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Lithospheric Thickness in Northeastern Eurasia

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Abstract: We constrain lithospheric thickness across northeastern Eurasia using a new thermo-compositional model that jointly interprets seismic tomography and gravity data, including gravity gradients from the GOCE mission. This integrative approach provides a self-consistent three-dimensional thermal structure of the lithosphere that incorporates compositional variations within lithospheric keels, yielding robust thickness estimates. The results demonstrate a strong link between lithospheric thickness and tectonic evolution. Archean and Proterozoic terranes such as the Siberian Craton and the eastern Fennoscandian Shield preserve thick keels (>200 km), reflecting early stabilization through melt depletion (and the interactions with mantle plumes and rifting episodes for the Siberian Craton), while the Timan–Pechora block also retains anomalously thick lithosphere, consistent with Paleozoic orogenic reworking and stabilization. The northeastern Barents Sea displays intermediate lithosphere (160 km to 180 km), likely representing a Proterozoic–Paleozoic fragment within the Arctic basement mosaic. In contrast, the Ural Orogen forms a sharp lithospheric boundary between the East European Craton and the thermally modified West Siberian Plate, which was profoundly affected by Mesozoic rifting and plume activity. East of the Verkhoyansk Range, lithospheric thickness decreases to less than 100 km in Phanerozoic terranes such as Chukotka, the Anadyr–Koryak Fold Belt, and Kamchatka, where subduction, terrane accretion, and arc magmatism maintain a hot, dynamic lithosphere. Overall, the lithospheric structure of northern Eurasia reflects the interplay of four fundamental processes: Archean craton stabilization, Paleozoic orogenesis, Mesozoic plume–rift modification, and ongoing Pacific subduction. These processes collectively shape the strong lateral contrasts that define the geodynamic framework of Eurasia.

Keywords: Northeastern Eurasia, lithospheric thickness, thermal model.

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Introduction

The lithosphere – the rigid outer shell of the Earth encompassing the crust and the uppermost portion of the mantle – is a key structural and mechanical component of the planet. Its thickness varies from a few tens of kilometers beneath young oceanic plates to over 200 km beneath ancient continental cratons. Understanding the spatial variability and controlling factors of lithospheric thickness is essential in modern geoscience, as it directly influences a wide spectrum of geological and geophysical processes. The estimation and interpretation of lithospheric thickness have become central to disciplines such as tectonics, geodynamics, seismology, natural hazard assessment, and resource exploration.

In the field of tectonics and geodynamics, lithospheric thickness provides critical constraints on the mechanical strength of the lithosphere and the dynamics of plate interactions. Variations in lithospheric thickness affect how tectonic plates respond to stresses, how they deform during continental collision, and how they break apart during rifting. For example, the localization of extension in continental rift zones and the formation of new plate boundaries are strongly influenced by the thermal and compositional structure of the lithosphere. Furthermore, the buoyancy forces that drive plate motions and mantle convection are modulated by lithospheric thickness and density, making it a vital parameter in geodynamic modeling.

In seismology, the lithosphere-asthenosphere boundary (LAB) is a key interface that affects the propagation of seismic waves. Accurate knowledge of lithospheric thickness improves seismic imaging and helps to interpret velocity anomalies in the upper mantle. In addition, variations in lithospheric thickness can correlate with seismic anisotropy and attenuation, offering insights into past and present mantle flow patterns.

Natural hazard assessment also benefits from an understanding of lithospheric structure. The distribution and magnitude of earthquakes are influenced by lithospheric strength and rheology, which are functions of its thickness and thermal state. Thicker lithosphere generally implies a stronger and more brittle behavior, influencing the style and depth of seismicity. Similarly, volcanic activity is often linked to regions of lithospheric thinning, where upwelling mantle material can partially melt due to decompression.

In the realm of resource exploration, lithospheric thickness is a key factor in the formation and preservation of natural resources. Many mineral deposits, including diamonds, nickel, and platinum group elements, are associated with deep lithospheric roots beneath cratons. In contrast, regions of thinned lithosphere may be favorable for hydrocarbon systems, as thermal structure and subsidence history affect sedimentary basin development and maturation of organic material. Geothermal energy potential is also influenced by lithospheric thickness, which controls the heat flux from the mantle to the surface.

