Probing the Diamond potential of the North American Lithosphere using seismic tomography

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Introduction

The North American continent records a protracted and complex tectonic history chronicling the assembly, alteration, rifting, and re-amalgamation (e.g., Whitmeyer & Karlstrom, 2007). Today, this history is recorded in the central core of the North American continent, the North American Shield. This relatively stable body is made up Archean and Paleo-Proterozoic cratonic nuclei, in addition to ancient orogenic belts and has remained relatively intact for the last 1Ga (Whitmeyer & Karlstrom, 2007; Eaton et al, 2009). At its western boundary is the North American Cordillera, a thousands kilometers long orogenic belt hosting numerous accreted terranes stitched to the western margin, and home to most of the present-day tectonic deformation. The North American shield, and its boundaries, hosts much of Canada's significant mineral and metal deposits, including ultramafic intrusions and pipes, which in many cases contain world-class diamond deposits.

Kimberlite magmas are volatile-rich, ultrabasic magmas that ascend rapidly from the Earth's mantle to the surface, often carrying diamonds and other mantle-derived xenoliths (e.g., Mitchell, 2013). In North America, the predominance of these ultramafic deposits are found within the Canadian Shield, with the majority of such pipes located in the Slave Craton and Superior Craton (Heaman et al, 2003). Studies have shown that kimberlite magmas ascend through the lithosphere via a network of faults and fractures, often utilizing pre-existing zones of weakness in the crust (Russell et al, 2019). The location of kimberlite pipes on the surface provides valuable constraints on the deep-seated conditions in the deep lithosphere and sub-lithospheric mantle, in the zone of stability where diamonds form and remain in-situ. Diamondiferous kimberlites at the surface imply that they traversed through a region where the lithospheric thickness was more than 150 km (required for diamond stability). Similarly, non-diamondiferous kimberlites would suggest that absence of diamond stability along the path of ascent, therefore implying that either the lithosphere was not thick enough, or transit time through the lithospheric mantle was slow enough that diamonds resolved back into the melt.

Seismic tomography provides a snapshot of the present-day lithospheric architecture through the mapping of seismic velocities as a function of spatial position and depth. This can be interpreted as a proxy for mantle properties (i.e, Schaeffer & Lebedev, 2014, Faure et al 2011), or converted into properties such as mantle temperature and composition (e.g., Dave et al, 2024). While we often infer the cratonic mantle lithosphere to be a strong and constant high-strength body, there is plenty of evidence detailing the many cases where it is deformed, altered, entirely removed, and even regenerated (Liu et al 2021; Pearson et al, 2021; Smit et al, 2014).

Studies have shown that kimberlite magmas are more likely to be diamond-bearing in areas where the lithosphere has been thickened and stabilized over time, such as in cratonic regions (Shirey et al, 2013). In this work we construct a model of the lithospheric architecture by extracting a thermally based lithosphere-asthenosphere boundary and use this model to evaluate the location of known kimberlite deposits. We then

perform several quantitative statistical tests to demonstrate that diamondiferous kimberlites are not randomly located with respect to lithospheric structure and preferentially sample regions surrounding continental keels, where the LAB depth ranges between 150 and 220 km. We further show that these results are robust to potential sampling bias that might be caused by difficulties in finding kimberlite pipes from surface observations. While this has often been assumed in the discussion of their locations, this is, to the best of our knowledge, the first time this has been statistically tested using models of lithospheric architecture.

