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Developing thermochemical models of Canada's lithosphere

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Introduction

The continental lithosphere of Canada holds a rich tectonic history and displays a collage of Archean cratonic blocks interconnected by Proterozoic collisional orogens and distinctive shear zones that have shaped the region over the past 4 billion years. Obtaining reliable estimates of its interior physical state (e.g., thermochemical structure, stress and strain distributions), particularly at lithospheric scale, is especially critical for supporting and resourcing the energy transition and related green technologies. We utilize a novel, thermodynamically-consistent, whole-lithosphere modelling approach called Multi-observable Thermochemical Tomography (MTT), which jointly inverts multiple geophysical data sets with complementary sensitivities to image the physical state of the lithosphere and assess the full range of uncertainties (Afonso et al., 2013a, 2013b, 2016). We analyse the output models from Superior province and Slave province, both with billions of years of geological history preserved in their rocks and a wealth of mineral resources, allowing us to investigate continental evolution and lithospheric thermochemical structure.

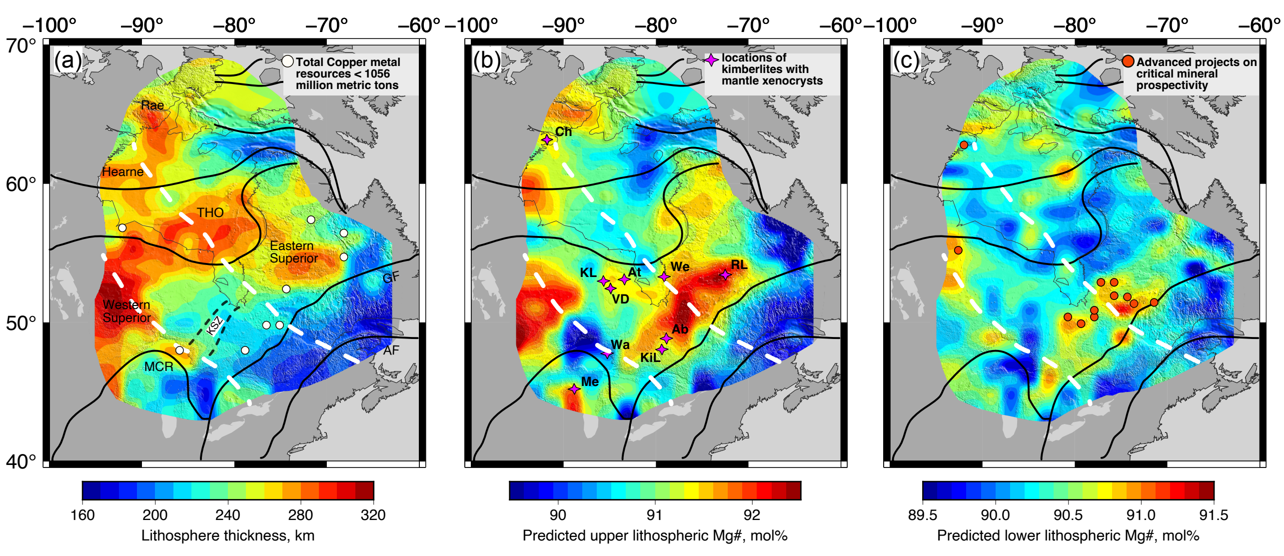

Fig.1: (a) Lithosphere thickness map of Superior province. (b), (c) Predicted Mg# of olivines of the upper and the lower lithospheric mantle beneath Superior province. White dashed lines mark the limits of the Great Meteor Hotspot related volcanism. Abbreviations: THO – Trans-Hudson Orogen, MCR – Mid-Continent Rift, AF – Appalachian Front, GF – Grenville Front, KSZ – Kapuskasing Structural Zone, VD – Victor and Delta areas, We – Wemindji, Me – Menominee, RL – Renard and Lynx, Wa – Wawa, Ch – Churchill, KL – Kyle Lake, Ab – Abitibi, At – Attawapiskat, KiL – Kirkland Lake.

Superior Province

The location of the Grenville front correlates with a transition boundary of steep gradient dividing regions of thick, depleted lithosphere beneath eastern Superior from thin and fertile domains beneath the Grenville indicating a transition in lithospheric identifiable units of different nature (Fig. 1). The regions of relatively thick and highly depleted lithosphere (240 km < LAB < 300 km; Mg# > 92-93) i.e., most of western Superior, the eastern Superior and the Hudson Bay, are also associated with the highest degrees of depletion in the shallower portions of the lithospheric mantle and fertile compositions in the lower lithosphere suggesting a distinct vertical stratification of the lithospheric mantle. Western Superior is separated from eastern Superior by a region of notably shallower LAB which correlates with the reconstructed track of the Great Meteor hotspot, including the location of Mesozoic kimberlite fields (Fig. 1). It also roughly correlates with regions of lower Mg# compared to the general cratonic/depleted nature of the rest of the Superior craton. The peridotitic xenoliths recovered from the Attawapiskat and Kyle Lake cluster reported olivines with an average Mg# of 91.9 (Smit et al., 2014) which matches our values. Olivine inclusions found in diamonds from the Victor mine have an average Mg# of ~ 91.3 at depth 157-167 km (Stachel et al., 2018) which are in perfect agreement with our estimates of olivine Mg# at those depths (Fig. 1). The Kirkland Lake field erupted mantle xenoliths around 150-160 Ma ago, with reported olivine Mg# of 91-94 (e.g., Griffin, et al., 2004; Lawley et al., 2018) with a clear vertical stratification (more depleted towards shallower depths) and average values around 92.4 agreeing with our observations. These distinct compositional domains seem to be reflecting deeper tectonic structures or domains and the magmatism associated with the hotspot primarily exploited zones of weaknesses arising from Precambrian rifts rather than affecting pristine cratonic lithosphere. The SW-NE trending Kapuskasing structural zone serves as a separation zone between the western and eastern blocks of the Superior province in terms of mantle composition (Fig. 1). The upper lithosphere compositional model shows approximate locations of the boundaries associated with the Trans-Hudson Orogen separating the highly depleted Hearne-Rae and Superior domains though significant portions of these domains extend well into the Hudson Bay. The Mid-Continent Rift exhibits clear evidence of large asthenospheric melts produced during active rifting, which percolated and reacted with the overlying lithospheric mantle imparting the fertile signature.

