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Reconciling seismic structures and Late Cretaceous kimberlite magmatism in northern Alberta, Canada

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ABSTRACT

The Late Cretaceous kimberlites in northern Alberta, Canada, intruded into the Paleoproterozoic crust and represent a nonconventional setting for the discovery of diamonds. Here, we examined the origin of kimberlite magmatism using a multidisciplinary approach. A new teleseismic survey reveals a low-velocity (−1%) corridor that connects two deep-rooted (>200 km) quasi-cylindrical anomalies underneath the Birch Mountains and Mountain Lake kimberlite fields. The radiometric data, including a new U-Pb perovskite age of 90.3 ± 2.6 Ma for the Mountain Lake intrusion, indicate a northeast-trending age progression in kimberlite magmatism, consistent with the (local) plate motion rate of North America constrained by global plate reconstructions. Taken together, these observations favor a deep stationary (relative to the lower mantle) source region for kimberlitic melt generation. Two competing models, mantle plume and slab subduction, can satisfy kinematic constraints and explain the exhumation of ultradeep diamonds. The plume hypothesis is less favorable due to the apparent age discrepancy between the oldest kimberlites (ca. 90 Ma) and the plume event (ca. 110 Ma). Alternatively, magma generation may have been facilitated by decompression of hydrous phases (e.g., wadsleyite and ringwoodite) within the mantle transition zone in response to thermal perturbations by a cold slab. The three-dimensional lithospheric structures largely controlled melt migration and intrusion processes during the Late Cretaceous kimberlite magmatism in northern Alberta.

INTRODUCTION

Kimberlites, one of the most deeply derived mantle melts, often carry xenoliths and diamonds from great depths (>150 km) to the surface and provide vital information on the composition and dynamic processes of the subcontinental lithosphere (Griffin et al., 2008; Heaman et al., 2004; Pearson and Wittig, 2008; Torsvik et al., 2010). Their scientific and economic significance has prompted growing research interest into the petrogenesis and migration of kimberlite melts. In North America, kimberlite eruptions have been reported in several regions that, based on their spatiotemporal distributions, can be classified into five distinctive age groups (Fig. 1A; Heaman et al., 2004). Their formation has been linked to tectonic processes involving subduction (e.g., McCandless, 1999; Currie and Beaumont, 2011), continental rifting and mantle plume (Bank et al., 1998; Heaman and Kjarsgaard, 2000; Eaton and Frederiksen, 2007), edge-driven convection (Kjarsgaard et al., 2017), and lithospheric flexure (Zhang et al., 2019).

In northern Alberta, Canada, kimberlite pipes have been discovered from three tectonic domains, including the Chinchaga domain, the Buffalo Head terrane (BHT), and the Taltson magmatic zone (TMZ), and they collectively form the northern Alberta kimberlite province (Fig. 1B; Eccles et al., 2004). The intrusions of diamondiferous kimberlites into the Paleoproterozoic crust signify a nonconventional setting for diamond exploration (Aulbach et al., 2004; Banas et al., 2007), where several types of diamonds have been discovered in association with a wide depth range of formation environment. For example, the type II (nitrogen-free) and type IaB (low to moderate nitrogen content) diamonds, with majoritic garnet, indicate a sublithospheric origin (Davies et al., 2004). Their temporal association with the host kimberlites was inferred from the absence of pyroxene exsolution, which suggests a short residence time of diamonds prior to their exhumation by kimberlite magmas (Banas et al., 2007). The relatively remote locations in northern Alberta compared to other kimberlite groups in North America (Fig. 1A) and highly variable isotopic signatures (e.g., Sr ratio: 0.704–0.709, and ε_{Nd} values from −7.4 to +2.7) further highlight the complex tectonic processes that triggered the Late Cretaceous kimberlite magmatism (Aulbach et al., 2004; Davies et al., 2004; Eccles et al., 2004; Banas et al., 2007). By combining seismic imaging with an analysis of the spatiotemporal emplacement pattern of kimberlites and plate reconstructions, this study sheds new light on the initiation and evolution of kimberlite magmatism in northern Alberta.

NORTHERN ALBERTA KIMBERLITE PROVINCE

Northern Alberta consists of a collage of northwesterly trending Proterozoic terranes that were accreted to the Archean western Churchill Province during a relatively short (2.0–1.8 Ga) geological time span (Fig. 1B; Hoffman, 1988; Ross et al., 1991). The Proterozoic crustal domain of Buffalo Head was suggested to have formed on an Archean-aged basement (Ross and Eaton, 2002), and its underlying mantle lithosphere exhibits isotopic signatures similar to those within Archean cratons (Aulbach et al., 2004).