Seismic Tomography and the LAB

We utilze the shear-wave velocity model SL2013NA of the North American continent to examine the lithospheric architecture of North America. This model was constructed using all available data (at the time) within the North American continent, and was inverted for the vertically polarized shear velocity structure and azumithal anisotropy. We use the isotropic VSv component to estimate a thermally-controlled depth to the lithosphere-asthenosphere boundary, following the method of Steinberger and Becker (2018). In Figure 1 we illustrate the structure of the North American continent in (a) Vsv, (b) LAB depth, and (c) the lateral gradient in LAB depth. We include the location of known kimberlite pipes from the CONSOREM databse for interpretation.
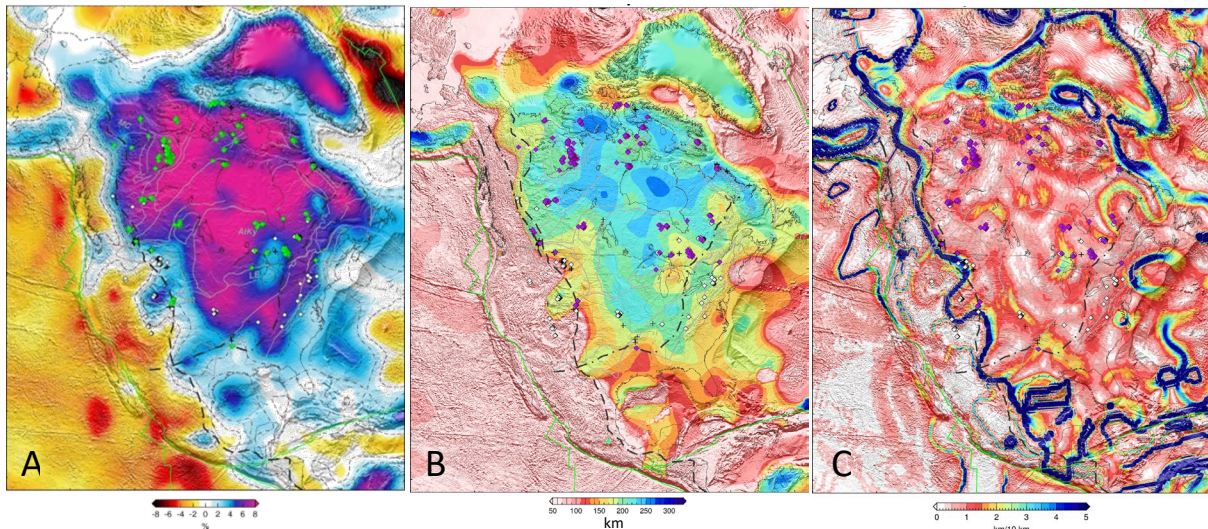
Figure 1: (A) Shear velocity structure of SL2013NA at 150 km depth. (B) LAB depth extracted from SL2013NA. (C) lateral velocity gradient in kms of vertical change per 100 km lateral change. Diamondiferous Kimberlites from the CONSOREM database plotted in green (A) and purple (B and C).

We observe in Figure 1 a spatial correlation between the location of known ultramafic kimberlites with morphology of the LAB (B&C), as well as the shear velocity structure at 150 km depth (A). Kimberlites appear where lithosphere is characterized by positive wave speed anomalies and LAB depths ranging between 150 to 220 km, in agreement with past studies (e.g., Shirey et al 2002; Faure et al 2011; Liu et al 2021). There are a few exceptions near the mid-continent rift as well as in the deformed cordilleran belt in the United States and Canada. Interestingly, we observe that kimberlites appear to avoid the thickets parts of the continent, where depths are >220 km. Finally, the locations do not appear to be correlated with regions of high or low later gradients in LAB depth.

Statistical Tests

We test the hypothesis that lithosphere structure influences the location of ultramafic magmatic eruptions through comparison of the density distribution of LAB depths (outside the Cordillera) to the density distribution of LAB depths around kimberlite deposits. We accomplish this by re-sampling LAB depths onto a spherically tessellated grid to obtain its density distribution. We then bin the kimberlite locations

onto this same grid and extract the density distribution of LAB depth for the bins that contain one or more kimberlite deposits (to minimize sampling bias) and plot both density distributions as histograms, as well as their respective cumulative distribution. We perform this operation for LAB depth and lateral gradient in LAB depth and Sediment thickness, and separately for diamondiferous kimberlites, non-diamondiferous kimberlites, those of unknown sources, and for all kimberlites combined. We use three statistical tests to examine differences in the means, standard deviations, and overall distributions using a student t-test, a chi-square test, and a Kolmogorov-Smirnov test, respectively.

Our results indicate that the null hypothesis applied to LAB depth and diamondiferous kimberlites can be rejected at the 99.9% confidence level for all three tests, implying that those kimberlites are not randomly sampling LAB depths and occur preferentially where the LAB depth is between 150 and 220 km depth. This test is not so conclusive for the other kimberlite sources, revealing that ultramafic eruptions do not systematically occur at a specific lithosphere thickness value, unlike those that carry diamonds. Conversely, we cannot reject the hypothesis that diamondiferous kimberlites randomly sample lateral gradients in LAB depth, preventing us from discussing possible links with heterogeneity in the lateral variations in LAB depth.

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