From a climate and surface processes perspective, lithospheric thickness indirectly affects topography and erosion patterns by controlling the isostatic response of the lithosphere to loading and unloading. For example, deglaciation is one such process. It has implications for sea-level changes, long-term landscape evolution, and sediment supply to basins.

Given these diverse applications, precise determination of lithospheric thickness is not only a fundamental geophysical problem but also a necessary input for applied studies across multiple subfields of geoscience. Advances in seismic imaging, magnetotellurics, gravity modeling, and thermomechanical simulations are continually improving our ability to map lithospheric structure at regional and global scales, thereby enhancing our understanding of Earth's dynamic system and enabling better-informed decisions in natural hazard mitigation and resource management.

Although Northeastern Asia remains one of the least studied regions in the world, there exist several studies of the lithospheric thickness based on multiple, non-equivalent observables: seismic methods (surface-wave dispersion and tomography, body-wave imaging), thermodynamic/heat-flow modeling, and mantle xenolith thermobarometry combined with geochemical analysis [e.g., *Artemieva and Mooney*, 2001; *Ashchepkov et al.*, 2013; *Koulakov and Bushenkova*, 2010; *Kuskov et al.*, 2011]. The lithosphere beneath Siberia and Northeastern Asia shows pronounced spatial variability, reflecting their distinct tectonic histories and thermal regimes. The Siberian Craton, one of the oldest and most stable continental blocks, is generally characterized by a thick, cold, and chemically depleted lithosphere, whereas the surrounding mobile belts, cratonic terranes, continental margins, and back-arc basins in Northeastern Asia have been either tectonically modified or formed due to accretional and collisional processes resulting in much thinner and hotter lithospheric roots [e.g., *Artemieva*, 2006, 2011; *Kuskov et al.*, 2011].

However, estimates of lithospheric thickness derived from different methods remain highly controversial. Thermodynamic and heat-flow modeling produces varying results depending on assumptions about crustal heat production, mantle adiabat, and thermal conductivity. While some models for the Siberian Craton suggest thicknesses up to 300 to 350 km, others infer significantly thinner lithosphere, ~180 to 220 km [e.g., *Artemieva*, 2011]. Mantle xenolith thermobarometry from kimberlites provides "ground-truth" constraints but remains spatially limited; for example, samples from the Udachnaya and Upper Muna kimberlite fields indicate geotherms consistent with lithospheric thicknesses of ~220 to 250 km, occasionally conflicting with seismic interpretations [*Ashchepkov et al.*, 2013; *Dymshits et al.*, 2020; *Griffin et al.*, 1999; *Skuzovatov et al.*, 2022]. Seismic tomography (body-wave and surface-wave) often predicts sharp contrasts between stable cratons and tectonically younger regions, suggesting lithospheric thicknesses of >250 km to 300 km beneath the Siberian Craton but <100 km in parts of Northeastern Asia [*Chen et al.*, 2008; *Lebedev and Van Der Hilst*, 2008; *Ma et al.*, 2023].

The discrepancies between methods highlight the complexity of defining the lithosphere–asthenosphere boundary (LAB), which may differ depending on whether it is defined thermally, mechanically, seismically, or rheologically. Reconciling these conflicting results is essential for understanding the tectonic evolution, craton stability, and mantle dynamics of Siberia and Northeastern Asia. Therefore, only an integrative analysis of different methods may provide a reliable model of the lithospheric thickness.

In this study, we utilize the thermo-compositional model of the North Eurasian upper mantle [*Kaban et al.*, 2025], developed using an integrated approach that combines the joint interpretation of seismic tomography and gravity data [*Kaban et al.*, 2014; *Tesauro et al.*, 2014]. To improve model resolution, we also incorporated gravity gradient data derived directly from the GOCE mission [*Boumann et al.*, 2016]. The temperature estimates were further constrained by results from thermodynamic and heat-flow modeling for the oldest part of the Siberian craton [*Artemieva*, 2006]. This comprehensive methodology provides new and robust insights into the spatial variability of lithospheric thickness across the region.

