that crustal thickness does not vary much along the profiles despite topographic variations. This was a surprising result since the age of surface rocks and topographic elevations vary widely from Archean to Cenozoic and from near sea level to more than 2,500 m along east-to-west profiles, respectively (Cook & Erdmer, 2005). This finding led to the suggestion that thermal processes have largely erased crustal thickness variations through lower crustal ductile flow or partial melting (Cook, 2002). Seismic velocity models derived from SNORCLE seismic refraction data also revealed a westward Proterozoic meta-sedimentary wedge directly to the west of the Tintina Fault and a flat Moho at ∼33–36 km depth (Clowes et al., 2005). Magnetotelluric data from SNORCLE revealed complex electrical resistivity structure throughout the NCC (*e.g.,* Ledo et al., 2002; Jones et al., 2005). Recently, Dehkordi et al. (2019) reprocessed the available Lithoprobe SNORCLE magnetotelluric data from 69 instruments along Line 2 and the resulting 2-D resistivity model showed significant variations within the crust on both sides of the Tintina Fault and beneath the LTZ. The authors suggest that the Tintina Fault may have juxtaposed two crustal blocks from the lower- and upper plate margins.

Following SNORCLE, there was a long hiatus in geophysical infrastructure development. Geophysical advances following SNORCLE were made using potential field data, heat flow measurements, seismicity data as well as campaign and continuous Global Navigation Satellite System (GNSS) data from surveys led by the Geological Survey of Canada. Most notably, those studies revealed that: 1) the entire NCC is characterized by low effective elastic thickness (T_e) and low Curie depth, implying a hot and weak crust (Flück et al., 2003; Audet et al., 2007; Gaudreau et al., 2019); 2) the Mackenzie Mountains are buttressed by rigid crustal blocks inferred from magnetic anomaly data (Saltus & Hudson, 2007); 3) heat flow is high throughout the NCC (Lewis et al., 2003); and 4) strain transfer from the Yakutat collision zone may drive deformation across the NCC all the way to the Cordilleran Deformation Front (CDF) (Mazzotti & Hyndman, 2002).

Two distinct tectonic models were developed to explain these observations, with the aim to describe contemporary deformation of the Cordillera and predict the role of the upper mantle. First, based on the orogenic float model of Oldow et al. (1990), Hyndman, et al. (2005) proposed that thermal expansion in the upper mantle buoyantly supports the high elevation (mean value of ∼1000 m above sea level) across the entire Canadian Cordillera. High Moho temperatures (∼ 900°C) give rise to zones of weakness in the lower crust and this helps to propagate stresses from the Yakutat collision zone that drive seismic activity in the Mackenzie Mountains (Mazzotti & Hyndman, 2002). This model inherently requires crust-mantle mechanical decoupling along a lower crustal detachment zone at the base of a thin crust (Hyndman, 2017), and therefore a minimal role of the upper mantle in controlling deformation. Alternatively, Finzel et al. (2015) modeled mantle convection across Alaska and the northern Canadian Cordillera and proposed that the current stress pattern can be explained by traction at the base of the lithosphere; this implies crust-mantle mechanical coupling, and therefore an important role for the upper mantle. Additional tectonic models were proposed to explain magmatism in the Northern Cordilleran slab window (Thorkelson et al., 2011), which implies retreating lithospheric support beneath the margin and potential destabilization of the Cordilleran lithosphere (*e.g.,* Currie et al., 2008).

Further evaluation of these models requires accurate representations of the structural makeup and architecture of the lithosphere and upper mantle beneath the NCC and surrounding regions. This information is most readily extracted from high-resolution seismic velocity models determined using broadband seismic data; unfortunately, the historical lack of a dense, passive, broadband seismograph network in northwestern Canada has hampered the development of such models until very recently. The first few seismograph stations in northwestern Canada were installed in the 1990s by the Canadian federal government to monitor earthquake activity across the country. Until the early 2000s, station coverage remained sparse with only a handful of seismic stations deployed in the NCC (Fig. 2). In 2003, the temporary CAnadian NOrthwest Experiment (CANOE, https://doi.org/10.7914/SN/XN_2003) seismograph network was deployed for two years. Over time, seismic station coverage continued to improve across the region, with a significant expansion starting in the 2010s. The Yukon-Northwest Territories Seismograph Network (https://doi.org/10.7914/SN/NY) as well as the Yukon Observatory network were installed in 2013 and 2016, respectively. 2017 marks the year of completion of the deployment of the EarthScope USArray TA (hereinafter referred to as TA) geophysical observatories across Alaska, USA and Yukon, Canada (Busby & Aderhold, 2020). Between 2016 and 2018, the Mackenzie Mountains EarthScope Project was deployed for two years along a SW-NE NCC-crossing profile (Baker et al., 2019).

Recent improvement in seismograph station coverage across northwestern Canada has enabled the use of a wide variety of seismic imaging techniques (i.e., ambient noise and earthquake-based surface-wave tomography, as well as regional and teleseismic body-wave tomography) to investigate the three-dimensional crustal and upper mantle seismic velocity structure at higher resolution. Body-wave travel-time models generally have better lateral resolution compared to surface wave methods due to crossing near-vertical and bending rays, but suffer from reduced vertical resolution due to limited ray path coverage and direction. Conversely, surface-wave models provide coverage along horizontal paths with generally lesser horizontal resolution. Other complementary models providing more localized estimates of crust and upper mantle structure were also utilized from these new data sets (e.g., receiver functions, teleseismic shear-wave splitting). Taken together, these recent studies have led to new discoveries and geodynamic model testing while simultaneously raising further questions about the past and present tectonics of this region. In this review, we provide a summary of passive-source seismological studies across the NCC, Alaska, and northwestern Canada, and propose ongoing research questions for the region.

2 Seismic velocity structure of the crust

2.1 3-D seismic velocity models

The first 3-D shear-wave velocity model of the crust in northwestern Canada was calculated by Dalton et al. (2011) using fundamental mode, group velocity Rayleigh and Love wave dispersion measurements at periods of 7–20 s from ambient noise data mainly recorded by the CANOE network. They found that: 1) low-velocity regions spatially correlate with known sedimentary basins at shallow crustal depths (< 5 km); and 2) at mid-crustal depths, there are several low-velocity zones within the western part of the Canadian Shield that extend beneath the NCC, which may reflect the westward tapering Proterozoic meta-sedimentary layers inferred from SNORCLE (Snyder et al., 2002). Unfortunately, this data set did not allow for high-resolution imaging of the lower crust and lithospheric mantle. In 2013, Kao et al. (2013) developed the first pan-Canadian S-wave velocity model of the crust and uppermost mantle obtained from ambient noise data (Figs. 3a-b and 4a-b). They found that the Cordilleran crust is characterized by low seismic velocities with large vertical S-wave velocity gradients at upper- to mid-crustal depths, speculated to represent the seismic signature of ductile detachments within the middle crust, e.g., consistent with the geodynamic hypothesis of Mazzotti and Hyndman (2002). However, only a handful of stations were used in the NCC and these large vertical S-wave velocity gradients are not present everywhere in the Cordillera, which made this interpretation tentative.

Prior to the roll-out of the TA into parts of the Yukon, McLellan et al. (2018) incorporated the then recently-available YNSN data and developed fundamental mode Rayleigh-wave phase-velocity maps of northwestern Canada using ambient noise and teleseismic data at periods between 8 and 80 s. They found that low phase velocities at periods < 25 s are confined to the NCC between the Tintina Fault and the CDF. Known sedimentary basins (e.g., the Selwyin Basin that encompass most of eastern Yukon, and the Liard Basin in southeastern NCC) are characterized by low-velocity anomalies at periods $\leq$ 15 s (Fig. 3g). Southwest of the Denali fault, another low-velocity anomaly was interpreted as the signature of underplated sediments at the base of the Chugach terrane (Ward, 2015; McLellan et al., 2018) due to the Yakutat flat-slab subduction. At mid- to lower-crustal depths, the Mackenzie Mountains were found to be underlain by a broad low-velocity feature (Fig. 3g-h). Higher resolution surface-wave tomography models refined these features by including data from the TA and Mackenzie Mountains EarthScope Project (Baker et al., 2019). Estève et al. (2021) showed that an anomalous low S-wave velocity structure ($\delta V_S < -3\%$) extends from the Pacific Ocean to the CDF, with the Mackenzie Mountains being underlain by a large low-velocity anomaly (Figs. 3c-d, 4c-d). Schutt et al. (2023) inverted ambient seismic noise-derived surface wave data between 6–40 s period to further resolve the lithospheric S-wave velocity beneath the Mackenzie Mountains and confirmed the presence of a large low-velocity anomaly beneath this area with a westward dip. This S-wave velocity model highlights the transcrustal continuity of this seismically slow region into the uppermost mantle (see section 4.5). Lastly, a 10–15 km-thick, low-velocity layer with variable amplitude can be traced at lower crustal depths everywhere across the NCC (Figs. 3e-f, 4e-f).

Those aforementioned seismic tomography models have different levels of resolution. For instance, Kao et al. (2013) show that their model resolves features of $\sim$ 100–200 km in dimension at short periods in western Canada. However, the resolution falls off for longer periods (*i.e.,* 35s, 200-300 km; 50s, 250-500km). Structures revealed by the tomography models of McLellan et al. (2018) with minimum dimensions of 200x200 km can be confidently interpreted within the NCC. However, their model is biased by dominant east-west path coverage due to the geometry of the seismic network, noise source locations and earthquake locations. The recent tomography models of Estève et al. (2021); Schutt et al. (2023) accurately recover features with a 300 km lateral extent.