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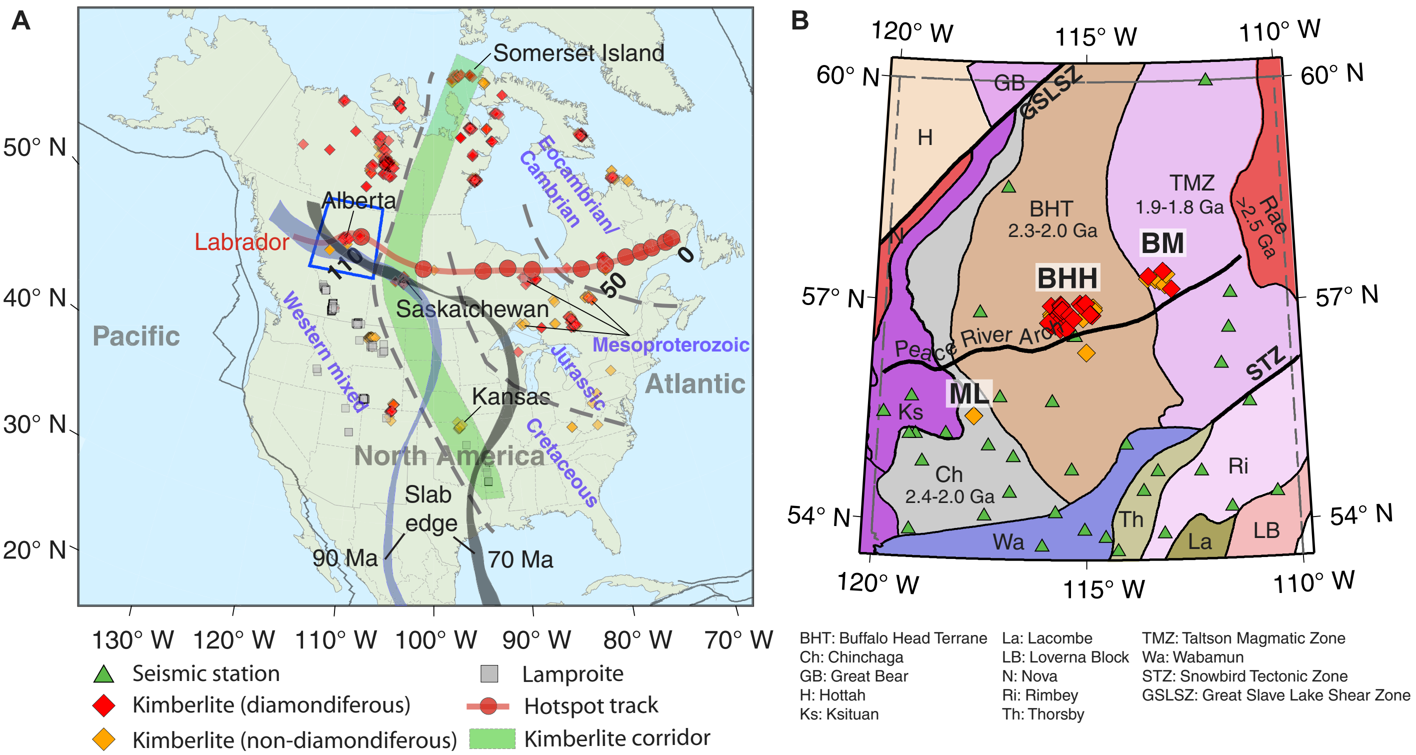

Figure 1. (A) Kimberlite and lamproite distribution in North America. Location of the study area is enclosed by blue polygon. Kimberlites are classified into five age groups separated by dashed lines. The Mid-Cretaceous kimberlite corridor (shaded green) contains the Somerset Island, Saskatchewan, and Kansas kimberlite fields (Kjarsgaard et al., 2017). The edge of the Farallon slab at 70 Ma and 90 Ma is shaded in black and blue colors, respectively (Spasojevic et al., 2009). The Labrador hotspot track from Heaman et al. (2004) is indicated by the red line, and the red circles mark the approximate ages at 10 m.y. intervals. (B) Geological map of the northern Alberta kimberlite province, which consists of three discrete kimberlite groups including Mountain Lake (ML), Buffalo Head Hills (BHH), and Birch Mountains (BM) (modified after Eccles, 2011).

According to Eccles et al. (2004), the three major crustal domains were intruded respectively by the Mountain Lake (ML), Buffalo Head Hills (BHH), and Birch Mountains (BM) kimberlites between 90 and 60 Ma. The spatial distribution of these kimberlite clusters forms a northeast-trending corridor that extends over 300 km, roughly overlapping with the Devonian Peace River Arch (Fig. 1B). The composition and evolutionary history of the subcontinental lithospheric mantle traversed by the kimberlites are mainly inferred from the entrained mantle xenoliths and xenocrysts (Aulbach et al., 2004; Eccles et al., 2004) as well as from diamond inclusions (Davies et al., 2004; Banas et al., 2007).

