

Long-term evolution, stability, and thickness of cratonic lithosphere

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ABSTRACT

The thickness of the cratonic lithospheric mantle (CLM) influences the composition of primary mantle melts, the formation and distribution of ore deposits, and the stability of continents. However, it remains debated whether the thickness of the CLM has changed through time. Some studies suggest progressive thinning due to extension, convective removal, mantle plumes, or subduction-driven erosion, while others propose long-term stability due to the intrinsic buoyancy or strength of the CLM. To address this question, we provide new constraints on the evolution of the CLM through time by comparing two recently developed datasets: (1) a global dataset of paleo-lithosphere-asthenosphere boundary (LAB) depth estimates (dating back to 2.1 Ga) produced by fitting geotherms to xenolith- and xenocryst-derived pressure and temperature estimates; and (2) the present-day LAB depth derived from seismic tomography combined with a scaling between wavespeed and temperature. Our results show that the thickness of the CLM beneath most cratons has changed by <50 km since the Paleoproterozoic, that there are no systematic secular trends in CLM thickness changes through time, and that there is no evidence for the previously proposed existence of substantially thicker (>300 km) CLM in the past. These findings suggest that in the majority of places, the cratonic lithosphere has remained largely unchanged for billions of years, reinforcing the idea that cratonic roots represent long-lived, stable features of Earth's lithosphere. Exceptions are regions with long histories in a supra-subduction setting, followed by the application of extensional stresses (e.g., North China).

INTRODUCTION

Cratons are stable blocks of Precambrian continental lithosphere that have remained tectonically stable for billions of years. The cratonic lithospheric mantle (CLM) in most cratons experienced high-degree partial melting followed by thickening during the Proterozoic or Archean (Pearson et al., 2021). The roots of cratons are generally thought to be long-lived due to a combination of their thickness, temperature, and composition, which between them result in CLM that is buoyant and mechanically strong (Jordan, 1978). However, some observations and models have implied that cratons may be periodically destabilized or destroyed by convective removal, extension, or basal ero-

sion (Bedle et al., 2021; Hua et al., 2025). Cratons thought to have been modified by these processes include the North China Craton (Liu et al., 2019; Wu et al., 2019) and the Wyoming Craton (Carlson et al., 2004; Dave and Li, 2016). These processes have attracted research interest due to their roles in driving magmatism (Elkins-Tanton, 2005), facilitating ore-deposit formation (Zhu et al., 2017), and offering insights into the spatio-temporal evolution of CLM. However, the prevalence and importance of these processes remains uncertain, and despite advances in our understanding of the CLM, key questions remain regarding the stability of cratonic roots and the processes, prerequisites, and time scales involved in their modification. Addressing these questions is critical for understanding the dynamic evolution of Earth's lithosphere and its implications for tectonics, magmatism, and resource distribution (Cawood et al., 2022; Hoggard et al., 2020; Zhu et al., 2017).

In this study, we combine two recently developed methodologies to perform a global

investigation of CLM stability through geological time. New data and models of kimberlite-hosted xenoliths and xenocrysts allow the ancient thickness of the CLM to be constrained (Sudholz and Copley, 2025). The combination of seismic tomographic models with the scaling between temperature and seismic wavespeed allows the present-day thickness of the CLM to be mapped (Priestley et al., 2024). In this paper, we combine these datasets to investigate CLM thickness evolution on a global scale since the Paleoproterozoic.