2.2 Moho depth model

Prior to the SNORCLE experiment, only sparse Moho depth estimates were available for the NCC. Lowe and Cassidy (1995) calculated P receiver functions and showed that the Moho is shallower beneath Dawson City than beneath Whitehorse, Yukon. Results from the Lithoprobe SNORCLE experiment highlighted a relatively shallow ($\sim$33–35 km) and flat Moho along the profiles (Clowes et al., 2005). These and other Lithoprobe results were interpolated to create the first Moho map of Canada at 5×5 degrees (Perry et al., 2002). A decade later, Rasendra et al. (2014) calculated P receiver functions for 11 broadband seismic stations near the Denali Fault in southwestern Yukon. Their results indicated a $\sim$4 km shallower Moho ($\sim$36 km) beneath stations located north and east of the Denali Fault compared to those located south and west ($\sim$39–40 km), which correlates with topographic variations across the Denali fault. Prior to the completion of the TA network, Tarayoun et al. (2017) calculated P receiver functions for stations of the YNSN, CN, CANOE and the first nine stations of the USArray TA EarthScope network in northwestern Canada and obtained Moho depth estimates using both the H-κ stacking technique and the harmonic decomposition method. Their results confirmed a sharp and nearly flat Moho across the NCC (mean of 32 $\pm$ 2 km), in good agreement with prior studies (*e.g.,* Clowes et al., 2005; Rasendra et al., 2014). Subsequently, Audet et al. (2019) used receiver functions to image the Moho along the western transect of the CANOE line from the CDF to Whitehorse, Yukon, and found similar results.

Audet et al. (2020) expanded on these results and investigated Moho depth variations across the entirety of the NCC with all available seismic stations (total of 173), including those belonging to the TA and the Mackenzie Mountains EarthScope Flexible Array seismic networks (Fig. 5). They obtained Moho depth estimates ranging from 27 to 43 km with a mean value of 33 km, again consistent with previous studies (Clowes et al., 2005; Rasendra et al., 2014; Tarayoun et al., 2017; Audet et al., 2019). The authors observed that seismic activity is partially correlated with areas exhibiting a Moho deeper than 36 km. These areas are southwest of the Denali Fault beneath the actively deforming St. Elias-Chugach Mountains, the northwestern part of the Mackenzie Mountains and the Richardson Mountains. It is intriguing to note that, north of the Tintina Fault, the Mackenzie Mountains EarthScope Project Flexible Array marks the limit between a shallower Moho ($\sim$28–30 km) across the southern Mackenzie Mountains compared to their northern counterpart ($\sim$40 km). If this observation were robust, it would imply a revision of the geological models of the deep Cordilleran crust and its evolution through time. However, this observation is inferred from interpolation of results with only a few stations, with large observational gaps on either side of the Mackenzie Mountains array. This highlights the need for additional instrumentation to fill the gaps in the current coverage.

2.3 Crustal seismic anisotropy

Estimates of seismic anisotropy within the crust inform the state of stress and/or large-scale tectonic fabrics. These estimates are typically obtained from either the inversion of surface-wave dispersion data, receiver functions or, for the shallowest crust, microseismicity shear-wave observations (*e.g.,* Aster & Shearer, 1992). Estimates of bulk crustal seismic anisotropy from receiver function data suggest the existence of a fabric with a fast-axis direction of propagation oriented to the NW-SE, consistent with the orientation of the Denali and Tintina faults (Rasendra et al., 2014; Tarayoun et al., 2017). Azimuthal anisotropy inferred from surface-wave tomography models (McLellan et al., 2018; Estève et al., 2021; Schutt et al., 2023) shows a similar NW-SE oriented large-scale pattern across the NCC at periods of 15 to 20 s, which are predominantly sensitive to crustal structure (Fig. 6). These results suggest a dominant tectonic fabric caused by large-scale motion of the crust, possibly related to the Mesozoic accretion of terranes in the NCC (*e.g.,* Johnston, 2008) and/or the crustal shearing caused by the large right-lateral fault network (Denali, Teslin and Tintina faults) across the NCC. Improving crustal seismic anisotropy models remains a focus for future studies.

First-order patterns of azimuthal anisotropy derived from surface wave tomography models across the NCC are similar. However, one can note a clear difference in amplitude between the study of McLellan et al. (2018) and Estève et al. (2021); Schutt et al. (2023). This difference could arise from different choices of parameterizations. McLellan et al. (2018) utilize a linearized and regularized inversion, where the results depend strongly on the choice and level of regularization. Estève et al. (2021) and Schutt et al. (2023) use the same Bayesian trans-dimensional tomographic approach, which presents the advantage of avoiding model regularization. It has been shown that regularization of azimuthal anisotropy and quantifying uncertainties in surface wave tomographic inversions are challenging (Gosselin et al., 2021). Nonetheless, resolution of the anisotropic component is similar to that of the isotropic component of the tomographic inversion (McLellan et al., 2018). The uncertainty of anisotropy fast-axis directions (σ_θ) calculated by Estève et al. (2021) ranges between a few degrees and 30° within the NCC, except for the central part of the Mackenzie Mountains, where $\sigma_\theta > 30°$. σ_θ values across the NCC from Schutt et al. (2023) are smaller compared to Estève et al. (2021) ($0° \leq \sigma_\theta < 25°$). Differences may arise from a better path coverage using ambient noise data compared to regional earthquake data.

3 Seismic velocity structure of the upper mantle

3.1 3-D body-wave velocity models

Studies of the northern Canadian Cordillera upper mantle velocity structure started in the late 1970s using short-period P-waves, surface waves and long-period S-wave travel-time residuals (Buchbinder & Poupinet, 1977; Wickens, 1977; Wickens & Buchbinder, 1980). These studies suffered from sparse station coverage and thus low resolution, but revealed low velocities and delayed residuals to the west of the CDF. The continental-scale S-wave velocity model of Grand (1994) was the first to image the Canadian mantle. This model showed that the entire North

American Cordillera is underlain by low S-wave velocities down to ∼100 km. Following the work of Grand (1994), various continental-scale body-wave velocity models were developed (*e.g.,* Schmandt & Lin, 2014), although most focused on the conterminous US and did not provide new insight on the Canadian Cordilleran mantle.

At the regional scale, Frederiksen et al. (1998) developed the first teleseismic P-wave tomography model of the NCC from relative arrival-time data using 17 seismic stations from the gulf of Alaska to Yellowknife, Northwest Territories. Their model revealed: 1) a low-velocity anomaly in southwestern Yukon, interpreted to reflect an upwelling of hot material caused by the opening of a slab window at 20-30 Ma (Thorkelson et al., 2011); and 2) the Cordillera-craton boundary may be located west of the Tintina Fault. Taking advantage of several temporary seismic network deployments, Mercier et al. (2009) developed teleseismic P- and S-wave tomography models across western Canada using a similar technique. Their models revealed a sharp transition between low- and high-velocity anomalies across the CDF in the NCC, interpreted to be the boundary between the Cordilleran and the cratonic mantle. Estève et al. (2019) later developed new P- and S-wave teleseismic body-wave models of northwestern Canada that encompassed the south-easternmost part of the NCC, and obtained results similar to Mercier et al. (2009).

Expansion of the seismic networks in the 2010s, most notably the EarthScope TA, facilitated the development of new high-resolution body-wave velocity models in the NCC. Estève et al. (2020b) used all available data from 320 broadband seismic stations located across northwestern Canada and eastern Alaska to produce new teleseismic P- and S-wave velocity models of the upper mantle, also based on relative arrival time data (Fig. 8). Most notably, these models revealed the juxtaposition of several high- and low-velocity anomalies at depths between 100 and 300 km beneath the NCC. The largest features include the high P-wave velocity anomalies buttressing the ends of the Mackenzie Mountains beneath the NCC, and the sharp changes from positive to negative P-wave velocity and S-wave velocity anomalies across the Tintina Fault. Several of these features are limited to depths ≤200 km, and unveil the fine-scale structure of the upper mantle beneath the NCC. Recently, Boyce et al. (2023) re-processed multiple teleseismic body-wave relative arrival-time data sets and developed an absolute teleseismic P-wave velocity model of North America, which confirmed the results of Estève et al. (2020b) in the NCC.

3.2 3-D surface-wave velocity models

The first continental-scale surface-wave seismic velocity models of North America by Frederiksen et al. (2001) provided the most detailed regional constraints on upper mantle structure beneath the NCC at that time. This model displayed consistent low S-wave velocities at upper mantle depths beneath the entire Canadian Cordillera. The slow expansion of the seismic network in northwestern Canada allowed refinements of these continental-scale models over time (*e.g.,* van der Lee & Frederiksen, 2005; Bedle & van der Lee, 2009); however, new insights on upper mantle structure beneath the NCC were limited. Following the completion of the TA network over the conterminous US, Schaeffer and Lebedev (2014) developed a continental-scale S-wave velocity model of the North American upper mantle using multi-mode surface-wave data from the US-Array and other global seismic networks. Their velocity model highlighted several features. In particular, the transition between low- and high-velocity anomalies in western Canada is characterized by a sharp velocity gradient beneath the surface expression of the Rocky Mountain Trench, in good agreement with Mercier et al. (2009). Further north, within the NCC, the eastern region of the Mackenzie Mountains and the Richardson Mountains are characterized by a high-velocity anomaly and the transition to the low-velocity anomaly lies further west, between the Tintina Fault and those mountain ranges.

