Deformation at the eastern margin of the Northern Canadian Cordillera: Potentially related to opening of the North Atlantic

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Funding information
National Geographic Research and Exploration grant, Grant/Award Number: 9484-14

Abstract
The Northern Canadian Cordillera (NCC) comprises the Mackenzie Mountains, which are characterized by earthquakes occurring ~1,000 km east of the western North American margin. However, no recognized convergence has occurred in this inboard region since the Mesozoic to early Cenozoic formation of the Cordillera. This lack of an obvious driver for the modern NCC deformation has generated considerable debate and various geodynamic models. We show here thermal histories derived from (U-Th-Sm)/He data that are interpreted to indicate reactivated deformation and formation of the eastern deformation front beginning ~30 Ma. At that time the western margin of North America was mainly a transform boundary, which typically transmits very limited amount of stress into the continent. Along the northeastern margin of North America, however, the North Atlantic was opening and may have caused horizontal forces that drove deformation far to the west where the rigid craton encountered the weak Cordillera.

1 | INTRODUCTION

The Northern Canadian Cordillera (NCC) comprises the Mackenzie Mountains, which are characterized today by earthquakes occurring ~1,000 km east of the northwestward moving Pacific Plate along the western North American margin (Figures 1 and 2). However, no convergence has occurred in this region since Mesozoic to early Cenozoic formation of the Cordillera (Coney, 1972). This lack of an obvious driver for modern NCC deformation has generated considerable debate and development of geodynamic models (Finzel, Flesch, & Ridgway, 2014; Finzel, Flesch, Ridgway, Holt, & Ghosh, 2015; Hyndman et al., 2005; Mazzotti & Hyndman, 2002; Mazzotti, Leonard, Hyndman, & Cassidy, 2008). The models are based on geophysical data and numerical modelling, but geological observations recording the Cenozoic history are rare from this remote region. This lack of data motivated the collection of samples along a SW–NE transect that crosses the Mackenzie Mountains and Mackenzie Plain. We present 34 apatite and 21 zircon (U-Th-Sm)/He data and derived thermal histories that record three phases of rock cooling.

2 | BACKGROUND

The Mackenzie Mountains are composed of Neoproterozoic to Devonian strata that deformed into the Cordilleran fold-thrust belt during Cretaceous to early Cenozoic east-west compression associated with subduction and terrane accretion at the western margin of North America (Coney, 1972; Cook, 1991; Eibach, 1981; Gabrielse, 1991) (Figure 1). The Plateau thrust system is the most prominent structure in the central Mackenzie Mountains (Cook, 1991; Gabrielse, Roddick, & Blusson, 1973) and to the northeast of it strata are folded into broad anticlines (Gordey, MacDonald, Roots, Fallas, & Martel, 2011) (Figures 2 and 3). Thin-skinned deformation reaches farther east and deforms the Cretaceous and underlying Devonian and older strata of the Mackenzie Plain along shallow detachment...
faults over cratonic basement (Fallas, MacNaughton, MacLean, & Hadlari, 2013; Vann, Graham, & Hayward, 1986) (Figure 2). Upper Cretaceous to Paleocene strata in the Mackenzie Plain was sourced from the emerging Mackenzie Mountains to the west and document synorogenic sedimentation (Thomson, Schröder-Adams, Hadlari, Dix, & Davis, 2011). No clear stratigraphic record of post-Paleocene deformation exists, due to removal of the younger strata by glacial erosion (Fallas et al., 2013). However, thermal maturity of Devonian strata suggests post-Paleocene erosion of 1–3 km (Feinstein, Issler, Snowdon, & Williams, 1996; Issler, Grist, & Stasuk, 2005), which may imply deformation and uplift. The timing and amount of crustal deformation can be measured when it results in surface uplift and erosion that causes rock exhumation and cooling.

3 | METHODS AND RESULTS

The cooling history of rocks can be revealed by low-temperature thermochronology. Analysing apatite and zircon with (U-Th-Sm)/He thermochronology quantifies cooling through temperatures of 40–
80°C (e.g. Shuster, Flowers, & Farley, 2006) and 140–200°C (Reiners, Spell, Nicolescu, & Zanetti, 2004), respectively, which typically occurs 1–10 km below earth surface. Here, we investigate the timing of Cenozoic deformation using (U-Th-Sm)/He analysis combined with thermal history modelling.