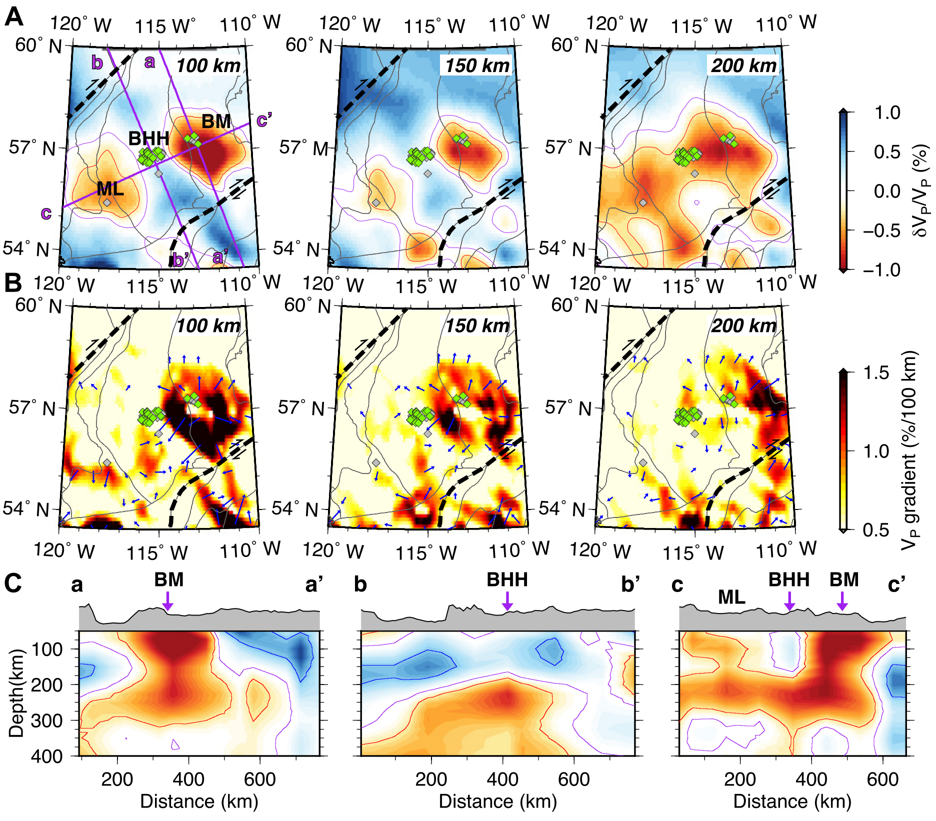

Figure 2. Seismic structures of the northern Alberta kimberlite province (Canada) showing (A) P-wave velocities, (B) gradient values at 100–200 km depths, and (C) cross-sectional view of P-wave velocities underlying kimberlite fields. Profile locations are marked by purple lines at 100 km depth. Blue arrows in B indicate directions of the largest velocity gradients, and purple arrows in C indicate locations of kimberlite groups along the profiles. Kimberlite fields: ML—Mountain Lake, BHH—Buffalo Head Hills, and BM—Birch Mountains.

SEISMIC VELOCITY STRUCTURES IN NORTHERN ALBERTA

We used finite-frequency traveltime tomography (Hung et al., 2011) to constrain the velocity structures of the upper mantle beneath northern Alberta (Section S1 in the Supplemental Material[1]). Benefiting from improved regional data coverage (Fig. 1B), our model offers new seismic constraints on this poorly sampled region. The most notable features are two low-velocity zones residing beneath the Proterozoic terranes: a stronger (−1.5%) anomaly near the boundary of the BHT and TMZ, and a less significant (−1%) anomaly located ~300 km to the southwest (Fig. 2A). Both anomalies exhibit a semicircular shape and extend subvertically to a depth of ~300 km, where they are connected by a horizontal northeast-southwest–trending low-velocity channel (Fig. 2C). The vertical scales of these anomalies are exaggerated by ~50 km due to the vertical smearing effects of body waves based on synthetic tests (e.g., Chen et al., 2018), where the robustness of the lateral velocity variations is evidenced by minimal horizontal smearing (Section S2). The BHH and BM kimberlites are located on each side of the highest (>1.5% per 100 km) velocity gradient at lithospheric depths (Fig. 2B). The reduced velocities near the BHT have been corroborated by a recent continental-scale tomographic model (Yuan et al., 2014).