The development of regional-scale surface-wave velocity models of northwestern Canada took advantage of the sudden increase in network coverage in the mid 2010s. For instance, Zaporozan et al. (2018) applied the two-station surface-wave interferometry technique of Meier et al. (2004) using the permanent stations of the CN network as well as temporary stations from the POLARIS network to map Rayleigh wave phase velocities across western Canada. Once again, their velocity model highlighted the sharp seismic velocity contrast between low-velocity Cordilleran mantle and high-velocity cratonic lithosphere. Interestingly, their transects through their S-wave velocity model showed dip variations of the sharp velocity contrast from north to south. McLellan et al. (2018) used the same technique but focused on the NCC only and incorporated legacy data from the CANOE and POLARIS network as well as new data from the YNSN and a handful of TA stations in northwestern Canada. Their long-period (40–80 s) surface-wave model indicates extension of high phase velocity anomalies beneath the NCC, east of the Tintina Fault. More recently, the surface-wave models of Estève et al. (2021) and Schutt et al. (2023) have provided further constraints on shallow upper-mantle structure, as mentioned previously. Notably, they find significant velocity variations to the west of the CDF (Figs. 7b-c).

3.3 Layered structure

Although the new seismic body-wave and surface-wave models afford an unprecedented view of the upper mantle beneath the NCC, they are generally insensitive to discontinuities in seismic velocity related to fine-scale structural layering of the lithosphere. Tarayoun et al. (2017) used receiver functions, which are sensitive to discontinuities, and identified a 10 km-thick, high-velocity, anisotropic sub-Moho NCC layer at 40–45 km depth, which was tentatively interpreted as the signature of a thin lithospheric mantle. Audet et al. (2019) reprocessed receiver functions along the western transect of the CANOE line using common conversion point stacking to image the layered structure beneath the NCC. This study confirmed the existence of a high-velocity layer directly beneath the Moho discontinuity, interpreted to represent thin lithospheric mantle, estimating the thickness of the mantle lithosphere to be 15±3 km and the total lithosphere thickness as 50±5 km. This imaging also unveiled a west-dipping feature in the uppermost mantle, compatible to that observed in the surface wave model of Schaeffer and Lebedev (2014) and analogous to observations from the southern Canadian Cordillera by Chen et al. (2019). However, the origin and longevity of this feature remains enigmatic.

3.4 Upper-mantle seismic anisotropy

Seismic anisotropy in the upper mantle is principally attributed to stress- or strain-induced alignment of olivine which may reflect present-day mantle convection and/or “fossil” deformation in the upper mantle (Savage, 1999; Park & Levin, 2002; Becker & Lebedev, 2021; Hansen et al., 2021). Teleseismic shear-wave splitting estimates (mainly from SKS and $SKKS$ core phases) in the NCC resolve an alignment between the fast axis of azimuthal anisotropy and the strike of the Tintina and Denali faults (Fig. 9), as well as a rotation towards absolute plate motion as one crosses eastward towards the the LTZ and the CDF (Snyder & Bruneton, 2007; Courtier et al., 2010; Rasendra et al., 2014; Audet et al., 2016; Bolton et al., 2021). If the lithosphere-asthenosphere boundary to the west of the CDF is only at a depth of 50–60 km (*i.e.,* Audet et al., 2019) then the bulk of the teleseismic shear wave splitting must be accumulated in the asthenosphere. This suggests a rotation in asthenospheric flow, from NW-SE near the coast, to NE-SW in the interior. These results were key in developing new tectonic evolution models of the NCC that are described below.

Seismic anisotropy measurements in the Canadian Shield are coherent and roughly parallel to the absolute plate motion direction of the North American plate (Fig. 9), however, fast-axis directions of SKS waves for seismic stations in the Slave craton deviate from it. Snyder and Bruneton (2007) show that SKS splitting measurements and surface waves are best fit by a two-layered mantle beneath the Slave craton. The shallow layer of anisotropy may be associated with a regional tectonic event at 2610-2580 Ma. The deep layer may be partly caused by the present-day absolute plate motion of the north American plate, but also locally to the formation of Kimberlite dykes (Snyder & Bruneton, 2007).

4 Discussion

4.1 Robust features of seismic tomography models of northwestern Canada

We search for common low- and high-velocity anomalies among published seismic tomography models of northwestern Canada by making vote maps (Fig. 10). We choose 3 velocity models for the crust (Kao et al., 2013; Estève et al., 2021; Schutt et al., 2023) and 4 for the uppermost mantle (Estève et al., 2020b; Estève et al., 2021; Schutt et al., 2023). We first define a criterion (see bottom right of each panel in Fig. 10) and search for it at each location within the model space. If this criterion is fulfilled then this location gets a value of 1, if not a value of 0. We repeat this for all seismic tomography models considered and then stack the models. For instance, a value of 4 means that the selected criterion appears at a given location in four different models, thus implying that this feature is robust. Figure 10 shows the resulting maps at 20 (Fig. 10 a-b) and 80 km depths (Fig. 10 c-d). Orange-red colors show robust features from the seismic tomography models considered in this analysis.

At 20 km depth, all three seismic tomography models (*i.e.,* value of 3) show a similar low-velocity anomaly ($\delta V_S < -2\%$) beneath several regions of the NCC: (*i*) the St Elias-Chugach Mountains, (*ii*) between the Tintina and Denali faults, (*iii*) the Mackenzie Mountains, and (*iv*) in the Yukon Flats of eastern Alaska (Fig. 10a). Common high velocity anomalies ($\delta V_S > 2\%$) highlight the Canadian Shield (Fig. 10b).

At 80 km depth, robust low-velocity anomalies (values of 3 and 4) are observed in the central part of the Mackenzie Mountains, directly east of the Tintina Fault, between the Tintina and the Denali fault and to the north in the Yukon Flats of eastern Alaska (Fig. 10c). High-velocity anomalies are observed in at least 3 models (value of 3) in the Canadian Shield. We note that high-velocity anomalies extend into the NCC in two areas, in the southernmost NCC and in Richardson/northern Mackenzie Mountains (Fig. 10d). The identified robust features are discussed in more details in the following paragraphs.

4.2 Current tectonics

Crustal deformation models of the NCC were developed to explain seismicity and GNSS data that suggest strain/stress transfer and thrusting at the CDF, ~800 km away from plate boundary forces (Mazzotti & Hyndman, 2002; Hyndman, et al., 2005; Finzel et al., 2014). Seismic velocity models of the crust developed in the last decade (i.e., since deployment of the US-Array TA EarthScope network) confirm that the Moho is broadly flat and shallow across the NCC, with only slight (~2 km) thickening inferred beneath the MM constrained by sparse data, indicating that there is no Airy-type or otherwise extensive Cordilleran crustal root. This is in contradiction with a satellite gravity gradiometric study (Cadio et al., 2016), which suggests that the topography is perfectly compensated across the NCC interior. In addition, these velocity models suggest that crustal temperatures throughout the NCC are exceptionally high with a Moho temperature reaching 800-900°C (Hyndman, 2017; Audet et al., 2019). The observed low S-wave velocity feature at mid- to lower-crustal depths throughout the NCC (Estève et al., 2021; Schutt et al., 2023) has been interpreted to reflect the elevated temperatures that would buoyantly support high elevations in the absence of a thick crustal root (Lewis et al., 2003; Hyndman & Currie, 2011) (Figs. 3 and 4). The observed low-velocity layer is interpreted by Schutt et al. (2023) as the seismic signature of the lower crustal, rheologically weak layer, described by Mazzotti and Hyndman (2002); Mazzotti et al. (2008), and required to transfer strain from the Yakutat collision zone to the CDF, thus reactivating pre-existing thrust fronts and resulting in the far-field seismicity observed in the Mackenzie Mountains.

Overall, these results favor the thermal isostasy model, where high topographic elevations across the NCC are supported isostatically by uppermost mantle thermal buoyancy due to high temperatures (Lewis et al., 2003; Hasterok et al., 2007; Hyndman & Currie, 2011). Furthermore, such Moho geometry requires that, at some point, the Cordilleran crustal root and associated Moho morphology were flattened out, or removed by thermally activated processes (lower crustal shearing or delamination) during one or several past tectonic events over the entire length of the Canadian Cordillera (*e.g.,* Bao et al., 2014; Chen et al., 2019, in the SCC). Hyndman (2017) suggests that lower crustal flow may have flattened the Moho over a few tens of millions of years. The hypothesis of mantle removal is explored in section 4.4.

Alternatively, Audet et al. (2016) used constraints from SKS splitting data to suggest that the structure of the Proterozoic Laurentian rifted margin may be preserved in the upper mantle (Lund, 2008). According to this model, the LTZ marks the transition from an upper plate margin in the south to a lower plate margin in the north. This is observed as a switch from SW-NE alignment of fast axis of seismic anisotropy coincident with with cratonic lithosphere fabric south of the LTZ, to SE-NW oriented fast axes north of the LTZ. This structure also coincides with the sudden appearance of seismicity north of the LTZ, suggesting that lithospheric mantle tectonic inheritance may partly control seismicity in southeastern NCC (Fig. 9). The buttressing model of Saltus and Hudson (2007) and Estève et al. (2020b) also points to the role of upper mantle strength near the LTZ in controlling the arcuate shape of the CDF in the NCC, with a potential role on Neotectonic activity.

4.3 Beaufort Sea margin

Seismicity and geodetic data suggest that the Beaufort Sea lithosphere is slowly converging ($\sim$2 mm yr^{-1}) with the North American margin, at least between the Canning and Richardson Mountains in northern Yukon, which may lead to or reflect subduction initiation (Hyndman, et al., 2005; Leonard et al., 2007). However, studies on seismicity have historically been limited by the sparse seismic network coverage in this remote region. With the recent availability of seismic data from the EarthScope TA at stations surrounding the Beaufort Sea continental margin, Estève et al. (2022) investigated the structure and deformation of the margin by relocating regional seismicity and developing regional 3-D P-wave, S-wave and V_P/V_S models.