Samples are collected along a SW–NE profile that crosses the main structures and geomorphic features including the Shale Lake and Plateau Faults, a large anticline that forms the mountain front, and thrust faults in the Mackenzie Plain (Figures 2 and 3a). Samples collected in the Mackenzie Mountains are from Proterozoic strata, while samples collected in the Mackenzie Plain are Devonian and Upper Cretaceous strata. More information on all eight samples is given in Tables S1 and S2.

FIGURE 2 Topography of the Mackenzie Mountains and Mackenzie Plain with main structures and geographic features. White box shows the Mountain River study area. Dots are earthquake from 1985 to 2018 (Earthquakes Canada, GSC, 2018) sized according to their magnitude and colour coded according to their depths. White boxes show sample locations. Note all sample names start with MAC followed by a number shown in the box. NW: Norman Wells [Colour figure can be viewed at wileyonlinelibrary.com]
Apatite and zircon grains were separated using standard separation techniques. Individual grains were examined and selected under a stereomicroscope, measured for grain size dimension for alpha-ejection correction (Farley, Wolf, & Silver, 1996), and packed in niobium packages. Packages were sent to the University of Arizona at Tucson for analysis of He, U, Th and Sm. We aimed to analyse five apatite and three zircon grains per sample. Single grain data are available in Tables S1 and S2. We found apatite (U-Th-Sm)/He ages that range from 140–15 Ma, with most grains yielding 80–50 Ma and 33–20 Ma ages (Table S1). Zircons yielded a wide range of single-grain ages from 300–50 Ma (Table S2). Age dispersion is not uncommon for (U-Th–Sm)–He analysis and can partly be explained by varying grain sizes (Farley, 2000), amounts of radiation damage, and helium inheritance (Flowers, Ketcham, Shuster, & Farley, 2009; Guenthner, Reiners, DeCelles, & Kendall, 2015) (Figure S1).

In order to better interpret the thermochronology data we conducted thermal history modelling using the program HeFTy v1.9.3 (Ketcham, 2005). We used the radiation damage accumulation and annealing models of Guenthner et al. (2015) for zircons, and Flowers et al. (2009) for apatite to conduct thermal history modelling (see Supplement Information for more details). For each sample we included all apatite and zircon single grain data in the model, except for samples where more than seven grains were dated (HeFTy has a maximum of seven helium models that can be run together). In Figure 3 we show the envelopes of possible T-t path solutions for the last 120 Ma, full histories are shown in Figure S2.

4 DISCUSSIONS AND CONCLUSION

Due to low apatite yield from the Proterozoic strata, our dataset is smaller than anticipated. However, the analysed samples document three phases of cooling and inferred rock exhumation (Figure 3b). The first two phases occur only in the Mackenzie Mountains and record cooling associated with previously documented (Powell, 2017; Powell, Schneider, Stockli, & Fallas, 2016) deformation during the Late Cretaceous (100–75 Ma) and Paleocene–Early Eocene (65–40 Ma). Late Cretaceous cooling is recorded in the hangingwall of the Shale Lake Fault (MAC-5) that represents northeastward thrusting of deep seated rocks along a steep ramp (Gordey et al., 2011) resulting in cooling from more than 160°C to below 50°C during the Late Cretaceous. A similar amount of cooling is indicated in sample MAC-33 farther east (Figure 3). The second phase of cooling occurs only northeast of the Shale Lake Fault and accommodated less cooling and exhumation. These samples (MAC-12, 39, 41) experienced very slow cooling or steady state conditions within 120–80°C throughout the Late Cretaceous followed by Paleocene–Early Eocene rapid cooling to below 50°C (Figure 3). These two phases of rock exhumation in the Mackenzie Mountains correlate well with the burial histories of the Devonian (MAC-44) and Upper Cretaceous (MAC-45) strata collected in the Mackenzie Plain (Figure 3b), and the apatite fission track multi-kinetic thermal models of Devonian (Issler et al., 2005) and Cretaceous strata (Powell, Schneider, & Issler, 2018) farther south. Our thermal history models of strata in the Mackenzie Plain suggest burial and heating up to ~140°C during Paleocene–Eocene time, which is coeval with cooling phase two documented in the Mackenzie Mountains (Figure 3).