Method and 3D Thermal Model

The thermo-compositional model of the upper mantle [*Kaban et al.*, 2025] is obtained by the integration of various data sets as explained in [*Haeger et al.*, 2022; *Kaban et al.*, 2015, 2022; *Tesauro et al.*, 2014]. The process begins by calculating the gravitational effect of variations in crustal structure, including differences in density and thickness, using available crustal models and density profiles. These effects are subtracted from the observed gravity field and vertical gravity gradients, while contributions from deeper density anomalies below 325 km [*Petrunin et al.*, 2013] are also removed. The resulting residual fields provide critical constraints on the upper mantle structure and allow estimation of residual topography, which reflects surface elevation anomalies unrelated to crustal isostasy.

Seismic velocities from tomography are then converted into an initial temperature distribution for the uppermost mantle (down to 325 km) using mineral physics relationships, initially assuming a uniform mantle composition. The corresponding density variations derived from this temperature field are removed from the residuals to isolate signals related to compositional heterogeneities. These refined residual gravity, gravity gradient, and topography data are jointly inverted, providing a first 3D density model with enhanced vertical resolution compared to single-parameter inversions.

The model is further improved by estimating compositional variations, particularly the depletion of dense iron-rich minerals such as garnet beneath cratonic regions, where the mantle is less dense under the same temperature-pressure conditions. The degree of depletion is inferred from density contrasts, and temperature and density fields are recalculated to account for this revised composition.

Then, the procedure enters an iterative refinement stage: seismic velocities are reconverted to temperature while incorporating compositional variations, density corrections are updated, and a new inversion is performed. This loop continues until the thermal, compositional, and density models are mutually consistent. However, the absolute temperature values derived in the final iteration may still be biased due to uncertainties in the input seismic tomography, as absolute seismic velocities are often poorly constrained and typically depend on the chosen reference model. To mitigate this issue, the absolute temperatures were calibrated using well-established geotherms, following the approach suggested by *Haeger et al.* [2022]. Specifically, we adopted geotherms derived for the coldest part of the Siberian craton [*Artemieva*, 2006; *Cherepanova and Artemieva*, 2015]. The modeled temperature field was calibrated to match these reference geotherms in the coldest region in terms of absolute values, while preserving the relative spatial variations across the study area [*Kaban et al.*, 2025]. Because cratonic geotherms are nearly linear within the lithospheric mantle, the only parameter that can significantly affect the results is the assumed maximum lithospheric thickness. For this purpose, we used a value of 275 km, consistent with the TC1 model [*Artemieva*, 2006] and broadly supported by mantle xenolith thermobarometry from kimberlites [e.g., *Ashchepkov et al.*, 2013; *Dymshits et al.*, 2020; *Skuzovatov et al.*, 2022]. Variations in this parameter would proportionally alter the absolute estimates of lithospheric thickness but would have only a minor impact on its relative spatial variations. The obtained temperature variations for the depths 100, 150 and 200 km on a 1°x1° grids are shown in Figure 1 [*Kaban et al.*, 2025].