P-wave and S-wave velocity models reveal a northwest-dipping low-velocity anomaly throughout the whole crust beneath the Arctic coast of northern Yukon. Interestingly, this low-velocity anomaly is collocated with an area showing no seismicity between November 2012 and August 2021 (the earthquake catalogue considered in this study). Based on these observations, the authors proposed two scenarios. First, the Beaufort Sea continental margin represents a zone of potential high strain rate, where the lack of seismicity may be indicative of aseismic creep or that strain rates are too low for seismic deformation beneath the Arctic coast of northern Yukon and, thus, current deformation occurs further north offshore within the Beaufort Sea. The authors noted that they could not confirm/reject the subduction initiation hypothesis without additional data from ocean-bottom seismometers deployed in the Beaufort Sea, leaving the question open.

4.4 Mackenzie craton

Prior to the TA deployment across Alaska and Yukon, seismic tomography models highlighted a high-velocity feature west of the CDF beneath northern Yukon (Schaeffer & Lebedev, 2014; McLellan et al., 2018) characteristic of cratonic lithosphere. A regional magnetic study identified a long-wavelength magnetic high across northern Yukon that is interpreted as mafic lower crust and underlying depleted upper mantle (Saltus & Hudson, 2007). Schaeffer and Lebedev (2014) suggested that this region was underlain by an Archean continental fragment buried beneath the sedimentary strata and that has no surface expression. The high velocity signature of this lithospheric root extends continuously from the Yukon Stable Block underlying central and Northern Yukon, westward through the Mackenzie River Valley and Mackenzie Platform east of the Richardson Mountains; together this lithospheric root is referred to as the Mackenzie craton.

Regional seismic tomography models of Alaska and adjacent northwestern Canada also identified a high-velocity feature west of the CDF beneath northern Yukon (Jiang et al., 2018; Feng & Ritzwoller, 2019; Berg et al., 2020). Estève et al. (2020b) further interpreted this relatively high-velocity anomaly within the uppermost mantle as a mechanically-strong and cold lithosphere, supporting the existence of the Mackenzie craton (Figs. 4b-d-f, 7 and 8a-b-g-h, labeled MC). Seismic anisotropy measurements (from SKS and $SKKS$ splitting data) across this area are similar to those observed across the Canadian Shield, implying that the two regions have preserved similar fabrics, which provides further evidence for the buried Mackenzie craton in northern Yukon (Fig. 9). The presence of the Mackenzie craton in the northern NCC has profound implications for the tectonic evolution of the orogen.

4.5 Cordillera-craton boundary

The arcuate shape and eastward excursion of the NCC is one of the defining features that differentiates it from the SCC. At the surface, the Cordillera-craton boundary is delimited by a sharp topographic change at the CDF that curves westward as one moves north. Such orogenic morphology is often referred to as the result of oroclinal bending, a process that may or may not involve the lithospheric mantle. Understanding this first-order topographic feature is key in constraining the evolution of the NCC. However, prior to the improvements in coverage by new seismograph networks in this region, there were relatively few constraints on the shape of the Cordillera-craton boundary at lower crustal to upper mantle depths.

The first 3-D seismic velocity models suggested that the Cordillera-craton boundary in the upper mantle may be located either at the Tintina Fault (Frederiksen et al., 1998) or at the CDF (Mercier et al., 2009). Subsequent models clearly indicated the presence of cratonic lithosphere underlying the eastern part of the NCC (Schaeffer & Lebedev, 2014; McLellan et al., 2018); thus this boundary was confined to lie somewhere between the Tintina fault and the CDF. In the northernmost NCC, these high seismic velocities west of the CDF are associated with aforementioned Mackenzie craton. Estève et al. (2020b) further proposed that the 3-D structure of the upper mantle plays a key role in controlling the arcuate shape of the NCC through the LTZ and Mackenzie craton acting as rigid buttresses, guiding mantle flow and crustal strain toward the Canadian Shield. This is in agreement with recent geodynamic modeling of the area (McConeghy et al., 2022), as well as the work of Schutt et al. (2023), which shows a zone of lithospheric weakness under the Mackenzie Mountains. The position of the CDF further east within the NCC compared to the SCC may result from weakening of the Proterozoic cratonic lithosphere in the east due to metasomatic modification (Boyce et al., 2023). South of the LTZ, the upper mantle seismic velocity structure of the Proterozoic cratonic lithosphere suggests that it has been preserved from alteration during the various episodes of deformation that affected the Canadian Cordillera (Boyce et al., 2023).

The absence of thick cratonic lithosphere in the central part of the NCC is enigmatic, as it implies either there never was any thick cratonic lithosphere in the first place, or that this cratonic mantle root was removed. The first clues that point to active removal of lithospheric mantle in the NCC came from Audet et al. (2019), who revealed a west-dipping structure connected to the CDF in the southern NCC. This feature is coincidentally observed as a west-dipping boundary between fast and slow mantle in some seismic velocity models (*e.*g., Schaeffer & Lebedev, 2014), where it places warm asthenospheric mantle overlying a wedge of cold, cratonic lithosphere. This unexpected "oro-ward" dipping boundary in the upper mantle is also resolved by magnetotelluric data and seismic velocity models in the southernmost SCC (*e.g.,* Rippe et al., 2013; Chen et al., 2019). It remains unclear whether these structures reflect the remnant of a mantle suture zone (*e.g.,* Chen et al., 2019; Audet et al., 2019) or represent a transient feature associated with gravitational instability, thermal erosion and mantle-flow driven stresses from a sub-vertical boundary in lithospheric thickness (*e.g.,* Eaton et al., 2018; Yu et al., 2022; Currie et al., 2023). Given the numerous configurations of the Cordillera-craton boundary observed spanning the Canadian Cordillera as a whole, we suggest that mapping this boundary at upper mantle depth is a primary target for future investigations.

4.6 Tintina Fault

The Tintina Fault is a major tectonic structure spanning the NCC that has accommodated more than 400 km of horizontal displacement between Late Cretaceous and Eocene time (Gabrielse et al., 2006; Hayward, 2015). Imaging the structure of the Tintina Fault was one of the objectives of the Lithoprobe SNORCLE experiment. Controlled-source seismic and magnetotelluric data suggested that the Tintina Fault is a crustal-scale feature (Cook & Erdmer, 2005; Dehkordi et al., 2019). Estève et al. (2020a) investigated the vertical extent of the Tintina Fault and its role in the tectonic evolution of the NCC by combining seismic observations from seismic anisotropy measurements and tomographic images of the upper mantle. They reported strong seismic velocity contrasts across the Tintina Fault associated with the progressive clockwise rotation of fast-axis directions and increasing delay times along most of its length. Such seismic velocity contrasts cannot be related to a thermal anomaly, as the Tintina Fault was last active in the Eocene. Instead, they proposed that the Tintina Fault is a trans-lithospheric fault bounding lithospheric mantle regions with distinct compositions. This is further supported by an estimated 2 % increase in P-wave velocity between NCC and Greenland (cratonic) xenoliths (see Supplemental material of Estève et al., 2020a).This interpretation brings into question the thrust-sheet model of terrane accretion over a Precambrian basement suggested by the SNORCLE data. Instead, these results indicate large-scale displacement of lithospheric material over several hundred kilometers between Late Cretaceous and the Eocene. In particular, two inferred cratonic fragments are thought to have been chiseled and displaced along the Tintina Fault (Fig. 8 a-b, labeled F1 and F2). Those cratonic fragments are associated with the Cassiar terrane in the southern area of the NCC and a remnant of the Mackenzie craton in eastern Alaska, USA.

To complement the teleseismic body-wave tomography model of Estève et al. (2020b), Estève et al. (2021) and Schutt et al. (2023) used surface-wave tomography and investigated the structure of the crust and the top 50 km of the uppermost mantle. The shallow uppermost mantle S-wave velocity structure (50–100 km depth) is consistent with the deeper uppermost mantle seismic velocity structure obtained from teleseismic body-wave tomography. The S-wave velocity model shows a vertical low-velocity region bounded by sharp S-wave velocity gradients occurring beneath the surface expression of the Denali and Tintina faults (Fig. 4d). Moreover, the overlying crust is thinner directly above this low-velocity region in the uppermost mantle. Interestingly, a similar low-velocity anomaly is present in the teleseismic body-wave tomography models of Estève et al. (2020b) and extends down to 500 km depth, but the authors loosely interpreted it in terms of compositional variations in the mantle (Fig. 8 g-h). Based on their velocity model and additional geological evidence, Estève et al. (2021) proposed that this low-velocity region in the uppermost mantle may represent the upwelling of deeper and hotter asthenospheric material caused by the 430 km of lithospheric-scale dextral motion along the Tintina Fault between the Late Cretaceous and the Eocene. Furthermore, this unusually hot region within the uppermost mantle may have thinned the base of the overlying crust through thermal erosion. Notably, these uppermost mantle velocity variations suggest a non-uniform temperature distribution in the mantle lithosphere, and a variable lithospheric thickness.