The most significant outcome of our study is the clear evidence of a third cooling phase that is interpreted as recoding deformation and exhumation during Oligocene–early Miocene (33–20 Ma; Figure 3b). Thermal history modelling of our data suggest cooling from 120–80°C started ~33 Ma and that the rocks were below 40°C and the resolution...
for (U-Th-Sm)/He analyses by 20 Ma (Figure 3). Assuming a geothermal gradient of 30–40°C/km (Hyndman et al., 2005), this cooling phase implies a minimum of 1–3 km of exhumation during the Oligocene–early Miocene. This phase is recorded within the Mackenzie Mountains only northeast of the Plateau Fault (MAC-29) and in the Mackenzie Plain (MAC-44, MAC-45; Figure 3). The spatial pattern of cooling suggests that deformation of strata in the eastern Mackenzie Mountains continued via reactivation of the underlying detachment fault that propagated farther east into the foreland, where it resulted in folding and thrusting of Upper Cretaceous strata in the Mackenzie Plain (Figure 3a). The documentation of this early post-Paleocene exhumation at the eastern front of the NCC is unexpected and raises questions regarding the driving mechanism of deformation.

Today, the Pacific Plate, along with an attached oceanic plateau named the Yakutat microplate, are moving northwestward along the North American margin and subducting beneath southern Alaska (Figure 1). Yakutat subduction started in the Oligocene and caused flat-slab subduction in south-central Alaska, which resulted in strong coupling between the upper and lower plate, surface uplift, basin inversion (Finzel, Trop, Ridgway, & Enkelmann, 2011) and localized rock exhumation at the plate boundary (e.g. Enkelmann, Garver, & Pavlis, 2008; Enkelmann, Piestrzeniewicz, Falkowski, Stübner, & Ehlers, 2017) and in the Alaska Range (e.g. Lease, Haeussler, & O'Sullivan, 2016). Yakutat subduction and ongoing collision plays a central part in the existing geodynamic models that have been proposed to explain modern seismic activity at the eastern margin of the NCC (Figure 2). The orogenic float model proposes that a small portion of northwest-directed Yakutat convergence is transferred towards the northeast via a decoupling layer in the hot and weak Cordilleran lower crust, which allows for the northeastward push of the rigid upper crust (Hyndman et al., 2005; Mazzotti & Hyndman, 2002; Mazzotti et al., 2008). Additional forces are generated by gravitational collapse of the high-elevation St. Elias Mountains at the active plate boundary (Mazzotti & Hyndman, 2002) (Figure 1). This model requires high elevations in the St. Elias Mountains by Oligocene time in order to produce the gravitational potential to cause the upper crust to flow northeastward. The St. Elias Mountains have been extensively studied using thermochronology, and collectively these data support rapid exhumation and inferred mountain building beginning 15–10 Ma (e.g. Enkelmann et al., 2017; Falkowski & Enkelmann, 2016; Falkowski et al., 2016; O'Sullivan & Currie, 1996). We therefore rule out this model as a feasible driving mechanism for early Oligocene–early Miocene deformation at the eastern NCC.

**Figure 4** Plate tectonic reconstructions of the Arctic and northern North America at 40, 30, 20 Ma and today using G Plates (Müller et al., 2018). Arrows show the reconstructed plate velocities from Seton et al. (2012) for the North American plate (black) and Greenland (red) in a Pacific hot spots reference frame [Colour figure can be viewed at wileyonlinelibrary.com]
The orogenic float model has been challenged due to a lack of sufficient horizontal displacement across major crustal-scale strike-slip faults (Denali and Tintina faults; Figure 1) that are located between the St. Elias and the Mackenzie Mountains (Audeit, Sole, & Schaeffer, 2016). Recent geodynamic investigations suggest that plate boundary and buoyancy forces alone cannot reproduce the observed deformation in the NCC, and instead attribute stresses associated with basal tractions from a deeper mantle convection cell that is coupled with the lithosphere to explain modern deformation patterns (Finzel et al., 2014, 2015). To apply the mantle traction model to Oligocene deformation at the eastern margin of the NCC requires that shallow subduction of the Yakutat slab beneath Alaska formed a wall in the mantle that caused divergence of a south-directed mantle convection cell resulting in drag to the NCC (Finzel et al., 2015). However, Yakutat flat-slab subduction is inferred to have begun ~36 Ma, which would require very early divergence of the mantle flow. The main argument against the mantle traction model is that deformation would have been continuous until the present day but cooling and inferred deformation ceased in the Mackenzie region after the early Miocene, and may have been reactivated very recently. Eocene and younger cooling ages have been recorded from the interior of the NCC and east-central Alaska, between the Tintina and the Denali faults (Figure 1). Since the Eocene, several hundred kilometres of dextral motion occurred on these faults, which caused block rotation accompanied by sinistral strike-slip and normal faulting, basin development, and magmatism (e.g. Dixit, Hanks, Rizzo, McCarthy, & Coakley, 2017; Dusel‐Bacon, Bacon, O’Sullivan, & Day, 2016; Dusel‐Bacon & Murphy, 2001). However, there is no record that convergent motion has crossed over the Tintina Fault to the east.