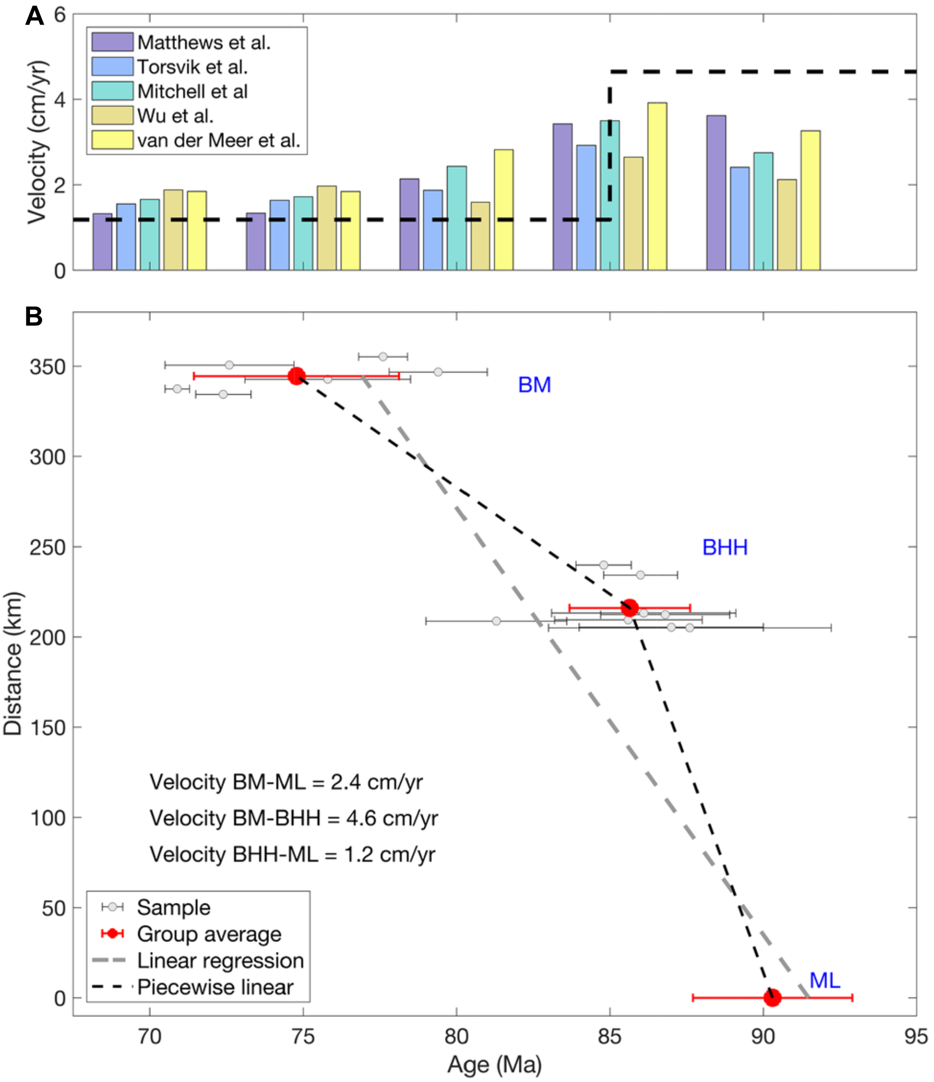

Figure 3. (A) Rates of plate motion in northern Alberta, Canada, obtained from five recent global reconstruction models (Van Der Meer et al., 2010; Mitchell et al., 2012; Torsvik et al., 2012; Matthews et al., 2016; Wu et al., 2017). Dashed line marks lateral migration rates of kimberlite magmatism estimated from spatiotemporal patterns of kimberlites. (B) Spatiotemporal distribution of northern Alberta kimberlites (ML—Mountain Lake, BHH—Buffalo Head Hills, and BM—Birch Mountains). Emplacement ages (horizontal axis) of kimberlite samples are summarized in Table S1 (see footnote 1), and their locations (vertical axis) are defined by the distance of each kimberlite intrusion relative to the Mountain Lake intrusion. Error bar for each kimberlite sample indicates 2σ uncertainty in age measurement. Red circles indicate mean values for kimberlite groups with the standard deviation shown by the red-colored error bar. Gray dashed line shows the weighted linear regression for all data points, and black dashed lines indicate the regression results for only nearby kimberlite groups.

SPATIOTEMPORAL DISTRIBUTION OF KIMBERLITES

A summary of the reported ages for northern Alberta kimberlites is presented in Table S1, together with a new perovskite U-Pb age of 90.3 ± 2.6 Ma obtained from the Mountain Lake South intrusion (Section S4). For further analysis, we only adopted high-precision measurements with uncertainty of <5 m.y. The average emplacement ages are 90, 85, and 75 Ma for the ML, BHH, and BM kimberlite groups, respectively, showing a general eastward younging trend (Fig. 3). The average migration speed for kimberlite magmatism is 2.4 cm/yr based on a linear-regression analysis, although the data from the BHH group exhibits significant deviations from the general trend. An improved data fit is achieved with a piecewise linear function, showing approximate velocities of 1.2 and 4.6 cm/yr for the BM-BHH and BHH-ML segments, respectively (Fig. 3). Assuming a single magma source for the three kimberlite clusters (i.e., a tectonic event lasting ~20 m.y.), this migration reflects the rate of relative motion between the source and the overlying North American plate. The variation in the migration speed generally correlates with the change in the absolute plate motion rate of northern Alberta (reference point: 57°N, 115°E) according to five global reconstruction models (Van der Meer et al., 2010; Mitchell et al., 2012; Torsvik et al., 2012; Matthews et al., 2016; Wu et al., 2017; see Section S3). The consistency between the migration rates of kimberlite intrusions and plate motion suggests a relatively fixed source region (relative to the lower mantle) for the kimberlite magmatism.