5 Conclusions and Perspective

The EarthScope USArray TA deployment, in combination with other seismological networks, has provided an unprecedented high-resolution seismic data set of Alaska and northwestern Canada in an area that until recently has been poorly instrumented. This data set enables addressing fundamental questions on current geodynamics and the tectonic evolution of the NCC. Numerous geophysical studies benefited from this data set and the results obtained have provided new insights regarding the structure, origin and deformation of the lithosphere in the NCC, for instance:

- Seismic tomography models revealed that the lower crust beneath the NCC is anomalously slow from the Yakutat collision zone to the CDF (Estève et al., 2021; Schutt et al., 2023). Such low seismic velocities reflect the widespread elevated temperatures across the Cordillera (temperatures at the Moho reach 800-900° C) and could also reflect the strain transfer from the Yakutat collision zone to the Mackenzie Mountains, described by Mazzotti and Hyndman (2002).
- The seismic velocity structure beneath the currently uplifting Mackenzie Mountains is marked by a large low-velocity anomaly extending from the upper crust into the uppermost mantle, which is interpreted as a transcrustal elevated temperature anomaly (Schutt et al., 2023). However, there are no signs of recent magmatism nor volcanism in this area. Future work should focus on identifying the nature and magnitude of the low-velocity anomaly underlying the Mackenzie Mountains. Deployment of magnetotelluric instruments in the region would provide complementary information to the currently available seismic data sets, and additional seismometers would better constrain the location of the anomaly.
- Seismic data and models support the notion that variations in mantle lithospheric strength control current mantle flow conditions and surface deformation in the NCC (Estève et al., 2020b; Estève et al., 2021; Schutt et al., 2023; Boyce et al., 2023). For instance, the LTZ in the southern NCC marks a lithospheric-scale boundary inherited from the Proterozoic rifting of Laurentia that may be controlling neotectonic activity in this region. Combined with the inferred cratonic root of the Mackenzie craton in the northern NCC, these thick and rigid lithospheric blocks may further control the arcuate morphology of the NCC through buttressing of the mantle flow.

- Lastly, seismic tomography models and seismic anisotropy measurements strongly suggest that the Tintina Fault penetrates into the lithospheric mantle and displaced cratonic fragments to the northwest over several hundreds of kilometers between late Cretaceous and the Eocene (Estève et al., 2020a), placing new constraints on plate reconstructions.

Future efforts should focus on refining estimates of the lithospheric thickness and the mantle transition zone throughout the NCC (e.g., using S-to-P receiver function analysis), as this will provide constraints on the development and stability of lithospheric plates. In addition, the crustal and upper mantle seismic attenuation structure of the NCC should be investigated, as this is a powerful tool that is sensitive to temperature variations and to the presence of melt, but less sensitive to composition when compared to seismic velocities (Dalton et al., 2009). It would be useful to convert the seismic velocity variations into temperature and viscosity, and geodynamically model these, to better understand how such variations control the location of orogenesis. Additionally, large velocity variations in the upper mantle to the west of the CDF suggest a complicated lithospheric structure, that may be caused by a delaminating lithosphere.

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Data Availability Statement

The facilities of IRIS Data Services, and specifically the IRIS Data Management Center, were used for archiving and access to waveforms, related metadata, and/or derived products used in this study. IRIS Data Services are funded through the Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE) Proposal of the National Science Foundation under Cooperative Agreement EAR-1261681. Data from the TA network were made freely available as part of the EarthScope USArray facility, operated by Incorporated Research Institutions for Seismology (IRIS) and supported by the National Science Foundation, under Cooperative Agreements EAR-1261681. Data are available on the IRIS Earthquake Data Center (https://ds.iris.edu/ds/nodes/dm The seismic models were directly provided by the corresponding authors. Figures were created using Generic Mapping Tools (Wessel et al., 2013). Figure 10 was created using the Geophysical Model Generator (https://github.com/JuliaGeodynamics/GeophysicalModelGenerator.jl) and Paraview (Ahrens et al., 2005).

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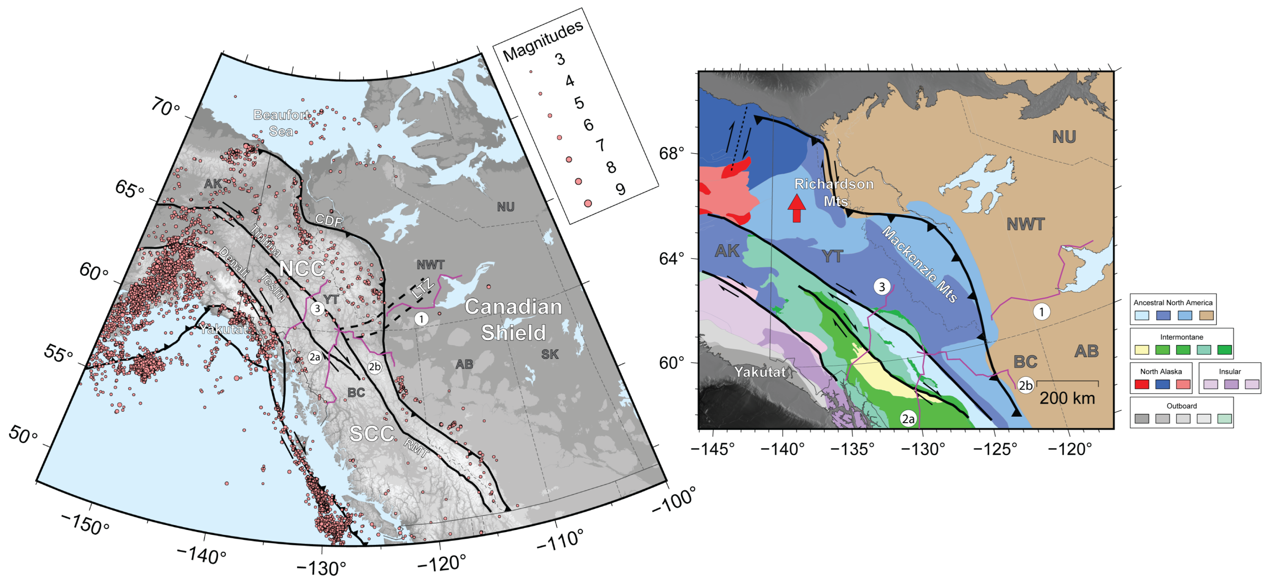

Figure 1. (a) Topographic map of western Canada and eastern Alaska. Red dots represent seismicity ($M_W \geq 3.0$) between 2012 and 2022 from the USGS and nrCAN catalogs. Purple lines denote the 3 Lithoprobe SNORCLE profiles across northwestern Canada. The dashed-line shows the Canning River deformation zone. (b) Terrane map of northwestern Canada and eastern Alaska. Single red arrow shows northward residual motion. Abbreviations: AB, Alberta; AK, Alaska; BC, British Columbia; CDF, Cordillera Deformation Front; LTZ, Liard Transfer Zone; NCC, Northern Canadian Cordillera; NU, Nunavut; NWT, Northwest Territories; SCC, Southern Canadian Cordillera; SK, Saskatchewan; RMT, Rocky Mountain Trench; YT, Yukon Territory. Terranes adapted from Colpron et al. (2007).

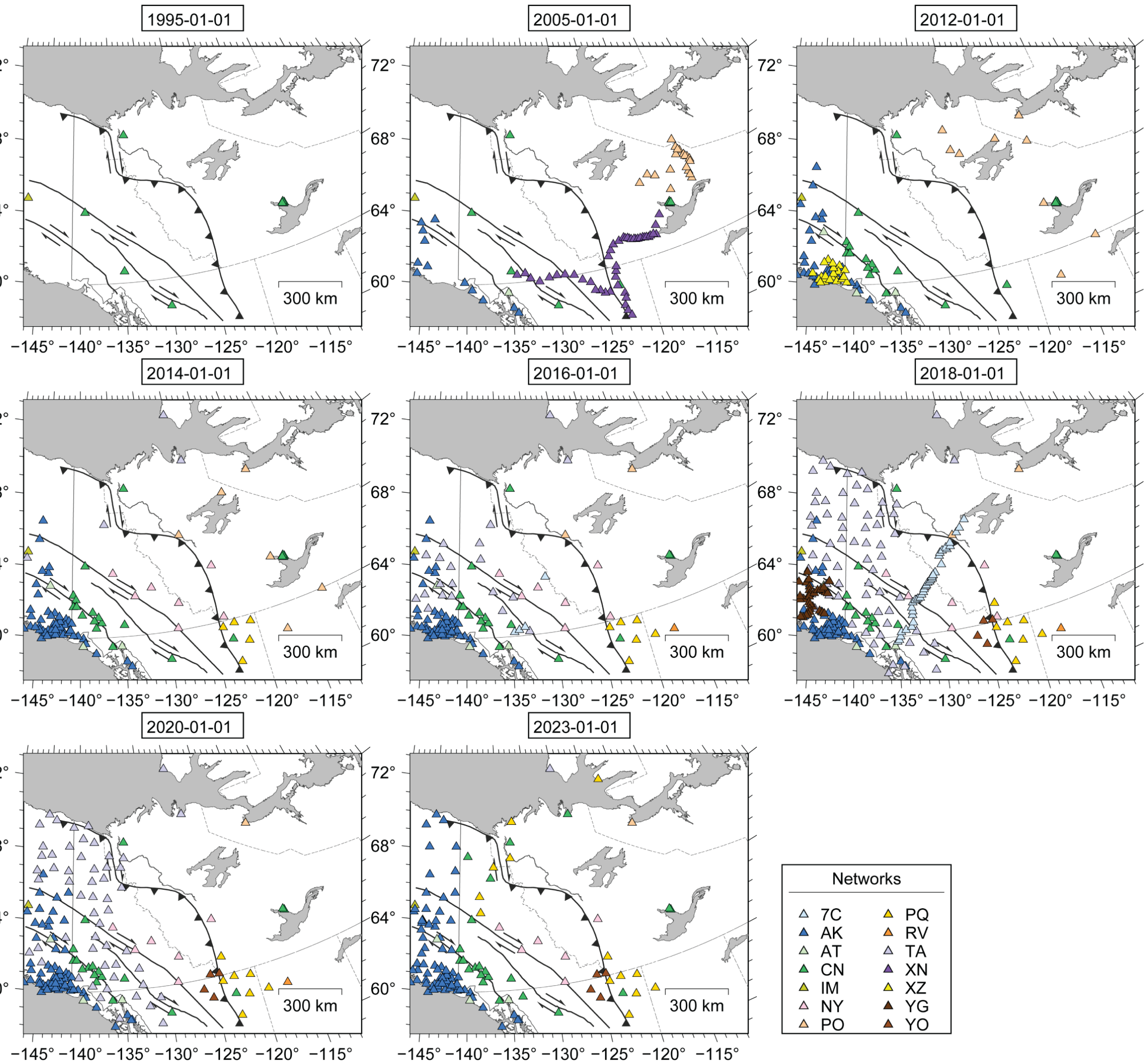

Figure 2. Seismic station coverage across northwestern Canada from January 1995 to January 2023. Triangles depict seismic stations and are color-coded by seismic network.