Given these factors, other potential driving mechanisms need to be considered to explain Oligocene deformation at the eastern NCC margin. Instead of focusing only on the processes occurring along the western margin of North America, we propose to consider stresses that originated from the eastern North American plate boundary located ~4,000 km northeast (Figure 4). Although spreading between Eurasia and Greenland started in the Late Paleocene (ca. 54 Ma), a major change in plate motions occurred in the Oligocene (33–30 Ma) (Gaina, Gernigon, & Ball, 2009). Ocean floor studies reveal that separation between Greenland and Eurasia developed in a series of failed rifts, plate boundary relocations and microcontinent development (Ellis & Stocker, 2014; Gaina et al., 2009). Oligocene–Miocene plate reorganization resulted in a link between the Reykjanes and Kolbeinsey ridges southeast of Greenland, which created the final break between Europe and North America and the emergence of Iceland (Ellis & Stocker, 2014). These reorganizational processes had a major influence on the motion of the North American plate, which rotated counterclockwise (from NW to SW direction) in the Oligocene (Gaina et al., 2009). From that time on, Greenland and North America moved together towards the west (Figure 4). Plate motion changed to eastward motion by 20 Ma, which may explain the observed decease of cooling and inferred deformation and rock exhumation at the eastern NCC. Today, North America is moving westward with high rates and may explain the ongoing deformation (Figures 2 and 4). Modern stress measurements reveal that the entirety of northern North America east of the Cordillera shows a NE–SW orientation of the maximum horizontal stresses, and that Cordilleran topography has a very limited affect on the eastern foreland stresses (Reiter, Heidbach, Haug, Ziegler, & Mocek, 2014). The correlation of the NE–SW orientation of maximum horizontal stresses with the orientation of the Mid-Atlantic ridge and the plate motion of North America (Henton, 2006) suggest crustal stress today is caused by ridge push and basal tractions from mantle convection (Coblentz & Richardson, 1995; Zoback et al., 1989).

We propose that Oligocene plate reorganization in the northwestern hemisphere initiated southwest-directed motion of cratonic North America that may have resulted in far-field deformation where the rigid crust of the craton was thrust under the weak Cordilleran fold- and thrust belt. Pre-existing structures in the Mackenzie Mountains were reactivated and deformation propagated into the foreland forming the eastern deformation front (i.e. Franklin Mountains; Figure 2), and development of back thrusters farther to the north where the foreland remained underformed (Vann et al., 1986). The early Miocene east directed plate motion as well as the previously suggested mantle drag from the northwest towards the east may have caused the decrease in deformation after ~20 Ma. More data from the eastern margin of the NCC are needed to test this hypothesis of Oligocene deformation.

**ACKNOWLEDGEMENTS**

This project was funded by a National Geographic Research and Exploration grant (EE#9484-14). We thank Richard Ketcham for helpful discussion on the modelling, Peter Reiners for laboratory assistance, and three anonymous reviewers for helpful comments.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Data S1. Deformation at the eastern margin of the Northern Canadian Cordillera: potentially related to opening of the North Atlantic.

How to cite this article: Enkelmann E, Finzel E, Arkle J. Deformation at the eastern margin of the Northern Canadian Cordillera: Potentially related to opening of the North Atlantic. Terra Nova. 2019;31:151–158. https://doi.org/10.1111/ter.12374