IMPLICATIONS FOR THE ORIGIN OF KIMBERLITES

The spatiotemporal affinity of the Cretaceous northern Alberta kimberlites to the mid-Cretaceous kimberlite corridor in western North America (see Fig. 1B) may suggest a common origin. Recently, two models centered on edge-driven convection (Kjarsgaard et al., 2017) and tensile stress (Zhang et al., 2019) have been invoked to explain the mid-Cretaceous kimberlite corridor (Fig. 1B). The former model attributes the eruption of kimberlite magma to mantle upwelling induced by a (secondary) convective cell located 200–300 km

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[1] Supplemental Material. Summary of northern Alberta kimberlite emplacement ages. Please visit https://doi.org/10.1130/GEOL.S.12298556 to access the supplemental material, and contact editing@geosociety.org with any questions.

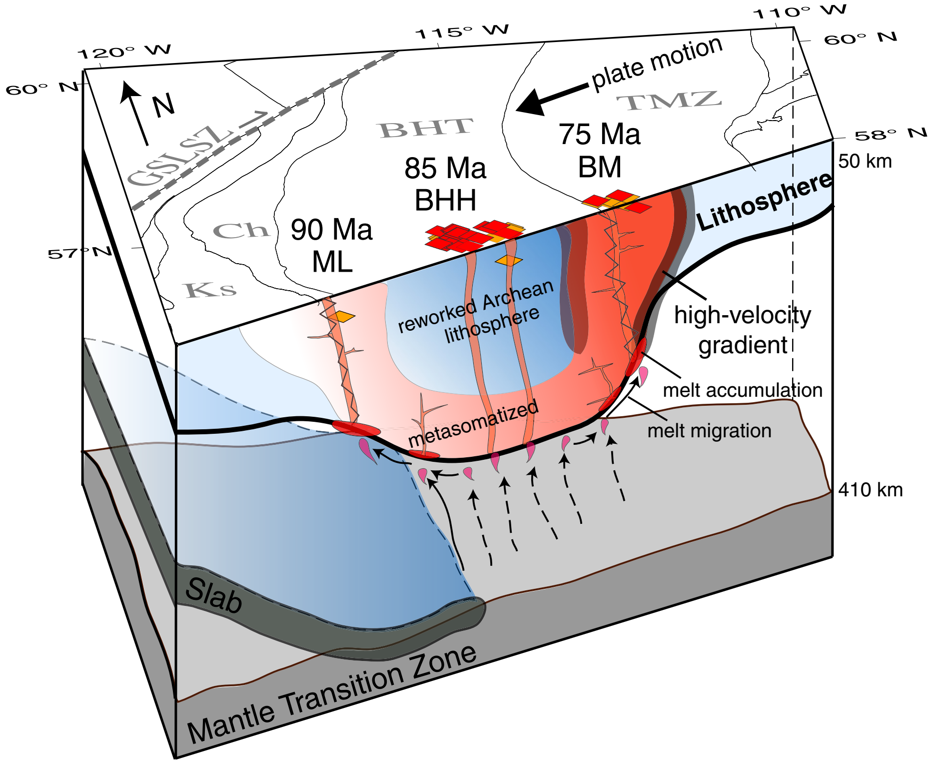

Figure 4. A schematic drawing illustrating potential mechanism(s) for kimberlite magmatism in northern Alberta, Canada. The slab was subducted beneath northern Alberta during 90–70 Ma and reached the mantle transition zone, where magma was transferred to the surface through lithospheric weak zones. The relatively stationary position of the steep slab and the overlying drifting North American plate caused the spatiotemporal distribution of kimberlite magmatism (dashed arrows). See Figure 1 for acronyms.

away from the attenuated lithospheric edge. The latter interpretation attributes the upward transport of melts to tensile flexure at the bottom of continental lithosphere that occurred 600–700 km inboard from a trench. However, the kimberlites in northern Alberta are located ~500 km away from the suggested craton margin (Schaeffer and Lebedev, 2014), a distance that is too short to induce tensile flexure and too large to initiate the convective cell. Furthermore, these models infer that the kimberlite magma intruded at relatively fixed distances from the continental margin, where a convective cell (Kjarsgaard et al., 2017) or tensile flexure (Zhang et al., 2019) would reside. The locations suggested by these models are inconsistent with the spatial patterns of the observations in northern Alberta where the kimberlite magmatism appears to migrate away from the craton margin. Thus, we favor an external triggering mechanism that involved a stationary subcontinental source acting upon the westward-drifting North American continent.

