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Seismic Thermography of Continental Lithosphere: Structure, Evolution, and Controls on the Distribution of Kimberlites and Other Mineral Deposits

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Introduction

The structure, thickness, lateral heterogeneity and temporal evolution of the lithosphere control the distribution of kimberlites, carbonatites and sediment-hosted mineral deposits (e.g., Boyd et al. 1985; Hoggard et al. 2020; Gibson et al. 2024). Seismic data are our primary source of information on the thermal structure of the lithosphere and underlying mantle at the present day. Igneous petrology and geochemistry offer evidence on the structure and dynamic processes at the time of magmatism. Joint analysis of these multi-disciplinary lines of evidence offers insights into the evolution of continental lithosphere over its long history (Celli et al. 2020; Liu et al. 2021; Pearson et al. 2021; Gibson & McKenzie 2023; Gibson et al. 2024).

Seismic imaging of the lithosphere: Resolving power and outstanding problems

Seismic tomography maps seismic-velocity variations in the mantle. These variations depend primarily on temperature variations. Temperatures are, thus, often inferred from tomography. Tomographic models, however, are non-unique solutions of inverse problems. Tomographers use inversion regularisation to reduce the non-uniqueness, but that typically encourages smooth seismic wavespeed variations, not plausible temperature distributions.

Surface-wave data are our richest source of information on the temperature and thickness of the lithosphere. Surface-wave and waveform tomography can constrain tightly the shear-wave velocity averages over sufficiently broad (>100 km) depth ranges at the mantle-lithosphere depths. Because of this, tomography-based tectonic regionalizations show impressive accuracy (Schaeffer & Lebedev, 2015), and tomography can map in detail the boundaries between cratons and surrounding mobile belts (e.g., Celli et al. 2020).

By contrast, tomography cannot determine accurately vertical variations at <50 km scales in the lithosphere, with strong trade-offs between seismic velocities at neighboring depths in the models. For example, most global tomography models show an increase in seismic velocities with depth below the Moho, in particular in Precambrian lithospheres (e.g., Garber et al. 2018). For a mantle composition varying moderately with depth, this requires temperature to commonly decrease with depth below the Moho, which is implausible. The structure has thus been attributed to ubiquitous, strong compositional layering (e.g., Garber et al. 2018). It turns out, however, that this gradient is not required by the data (Fullea et al. 2021; Xu et al. 2023) (Fig. 1), and models with standard peridotite compositions can fit the data equally well or better (Davison et al. 2023). The exotic compositions inferred from the spurious gradient illustrate the disadvantages of relating seismic data to temperatures via non-unique seismic-velocity models. This problem is not solved by probabilistic inversion either: Markov-chain Monte Carlo inversions also get caught within the parts of the long misfit valleys that show the feature (e.g., Ravenna et al., 2018). Instead, the problem is solved by thermodynamic inversions of seismic data for temperature, which include prior information on plausible temperature distributions and find solutions with both the smallest data-synthetic misfits and realistic temperature profiles.

Seismic Thermography

Inversion of seismic data directly for temperature within the Earth is a key emerging branch of seismic imaging, which we term Seismic Thermography (Lebedev et al. 2024). While the general idea of inversion for temperature and composition has been around for decades, today's maturity of methods and abundance of data enable a rapid advance. Seismic thermography yields more accurate thermal models, more accurate seismic models, and a platform for effective quantitative integration of geophysical and petrological data.

Recently developed thermodynamic inversion methods use computational petrology and thermodynamic databases to invert seismic and other data for temperature and composition (e.g., Fullea et al. 2021). Because seismic-velocity sensitivity to composition is much weaker than to temperature, we can invert seismic data primarily for temperature, with reasonable assumptions on composition and other relevant properties and with additional inversion parameters such as anisotropy.

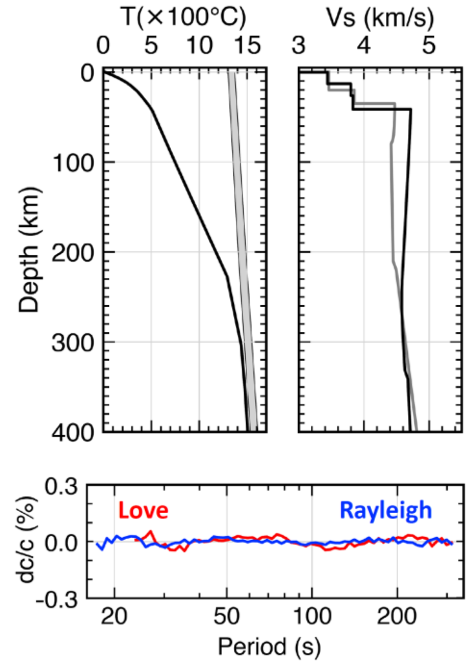

Figure 1: Average phase-velocity curves for cratons globally are matched nearly perfectly (misfits < 0.1%) by a seismic-thermography model with an equilibrium geotherm and a V_S decrease below the Moho. Gray: V_S and temperature (T) global reference profiles.

Seismic thermography can map even subtle variations in the lithospheric temperature and thickness, which turn out to have major effects on tectonics and magmatism. For example, the recently discovered variations in the lithospheric thickness in Britain and Ireland in a 80-110 km range gave a solution to a long-standing puzzle of their highly uneven distribution of intraplate earthquakes (Lebedev et al. 2023) and revealed the lithospheric thickness control on the eastern North Atlantic Igneous Province magmatism (Bonadio et al. 2024), as has also been seen elsewhere (Celli et al. 2021; Civiero et al. 2022).

Lithosphere and magmatism

Comparisons of the distributions of different types of volcanic rocks with maps of lithospheric structure and thickness derived from seismic imaging reveal systematic patterns that characterise basic causal relationships. For example, Cenozoic intraplate basalts occur exclusively on thin lithosphere—a pattern that can now be resolved consistently due to the increasing resolution of the imaging. Diamondiferous kimberlites are found primarily atop thick cratonic lithosphere, as expected (e.g., Boyd et al. 1985). Exceptions from this rule—well known and newly identified—present evidence for modification and erosion of cratonic lithosphere since kimberlite emplacement. The erosion of the thick lithosphere often follows within a few tens of m.y. after a plume impact (Celli et al. 2020) and may relate to metasomatism by volatile-rich proto-kimberlite melts (Jackson & Gibson, 2023; Heckel et al., 2023). The maps of lithospheric structure also show that Phanerozoic carbonatites tend to locate on thinner lithosphere than kimberlites and, also, often concentrate near lithospheric-thickness contrasts, which is consistent with rifting as one underlying mechanism for their origin (Gibson et al. 2024).

By combining high-resolution models of the thermal structure and thickness of the lithosphere and the temperature in the underlying mantle that are produced by seismic thermography with evidence from petrology and geochemistry, we can produce improved constraints on lithospheric dynamics and evolution and on the origin and distributions of different types of intraplate magmatism and their associated mineral deposits.

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