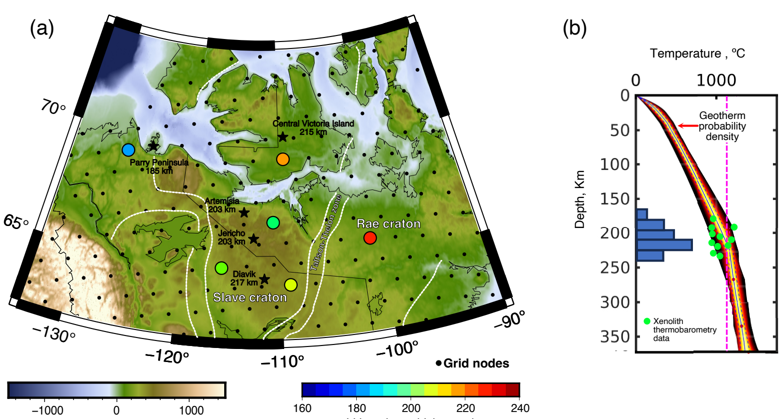

Fig.2: (a) Map of Slave craton and surrounding regions. Black stars show the locations of the kimberlite pipes and peridotite xenoliths with the lithospheric thickness determined by palaeogeotherms at the time of kimberlite eruption (Liu et al., 2021). White lines denote the boundaries of the Archaean and Palaeoproterozoic tectonic domains. Colored circles estimate the predicted lithospheric thickness from 1-D inversion for select grid nodes (b) Average posterior probability distribution for the present day geotherms beneath Slave province along with P-T estimates from xenolith data (Liu et al., 2021). Blue histogram denotes average posterior Probability Density Functions (PDF) for LAB depth for Slave province.

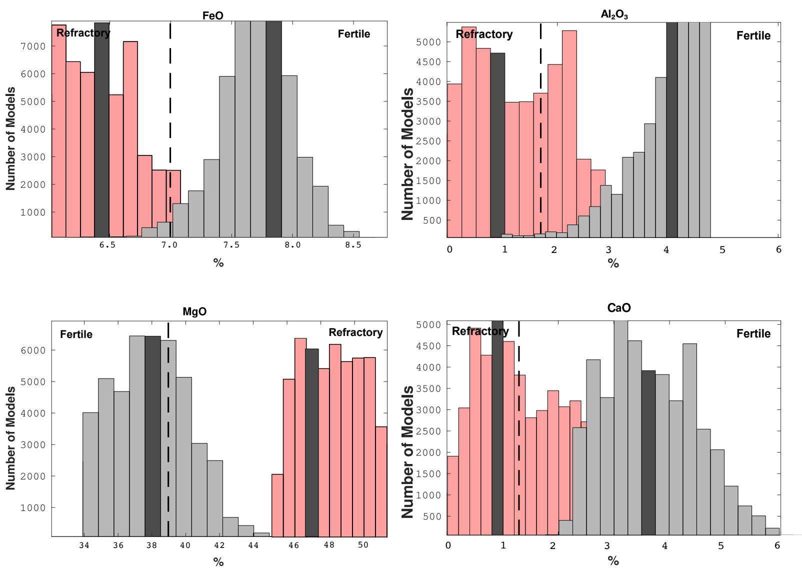

Fig.3: Average posterior PDFs for bulk compositions (FeO, Al_2O_3, MgO, CaO) beneath Slave province. Pink histogram denotes posterior PDFs for upper lithosphere, grey histogram denotes posterior PDFs for lower lithosphere.

Slave Province

The predicted lithospheric thickness for various locations within the Slave province agrees well with the lithospheric thicknesses determined by palaeogeotherms from kimberlitic data (Fig. 2a).

Average posterior PDFs for bulk compositions for four main oxides indicates marked vertical chemical stratification beneath the region (Fig. 3). Upper lithosphere shows as depleted and refractory, while lower lithosphere is associated with fertile compositional signatures. The gradual increase in fertility with depth below the Slave province points to age stratification and younging with depth.

This may have occurred due to incremental addition of mantle lithosphere with time and/or heating by magma emplacement at great depth and metasomatism (Kopylova et al., 2000, Heaman et al., 2010).

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