Plumes and slabs are two geological features that can retain a relatively fixed position in the asthenosphere (e.g., Torsvik et al., 2010; Sigloch and Mihalynuk, 2013). On the global scale, most Phanerozoic kimberlites have been linked to deep mantle plumes (Torsvik et al., 2010). Regionally, the Cretaceous diamondiferous kimberlites near the Trans-Hudson orogen in Saskatchewan (Fig. 1B) have been linked to Cretaceous plume activity (Bank et al., 1998). The plume hypothesis is further evidenced from the reported trajectory of the Labrador hotspot, showing that a plume resided beneath northern Alberta at ca. 110 Ma (Heaman et al., 2004). Considering the westward-drifting North America, this could have caused the apparent northeast migration of the kimberlite magmatism (Fig. 1B). Davies et al. (2004) suggested a potential plume environment for diamond growth based on an analysis of inclusion minerals, which further strengthens the tectonic impact of a plume. One pitfall of this model is that the emplacement age of kimberlites (90–70 Ma) is at least 20 m.y. younger than the initiation of the plume event (ca. 110 Ma; Fig. 1A), though uncertainties in both kimberlite age and plume track location may partially account for this inconsistency.

We propose an alternative interpretation that involves a steeply subducted slab impinging on the mantle transition zone to explain the kimberlite magmatic events (Fig. 4). A candidate slab is the eastward-subducted Farallon plate (Currie and Beaumont, 2011), the northern edge of which traversed northern Alberta while entering the mantle transition zone (400–600 km) during the period of kimberlite magmatism (90–70 Ma; Fig. 1A; Liu et al., 2008; Spasojevic et al., 2009). Alternatively, the westward subduction of the Angayucham (ANG) slab, owing to a fixed trench position, produced a vertical slab wall that remained stationary (laterally) relative to the lower mantle. The ANG slab sank through the mantle transition zone and was overridden by western Canada in the Late Cretaceous (Sigloch and Mihalynuk, 2013), coinciding with the kimberlite events. In either case, the slab edge retained a relatively fixed position in the mantle transition zone, such that the migration trend of kimberlites was largely controlled by the movement of the overlying continent.

In the slab hypothesis, the magma may have been generated through water-fluxed decompression melting of mantle transition zone minerals (Kjarsgaard et al., 2017). The cold thermal regime of the subducting slab could have cooled and thickened the mantle transition zone. The subsequent thermal equilibrium (i.e., temperature increase) process would lower the H_2O solubility in the hydrous compositions (ringwoodite or wadsleyite phases), triggering the water release and melting of the overlying mantle (Kjarsgaard et al., 2017). A sublithospheric origin for the northern Alberta kimberlites is also evidenced by the mineral inclusions in the diamonds (Davies et al., 2004). These melts were transported upward from the source region atop the mantle transition zone through subduction-induced return flow (mantle upwelling; Piromallo et al., 2006; Schmandt et al., 2012), thereby causing metasomatic enrichment of the adjacent mantle (lithosphere) and reduction in seismic velocity (Fig. 4; O'Reilly and Griffin, 2013). We further conjecture that the melt transfer to the surface was controlled by the intrinsic lithospheric structures, as the shape of the three-dimensional craton tends to focus the kimberlite melts and their migration toward the thinner parts of the lithosphere (Griffin et al., 2013). In northern Alberta, mantle xenolith inclusions suggest a deep (180 km) lithospheric root beneath the BHT (Aulbach et al., 2004), which is corroborated by seismic observations of a thicker BHH lithosphere than that of adjacent domains (Bao and Eaton, 2015). For these reasons, we conclude that melt was likely channeled away from the deep craton (BHH) toward the relatively thin mantle lithosphere beneath the ML and BM groups. In both regions, the eruptions of kimberlites were likely facilitated by the presence of domain boundaries where the lithosphere could have been weakened by faulting and metasomatic modifications prior to kimberlite magmatism (Aulbach et al., 2004). These lithospheric weak zones would have provided effective pathways for the eruption of kimberlite melts (Griffin et al., 2013).

SUMMARY

We report the results of an integrated seismic and geochronological study to explain the Late Cretaceous kimberlite magmatism in northern Alberta. The proposed model involves the steep subduction of an oceanic plate, in which kimberlite magma generation was facilitated by water released near the mantle transition zone and brought upward by subduction-induced return flow. An alternative model invokes a plume, but the delayed (by 20 m.y.) response of kimberlite eruption to plume activity requires further reconciliation. The kimberlite melts likely migrated toward the thinner lithosphere and erupted through lithospheric weak zones near the domain boundaries. In summary, our study reconciles seismic structures with the kimberlite magmatism in northern Alberta and sheds new light on the origin of kimberlites in the Late Cretaceous.

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REFERENCES CITED

Aulbach, S., Griffin, W.L., O'Reilly, S.Y., and McCandless, T.E., 2004, Genesis and evolution of the lithospheric mantle beneath the Buffalo Head terrane, Alberta (Canada): Lithos, v. 77, p. 413–451, https://doi.org/10.1016/j.lithos.2004.04.020.