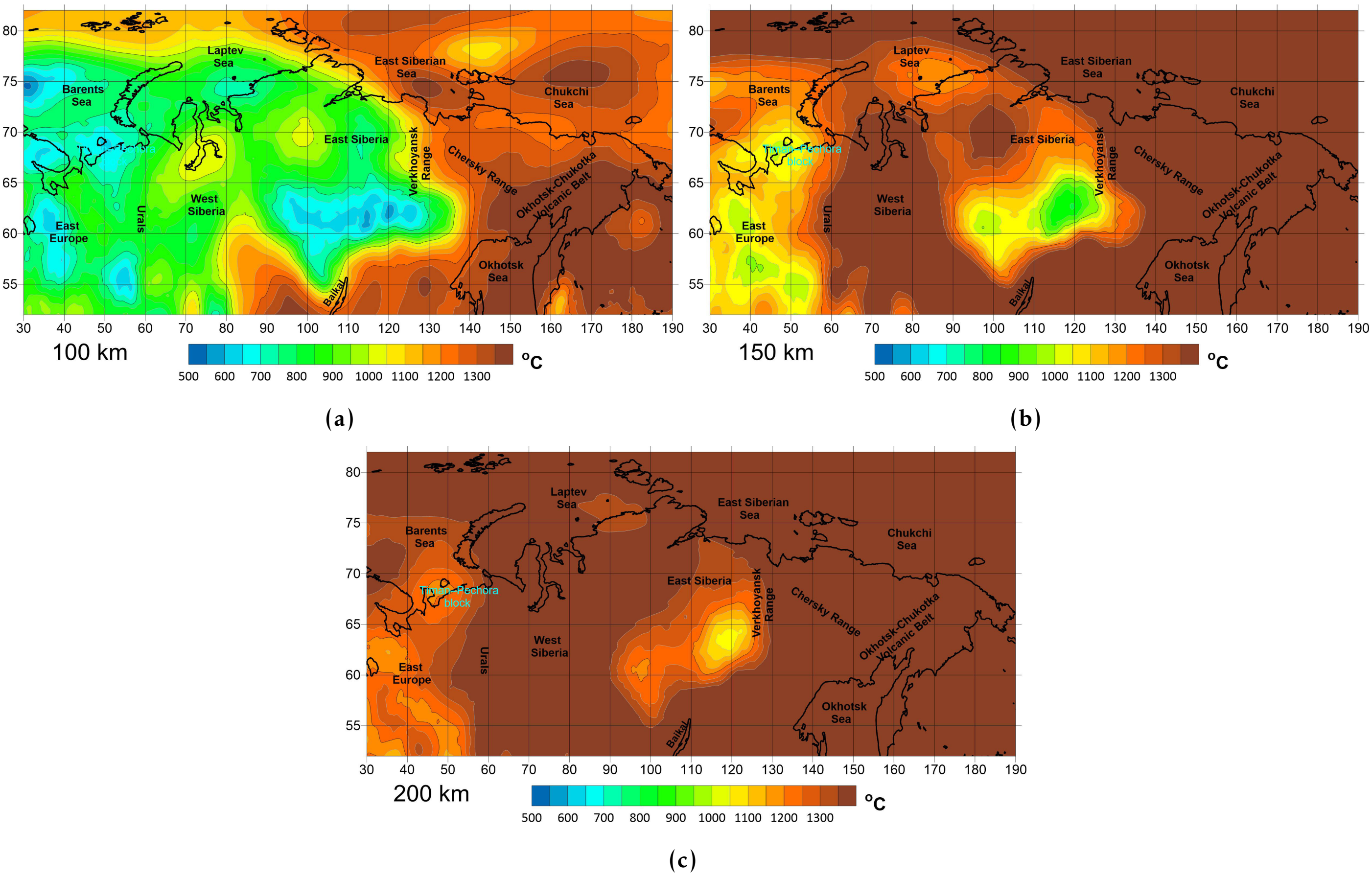

Figure 1. Temperature variations at the depths 100, 150 and 200 km [*Kaban et al.*, 2025].

Thickness of the Lithosphere

Based on the temperature distribution, we have determined the depth to the lithosphere bottom on a $1° \times 1°$ grid (Figure 2), which is defined as the 1300 °C isotherm [e.g., *Artemieva*, 2006]. It varies from 30–70 km in the Okhotsk-Chukotka Volcanic Belt to 275 km in the coldest areas of the East European and Siberian Cratons. The determined distribution of the lithospheric thickness across northern Eurasia broadly correlates with the age and tectonic character of major lithospheric domains, reflecting the long-term imprint of continental assembly and subsequent geodynamic reworking.

Compared with the well-known global model LITHO1.0 [*Pasyanos et al.*, 2014], both models show approximately the same range of the lithospheric thickness in the study area. However, LITHO1.0 reveals only features on a very large scale, such as Eastern Europe, Western Siberia, the Siberian Craton, and the easternmost region. Additionally, it contains many smaller-scale artifacts not related to tectonic fragmentation of the lithosphere.