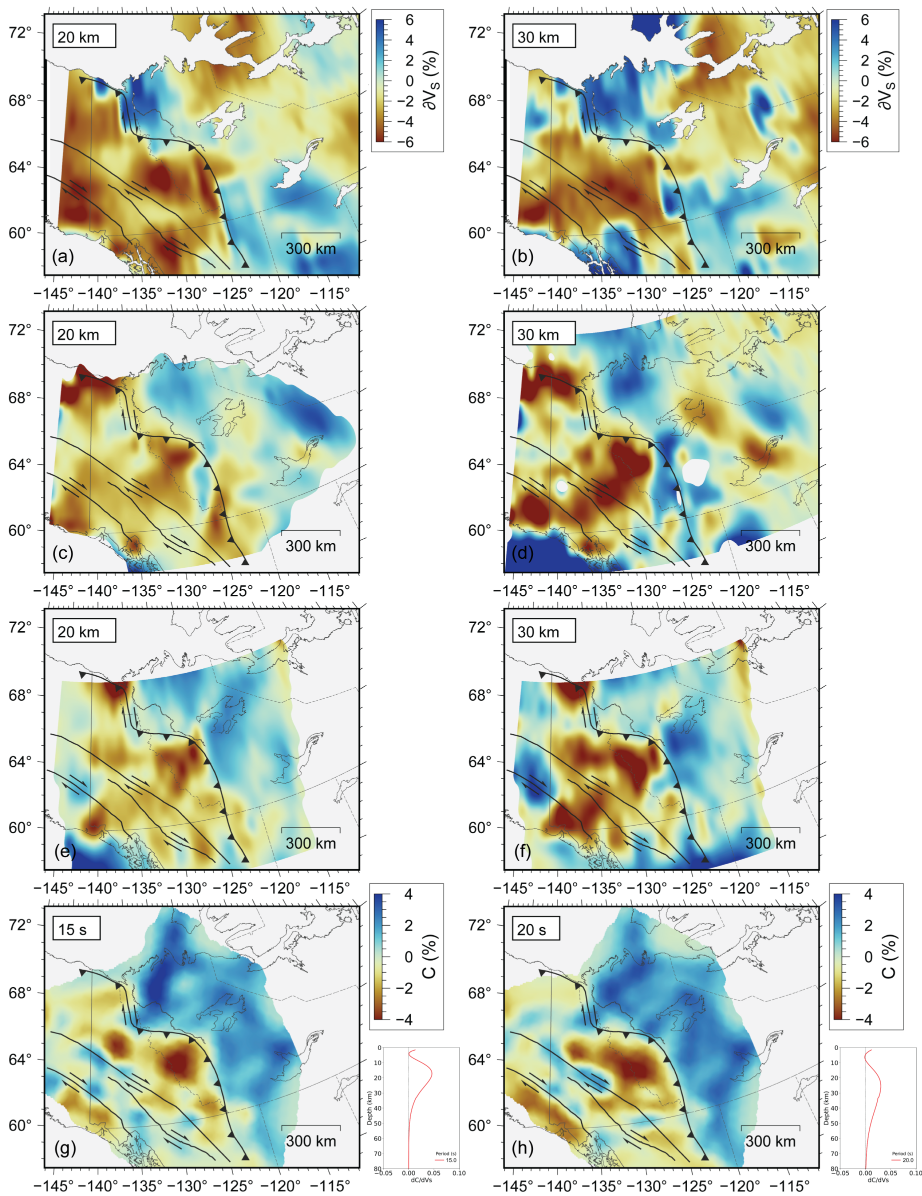

Figure 3. 20 and 30 km depth slices through the S-wave velocity models of Kao et al. (2013, a-b), Estève et al. (2021, c-d) and Schutt et al. (2023, e-f). Phase velocity maps at periods of 15 and 20 s from McLellan et al. (2018, g-h) and corresponding phase velocity sensitivity kernels calculated from a simplified version of the global velocity model AK135 (Kennett et al., 1995).

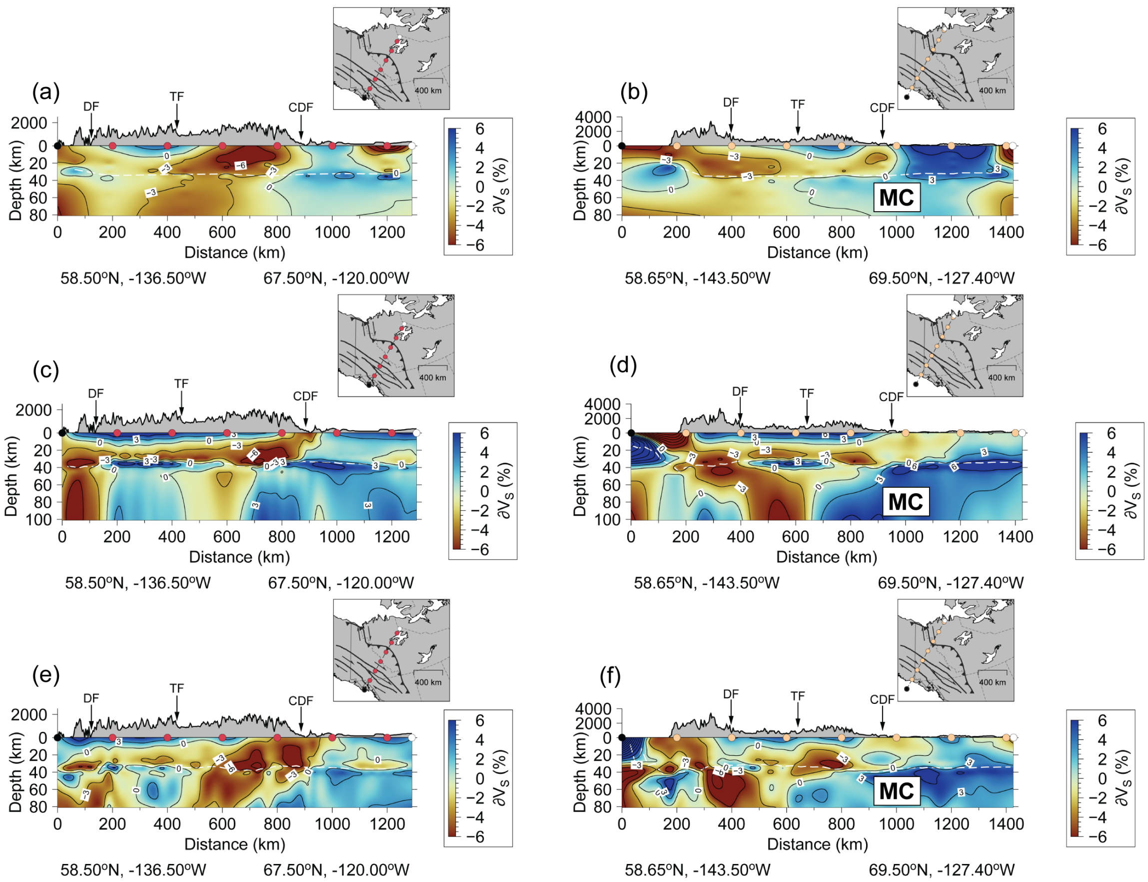

Figure 4. Profiles through the *S*-wave velocity models of Kao et al. (2013, a-b), Estève et al. (2021, c-d) and Schutt et al. (2023, e-f). Inset maps show the profiles locations. Velocity contours are every 3%. White dashed line represents the Moho. Abbreviations: MC, Mackenzie craton.

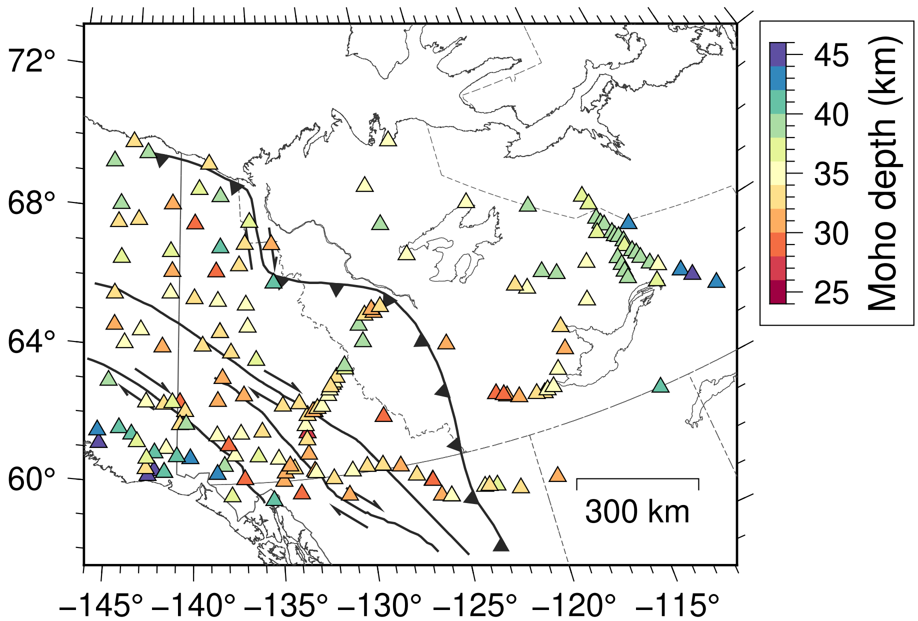

Figure 5. Moho depth estimates across northwestern Canada obtained from Audet et al. (2020); Miller et al. (2018); Postlethwaite et al. (2014).