Banas, A., Stachel, T., Muehlenbachs, K., and McCandless, T.E., 2007, Diamonds from the Buffalo Head Hills, Alberta: Formation in a non-conventional setting: Lithos, v. 93, p. 199–213, https://doi.org/10.1016/j.lithos.2006.07.001.

Bank, C.G., Bostock, M., Ellis, R., Hajnal, Z., and VanDecar, J., 1998, Lithospheric mantle structure beneath the Trans-Hudson orogen and the origin of diamondiferous kimberlites: Journal of Geophysical Research, v. 103, B5, p. 10103–10114, https://doi.org/10.1029/97JB03746.

Bao, X., and Eaton, D.W., 2015, Large variations in lithospheric thickness of western Laurentia: Tectonic inheritance or collisional reworking?: Precambrian Research, v. 266, p. 579–586, https://doi.org/10.1016/j.precamres.2015.05.010.

Chen, Y., Gu, Y.J., and Hung, S.H., 2018, A new appraisal of lithospheric structures of the Cordillera-Craton Boundary Region in Western Canada: Tectonics, v. 37, p. 3207–3228, https://doi.org/10.1029/2018TC004956.

Currie, C.A., and Beaumont, C., 2011, Are diamond-bearing Cretaceous kimberlites related to low-angle subduction beneath western North America?: Earth and Planetary Science Letters, v. 303, p. 59–70, https://doi.org/10.1016/j.epsl.2010.12.036.

Davies, R.M., Griffin, W.L., O'Reilly, S.Y., and McCandless, T.E., 2004, Inclusions in diamonds from the K14 and K10 kimberlites, Buffalo Hills, Alberta, Canada: Diamond growth in a plume?: Lithos, v. 77, p. 99–111, https://doi.org/10.1016/j.lithos.2004.04.008.

Eaton, D.W., and Frederiksen, A., 2007, Seismic evidence for convection-driven motion of the North American plate: Nature, v. 446, p. 428–431, https://doi.org/10.1038/nature05675.

Eccles, D.R., 2011, Northern Alberta Kimberlite Province: The First 20 Years: Edmonton, Canada, Energy Resources Conservation Board, ERCB/AGS Bulletin 65, 116 p.

Eccles, D.R., Heaman, L.M., Luth, R.W., and Creaser, R.A., 2004, Petrogenesis of the Late Cretaceous northern Alberta kimberlite province: Lithos, v. 76, p. 435–459, https://doi.org/10.1016/j.lithos.2004.03.046.

Griffin, W.L., O'Reilly, S.Y., Afonso, J.C., and Begg, G.C., 2008, The composition and evolution of lithospheric mantle: A re-evaluation and its tectonic implications: Journal of Petrology, v. 50, p. 1185–1204, https://doi.org/10.1093/petrology/egn033.

Griffin, W.L., Begg, G.C., and O'Reilly, S.Y., 2013, Continental-root control on the genesis of magmatic ore deposits: Nature Geoscience, v. 6, p. 905–910, https://doi.org/10.1038/ngeo1954.

Heaman, L.M., and Kjarsgaard, B.A., 2000, Timing of eastern North American kimberlite magmatism: Continental extension of the Great Meteor hotspot track?: Earth and Planetary Science Letters, v. 178, p. 253–268, https://doi.org/10.1016/S0012-821X(00)00079-0.

Heaman, L.M., Kjarsgaard, B.A., and Creaser, R.A., 2004, The temporal evolution of North American kimberlites: Lithos, v. 76, p. 377–397, https://doi.org/10.1016/j.lithos.2004.03.047.

Hoffman, P.F., 1988, United Plates of America, The birth of a craton: Early Proterozoic assembly and growth of Laurentia: Annual Review of Earth and Planetary Sciences, v. 16, p. 543–603, https://doi.org/10.1146/annurev.ea.16.050188.002551.

Hung, S.-H., Chen, W.-P., and Chiao, L.-Y., 2011, A data-adaptive, multiscale approach of finite-frequency, traveltime tomography with special reference to P and S wave data from central Tibet: Journal of Geophysical Research: Solid Earth, v. 116, B06307, https://doi.org/10.1029/2010JB008190.

Kjarsgaard, B.A., Heaman, L.M., Sarkar, C., and Pearson, D.G., 2017, The North America mid-Cretaceous kimberlite corridor: Wet, edge-driven decompression melting of an OIB-type deep mantle source: Geochemistry Geophysics Geosystems, v. 18, p. 2727–2747, https://doi.org/10.1002/2016GC006761.

Liu, L., Spasojević, S., and Gurnis, M., 2008, Reconstructing Farallon plate subduction beneath North America back to the Late Cretaceous: Science, v. 322, p. 934–938, https://doi.org/10.1126/science.1162921.

Matthews, K.J., Maloney, K.T., Zahirovic, S., Williams, S.E., Seton, M., and Müller, R.D., 2016, Global plate boundary evolution and kinematics since the late Paleozoic: Global and Planetary Change, v. 146, p. 226–250, https://doi.org/10.1016/j.gloplacha.2016.10.002.