METHOD: LITHOSPHERIC THICKNESS ESTIMATES

Kimberlites and related rocks contain fragments of the lithospheric mantle (i.e., xenoliths and xenocrysts) that were entrained during their rapid ascent to the surface. By applying geothermobarometers and geotherm modeling to these samples, they can be used to constrain the temperature and thickness of the CLM at the time of eruption. In this study, we have used an expanded version of the database reported in Sudholz and Copley (2025). The equilibration pressure and temperature (P - T) of the samples were calculated using the geothermobarometers of Nimis and Taylor (2000) and Sudholz et al. (2021) (which is more accurate at high- P than the Nimis and Taylor [2000] geobarometer), after filtering using the method of Ziberna et al. (2016). Our samples come from ~80 volcanic pipes from ~15 cratons (Fig. 1). The emplacement ages range from Miocene (ca. 20 Ma) to Paleoproterozoic (ca. 2100 Ma), although most samples have ages <500 Ma. To fit geotherms to these data, and estimate lithosphere-asthenosphere boundary (LAB) depth, we use the approach of Sudholz and Copley (2025). This method does not fix the values of poorly known parameters (e.g., the thickness of the crust and the distribution of radiogenic heating), but instead tests all geologically viable parameter combinations and obtains the full range of geo-

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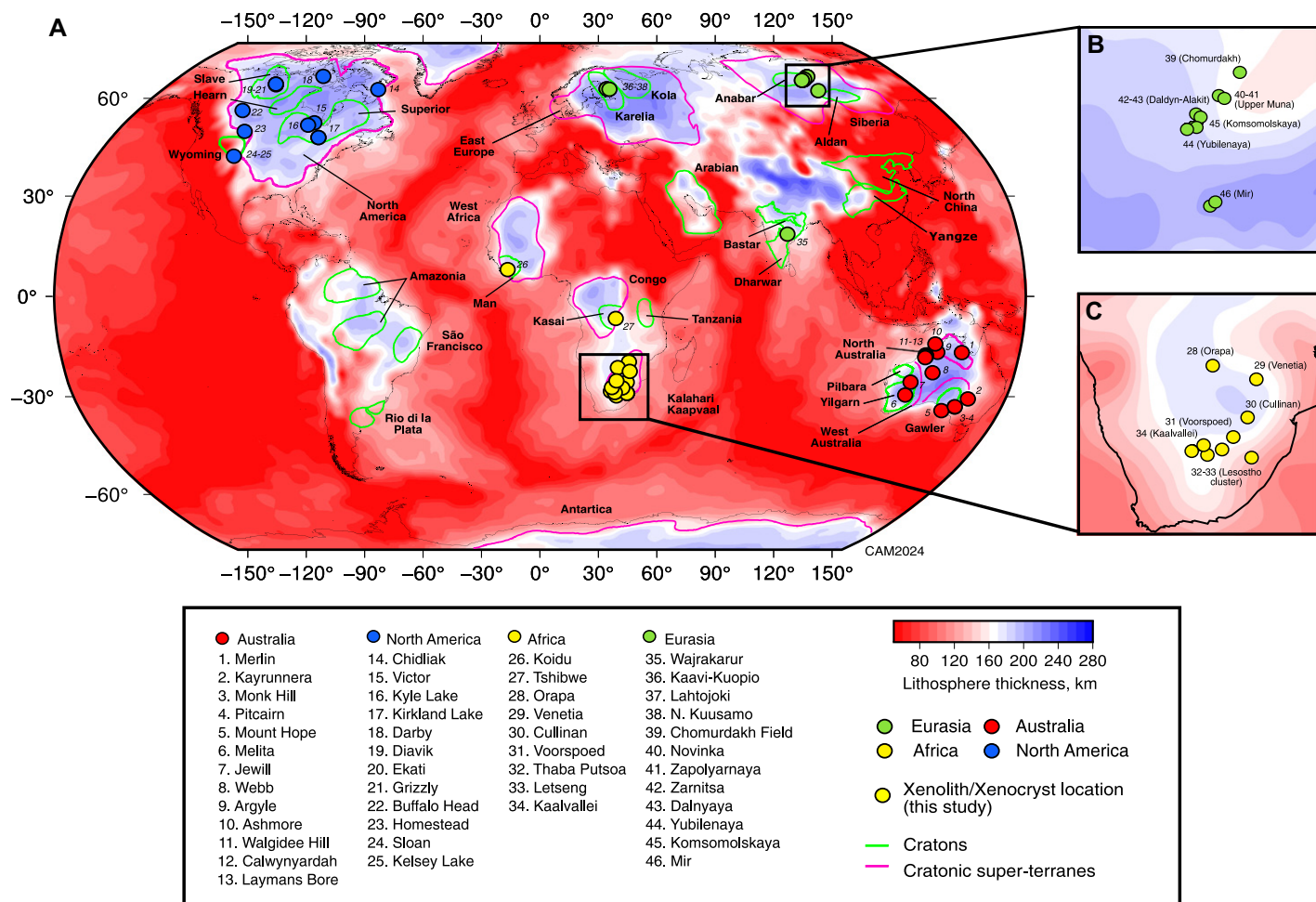