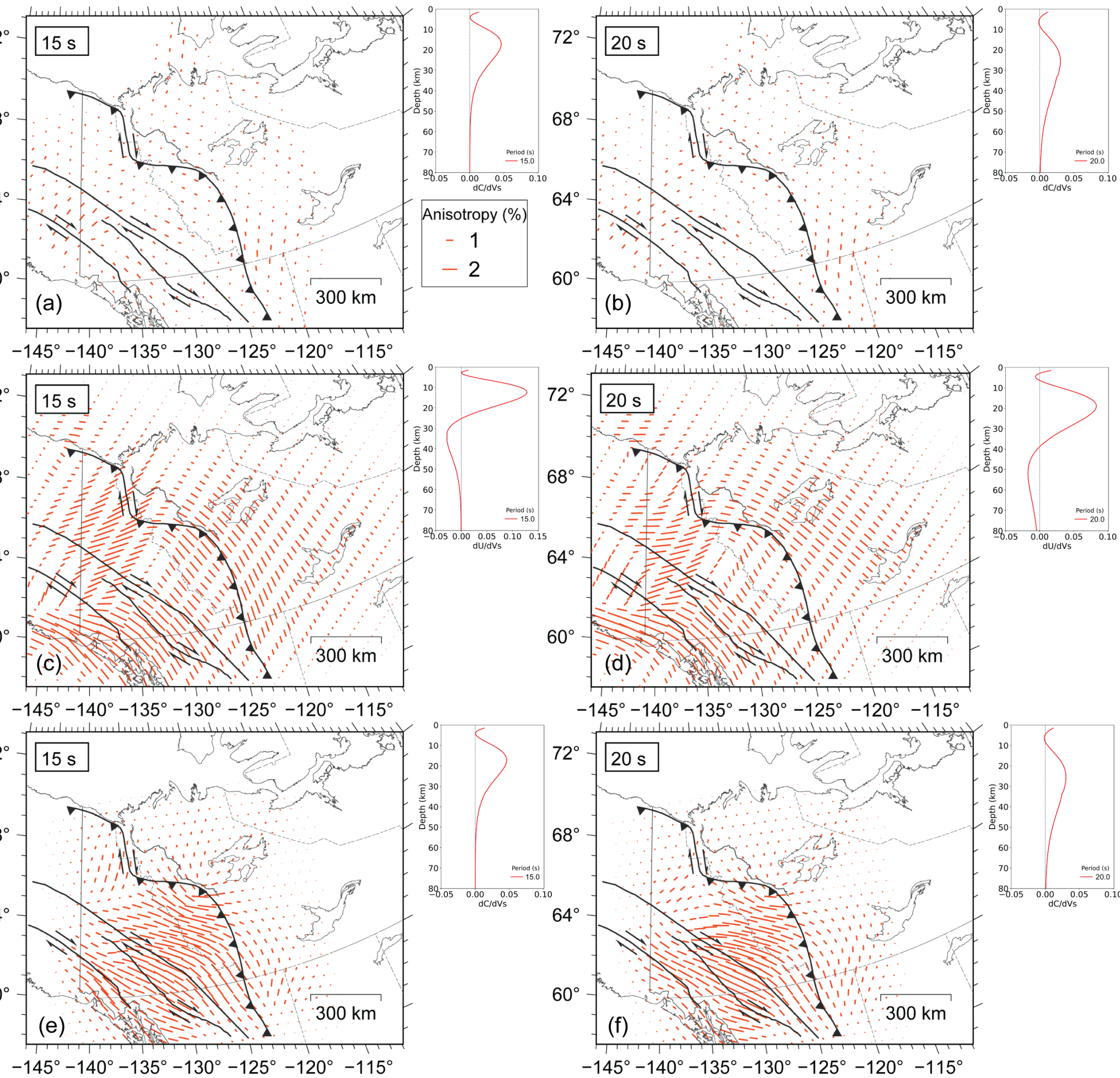

Figure 6. Maps showing azimuthal anisotropy of northwestern Canada at periods of 15 and 20 s from McLellan et al. (2018, a-b), Estève et al. (2021, c-d) and Schutt et al. (2023, e-f). Also shown, phase (a, b, e and f) and group (c, d) velocity sensitivity kernels at 15 and 20 s calculated from a simplified version of the global velocity model AK135 (Kennett et al., 1995).

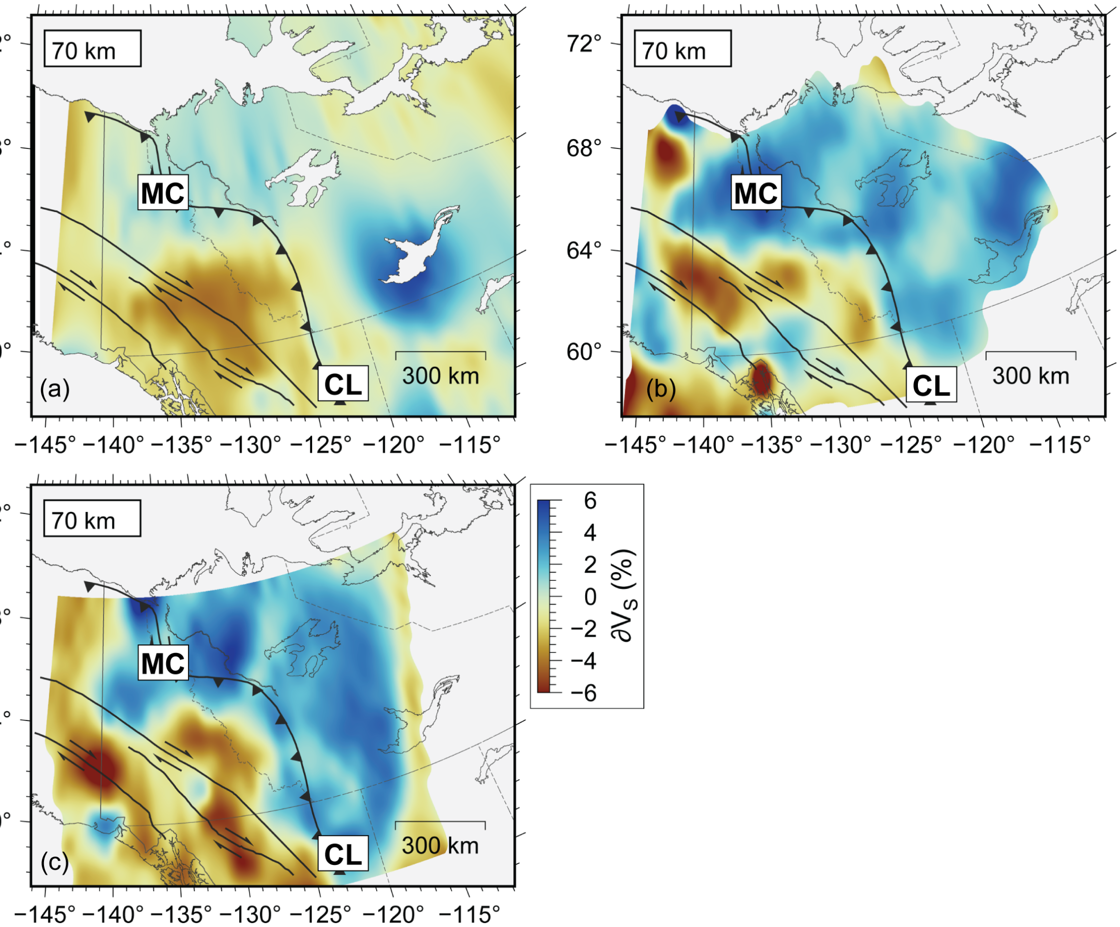

Figure 7. 70-km depth slice through the *S*-wave velocity models of Kao et al. (2013, a), Estève et al. (2021, b) and Schutt et al. (2023, c). Abbreviations: CL, cratonic lithosphere; MC, Mackenzie craton.