McCandless, T.E., 1999, Kimberlites: Mantle expressions of deep-seated subduction, *in* Gurney, J.J., Gurney, J.L., Pascoe, M.D., and Richardson, S.H., eds., Proceedings of the 7th International Kimberlite Conference, Volume 2: Cape Town, South Africa, Red Roof Publishers, p. 545–549.

Mitchell, R.N., Kilian, T.M., and Evans, D.A.D., 2012, Supercontinent cycles and the calculation of absolute palaeolongitude in deep time: Nature, v. 482, p. 208–211, https://doi.org/10.1038/nature10800.

O'Reilly, S.Y., and Griffin, W.L., 2013, Mantle metasomatism, *in* Harlov, D.E., and Austrheim, H., eds., Metasomatism and the Chemical Transformation of Rock: Berlin, Springer, Lecture Notes in Earth System Sciences, p. 467–528, https://doi.org/10.1007/978-3-642-28394-9_12

Pearson, D.G., and Wittig, N., 2008, Formation of Archaean continental lithosphere and its diamonds: The root of the problem: Journal of the Geological Society [London], v. 165, p. 895–914, https://doi.org/10.1144/0016-76492008-003.

Piromallo, C., Becker, T.W., Funiciello, F., and Faccenna, C., 2006, Three-dimensional instantaneous mantle flow induced by subduction: Geophysical Research Letters, v. 33, L08304, https://doi.org/10.1029/2005GL025390.

Ross, G.M., and Eaton, D.W., 2002, Proterozoic tectonic accretion and growth of western Laurentia: Results from Lithoprobe studies in northern Alberta: Canadian Journal of Earth Sciences, v. 39, p. 313–329, https://doi.org/10.1139/e01-081.

Ross, G.M., Parrish, R.R., Villeneuve, M.E., and Bowring, S.A., 1991, Geophysics and geochronology of the crystalline basement of the Alberta Basin, western Canada: Canadian Journal of Earth Sciences, v. 28, p. 512–522, https://doi.org/10.1139/e91-045.

Schaeffer, A.J., and Lebedev, S., 2014, Imaging the North American continent using waveform inversion of global and USArray data: Earth and Planetary Science Letters, v. 402, p. 26–41, https://doi.org/10.1016/j.epsl.2014.05.014.

Schmandt, B., Dueker, K., Humphreys, E., and Hansen, S., 2012, Hot mantle upwelling across the 660 beneath Yellowstone: Earth and Planetary Science Letters, v. 331–332, p. 224–236, https://doi.org/10.1016/j.epsl.2012.03.025.

Sigloch, K., and Mihalynuk, M.G., 2013, Intra-oceanic subduction shaped the assembly of Cordilleran North America: Nature, v. 496, p. 50–56, https://doi.org/10.1038/nature12019.

Spasojevic, S., Liu, L., and Gurnis, M., 2009, Adjoint models of mantle convection with seismic, plate motion, and stratigraphic constraints: North America since the Late Cretaceous: Geochemistry Geophysics Geosystems, v. 10, Q05W02, https://doi.org/10.1029/2008GC002345.

Torsvik, T.H., Burke, K., Steinberger, B., Webb, S.J., and Ashwal, L.D., 2010, Diamonds sampled by plumes from the core-mantle boundary: Nature, v. 466, p. 352–355, https://doi.org/10.1038/nature09216.

Torsvik, T.H., et al., 2012, Phanerozoic polar wander: Palaeogeography and dynamics: Earth-Science Reviews, v. 114, p. 325–368, https://doi.org/10.1016/j.earscirev.2012.06.007.

Van der Meer, D.G., Spakman, W., Van Hinsbergen, D.J.J., Amaru, M.L., and Torsvik, T.H., 2010, Towards absolute plate motions constrained by lower-mantle slab remnants: Nature Geoscience, v. 3, p. 36, https://doi.org/10.1038/ngeo708.

Wu, L., Kravchinsky, V.A., Gu, Y.J., and Potter, D.K., 2017, Absolute reconstruction of the closing of the Mongol-Okhotsk Ocean in the Mesozoic elucidates the genesis of the slab geometry underneath Eurasia: Journal of Geophysical Research: Solid Earth, v. 122, p. 4831–4851, https://doi.org/10.1002/2017JB014261.

Yuan, H., French, S., Cupillard, P., and Romanowicz, B., 2014, Lithospheric expression of geological units in central and eastern North America from full waveform tomography: Earth and Planetary Science Letters, v. 402, p. 176–186, https://doi.org/10.1016/j.epsl.2013.11.057.

Zhang, W., Johnston, S.T., and Currie, C.A., 2019, Kimberlite magmatism induced by west-dipping subduction of the North American plate: Geology, v. 47, p. 395–398, https://doi.org/10.1130/G45813.1.

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