Cratonic domains. Ancient cratons such as the Siberian Craton and the eastern Fennoscandian Shield retain thick, refractory lithospheric keels that exceed 200 km in thickness (Figure 2). These keels formed during Archean lithospheric stabilization through extensive melt extraction, which produced chemically depleted, buoyant subcontinental lithospheric mantle resistant to later tectono-thermal modification. The observed southward displacement of the Siberian lithospheric keel (Figure 2) relative to earlier reconstructions [e.g., *Rosen*, 2002] may reflect asymmetric lithospheric modification during the Proterozoic collisional events that assembled the Siberian platform, or later interactions with mantle plumes and rifting episodes during the formation of the Siberian Traps large igneous province in the Late Paleozoic – Early Mesozoic. Such offsets highlight the potential mobility of lithospheric roots in response to deep mantle dynamics [*Kaban et al.*, 2015].

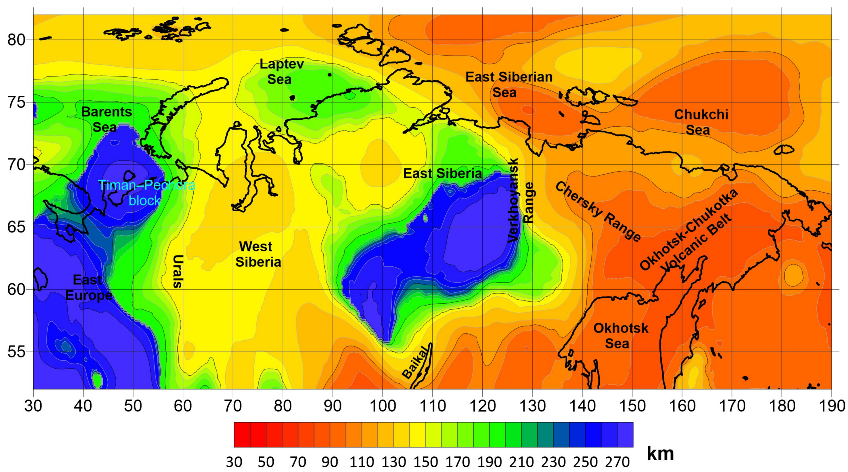

Figure 2. Depth to the lithosphere bottom defined as the 1300 °C isotherm.

Timan–Pechora block. Although distinct from these Archean cratons, the Timan–Pechora region is also characterized by anomalously thick lithosphere. This feature supports the interpretation that it represents a composite tectonic block, with a basement comprising Neoproterozoic continental crust overlain by Paleozoic accretionary complexes [*Drachev*, 2016]. The preservation of a thick lithosphere beneath Timan–Pechora suggests strong lithospheric reworking and stabilization during Paleozoic orogenesis, possibly through underthrusting and lithospheric stacking associated with the closure of the Uralian Ocean. This block therefore provides an example of lithospheric thickening outside of the Archean stabilization context, illustrating how Paleozoic orogens may also give rise to long-lived lithospheric keels.

Barents Sea domain. In contrast, the northeastern Barents Sea displays lithosphere of intermediate thickness, with the 1300 °C isotherm at 160 km to 180 km (Figure 1). Although thinner than adjacent cratonic domains, the Barents lithosphere remains cold and mechanically strong, likely reflecting a Proterozoic–Paleozoic subcontinental lithospheric fragment that escaped extensive melt depletion or delamination during later tectonic cycles. This block is tectonically significant as part of the Arctic basement mosaic, where Proterozoic microcontinents and Paleozoic accretionary systems are juxtaposed with younger rift-related structures.

The Ural suture. The Urals orogen marks a first-order lithospheric boundary separating the East European Craton to the west from the West Siberian Plate to the east. The East European Craton retains thick lithosphere exceeding 200 km, while the West Siberian Plate is characterized by markedly thinner lithosphere. The West Siberian lithosphere was profoundly modified during Mesozoic rifting and plume-related magmatism, resulting in a hot, mechanically weak lithosphere. The juxtaposition across the Urals therefore records the suture of an Archean–Proterozoic craton against younger accretionary and rift-related lithospheric blocks, with thermal anomalies beneath West Siberia potentially indicating asthenospheric upwelling or the lingering effects of the Late Paleozoic – Early Mesozoic plume–lithosphere interaction.