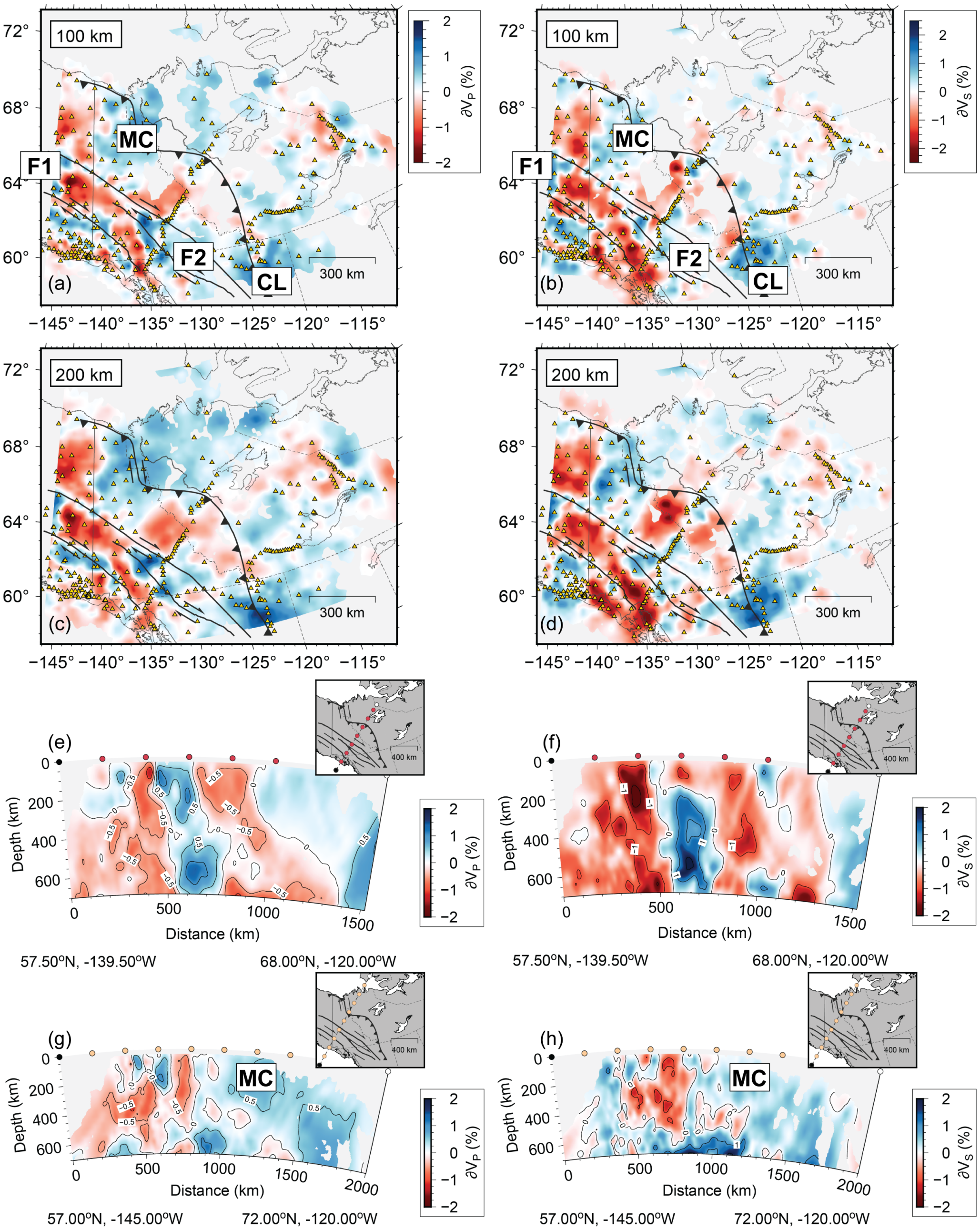

Figure 8. Teleseismic P- and S-wave tomography models of northwestern Canada (Estève et al., 2020b). 100 and 200-km depth slices through the P- (a,c) and S-wave (b,d) models. Profiles through the P- (e,g) and S-wave (f,h) models. Inset maps show the profile locations. Yellow triangles depict seismic stations. Abbreviations: CL, cratonic lithosphere; F1, fragment 1; F2, fragment 2; MC, Mackenzie craton.

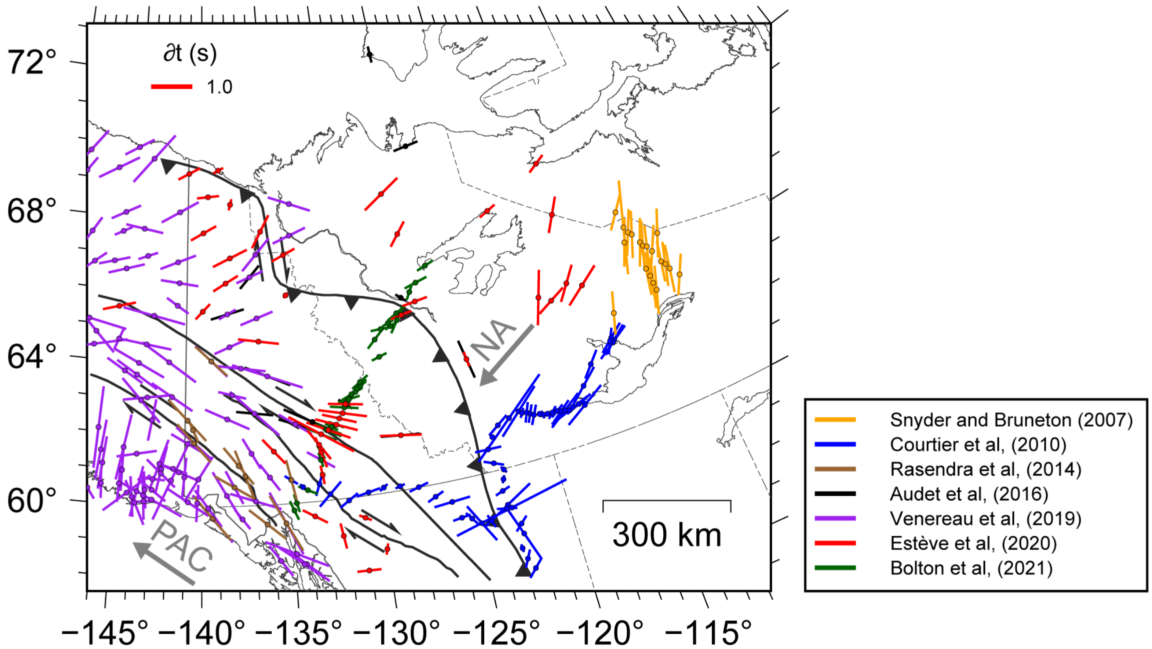

Figure 9. Station average core phase splitting parameters throughout northwestern Canada compiled from Snyder and Bruneton (2007); Courtier et al. (2010); Rasendra et al. (2014); Audet et al. (2016); Venereau et al. (2019); Estève et al. (2020a); Bolton et al. (2021). Colored bars depict the fast-axis direction of propagation scaled by delay time. Grey arrows represent absolute plate motion directions of the North American (NA) and Pacific (PAC) plates from DeMets et al. (2010).

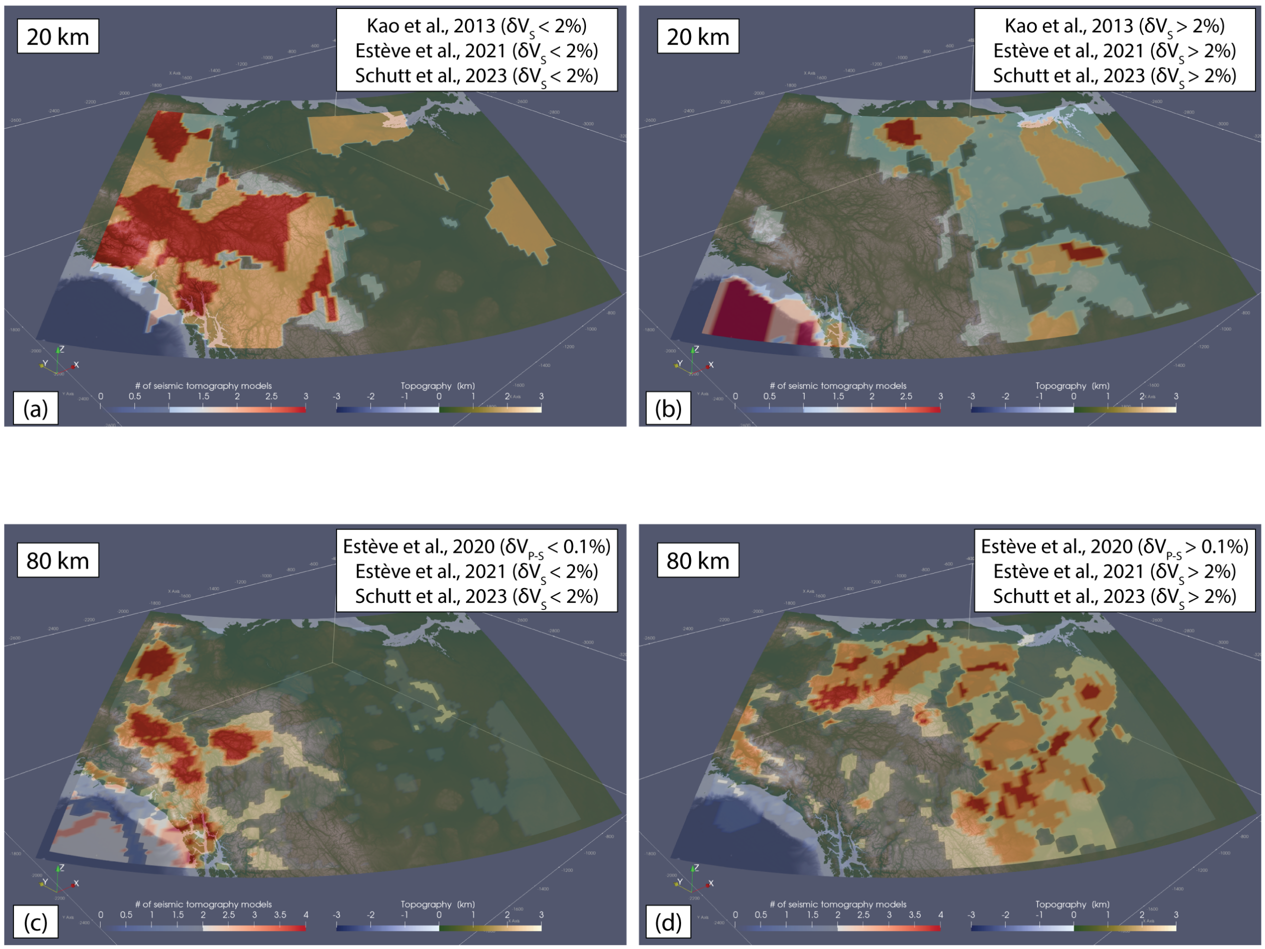

Figure 10. Low-velocity (a,c) and high-velocity (b,d) vote maps at 20 and 80 km depth. Regions where seismic tomography models considered here agree are shown in red. Criteria are shown in top right corner of each panel.