Eastern Eurasian orogenic belts. East of the Verkhoyansk Range, lithospheric thickness decreases sharply across a suite of Phanerozoic tectonic domains, including the Chukotka Terrane, the Anadyr–Koryak Folded System (AKFS), and the Kamchatka segment of the Kuril–Kamchatka volcanic arc. These regions are tectonically young, with lithospheric thicknesses commonly below 100 km. The Chukotka Terrane and AKFS represent accretionary orogens formed during Mesozoic subduction and terrane accretion, while Kamchatka reflects an actively evolving volcanic arc shaped by ongoing Pacific Plate subduction and slab rollback. High upper mantle temperatures, persistent arc magmatism, and asthenospheric upwelling preclude lithospheric thickening in these domains, underscoring the dynamic tectonic regime of the Pacific margin.

Taken together, the lithospheric structure of northeastern Eurasia reflects the interplay of several geodynamic processes: (i) stabilization of Archean cratonic keels through melt depletion and secular cooling; (ii) lithospheric thickening during Paleozoic orogenesis and continent–continent collision between Laurussia and Siberia; (iii) lithospheric attenuation and thermal modification associated with Mesozoic rifting and mantle plumes; and (iv) ongoing subduction, terrane accretion, and arc magmatism along the Pacific margin. The contrasts between thick, stable lithosphere in the cratonic core and thin, tectonically active lithosphere at the eastern margin illustrate the long-lived role of major tectonic sutures in defining the geodynamic architecture of Eurasia.

Conclusions

In this study, we constrain lithospheric thickness across northeastern Eurasia using a new thermo-compositional model of the lithosphere [*Kaban et al.*, 2025]. The model is derived from an integrative methodology that jointly interprets seismic tomography and gravity data, including gravity gradients obtained directly from the GOCE mission. This combined approach provides a self-consistent three-dimensional thermal structure of the lithosphere that explicitly accounts for compositional variations within lithospheric keels. As a result, the lithospheric thickness estimates are considered robust. The greatest source of uncertainty lies in the maximum depth of the lithosphere, which is set at 275 km based on thermodynamic and heat-flow modeling, as well as mantle xenolith thermobarometry. Although moderate adjustments to this absolute depth are possible, the relative spatial variations in lithospheric thickness are expected to remain essentially unchanged. Based on this study, we formulate the following conclusions:

- Lithospheric thickness across northern Eurasia shows a clear correlation with the age and tectonic evolution of major domains, reflecting the long-term imprint of continental assembly and subsequent geodynamic modification.
- Archean and Proterozoic terranes, such as the Siberian Craton and the eastern Fennoscandian Shield, preserve thick lithospheric keels (>200 km) formed through early melt depletion and stabilization. The apparent southward offset of the Siberian keel relative to earlier reconstructions suggests later modification, possibly linked to Proterozoic collision or Late Paleozoic—Early Mesozoic plume–rift interactions.
- The Timan–Pechora block, although younger, is also underlain by thick lithosphere, supporting its interpretation as a composite tectonic unit stabilized during Paleozoic orogenesis. This provides evidence that lithospheric thickening is not limited to Archean domains but may also occur in younger collisional systems.
- The northeastern Barents Sea represents an intermediate lithospheric fragment (160–180 km) that remains cold and mechanically strong, consistent with a Proterozoic–Paleozoic subcontinental block incorporated into the Arctic basement mosaic.

- The Ural Orogen constitutes a major lithospheric boundary, juxtaposing the thick East European Craton against the thinner and thermally modified West Siberian Plate. The latter records profound Mesozoic rifting and plume activity, with potential asthenospheric upwellings contributing to its present lithospheric structure.
- East of the Verkhoyansk Range, the lithosphere is thin (<100 km) and tectonically dynamic across the Chukotka Terrane, Anadyr–Koryak Fold Belt, and Kamchatka arc. These domains are shaped by Phanerozoic subduction, terrane accretion, slab rollback, and ongoing arc magmatism, processes that inhibit lithospheric stabilization.
- Overall, the lithospheric architecture of northern Eurasia reflects the interplay of four major geodynamic processes: (i) stabilization of the Archean and Proterozoic terranes, (ii) lithospheric thickening during Paleozoic orogenesis, (iii) attenuation and modification during Mesozoic plume–rift events, and (iv) active subduction and arc processes along the Pacific margin. These results underscore the importance of sutures and terrane boundaries in maintaining strong lateral contrasts in lithospheric thickness and in shaping the long-term geodynamic framework of Eurasia.

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