Figure 1. (A) Map of lithosphere-asthenosphere boundary depth (km) based on CAM2024 (Priestley et al., 2024). Overlain are the locations of the mantle xenolith and xenocryst samples used in this study. (B) Inset map of Siberian craton. (C) Inset map of southern Africa. Figure modified after Sudholz and Copley (2025).

therms that are consistent with the data (which have a resolution in P - T of 35–50 °C and 2.5–4.5 kbar). The range in possible LAB depths was estimated as the depth range over which the paleogeotherm(s) that are able to reproduce the data intersect the mantle adiabat. We express this range as a mean value and standard deviation. The adiabat was calculated using a fixed mantle potential temperature (T_p) of 1315 °C (for the reasons outlined in Sudholz and Copley, 2025). We discuss below the effects of using alternative values for T_p . An example paleogeotherm for the Wajrakarur Kimberlite Field is shown on Figure 2. We only perform paleogeotherm modeling for the subset of locations (shown on Fig. 1), where the samples exhibit a large range of equilibration pressures, leading to a well-constrained paleogeotherms, and with an absence of the high-temperature scatter that implies re-equilibration with mantle-derived melts before eruption (Sudholz and Copley, 2025).

Priestley et al. (2024) created an upper-mantle thermal model using a tomographic model derived from a large surface waveform dataset (e.g., Priestley et al., 2018) and by applying a parametrization between S-wave velocity (V_s)

and temperature (T). The tomographic inversion was performed on a $2^\circ \times 2^\circ$ geographic grid. Priestley et al. (2024) constructed the parameterization using the relation between V_s , T , and depth in the oceanic lithosphere (with the thermal model constrained by the relation between plate age and bathymetric depth), and by also incorporating P - T estimates from continental mantle xenoliths. This approach is empirical and makes no assumptions about the physical controls on the relationship between V_s and T . The temperature estimates from the seismological results are only reliable near the base of the lithosphere, beneath the effects of crustal contamination in the estimated seismic velocities. When comparing LAB-depth estimates from these models with our xenolith-derived paleogeotherm, the potential circular reasoning related to the use of xenoliths in the calibration is mitigated in two ways. First, the parameterization of the V_s - T relationship is primarily based on observations from oceanic lithosphere. Second, the continental xenoliths used by Priestley et al. (2024) differ significantly from those in our study: of our ~80 sample locations, only eight were included in the

calibration of Priestley et al.'s model, and with the exception of the Zero and Cullinan pipes, all of their samples were from kimberlites with Phanerozoic emplacement ages. In contrast, our dataset includes 14 locations with emplacement ages exceeding 450 Ma. Additionally, our P - T estimates were derived using a different set of geothermobarometers (see above).

To constrain the present-day values for LAB, we used the variation of T with depth from the seismological results of Priestley et al. (2024) in the four locations surrounding our xenolith locations on the $2^\circ \times 2^\circ$ geographic grid. For consistency with the petrological results, we estimate the LAB depth using an equivalent methodology of fitting multiple possible gradients to the conductive and convective parts of the temperature-depth profile and examining where those lines intersect (see item S2 in the Supplemental Material¹). The combination of using seismic

¹Supplemental Material. Online dataset and supplementary figures. Please visit <https://doi.org/10.1130/GEOLOGY.30090637> to access the supplemental material; contact editing@geosociety.org with any questions.

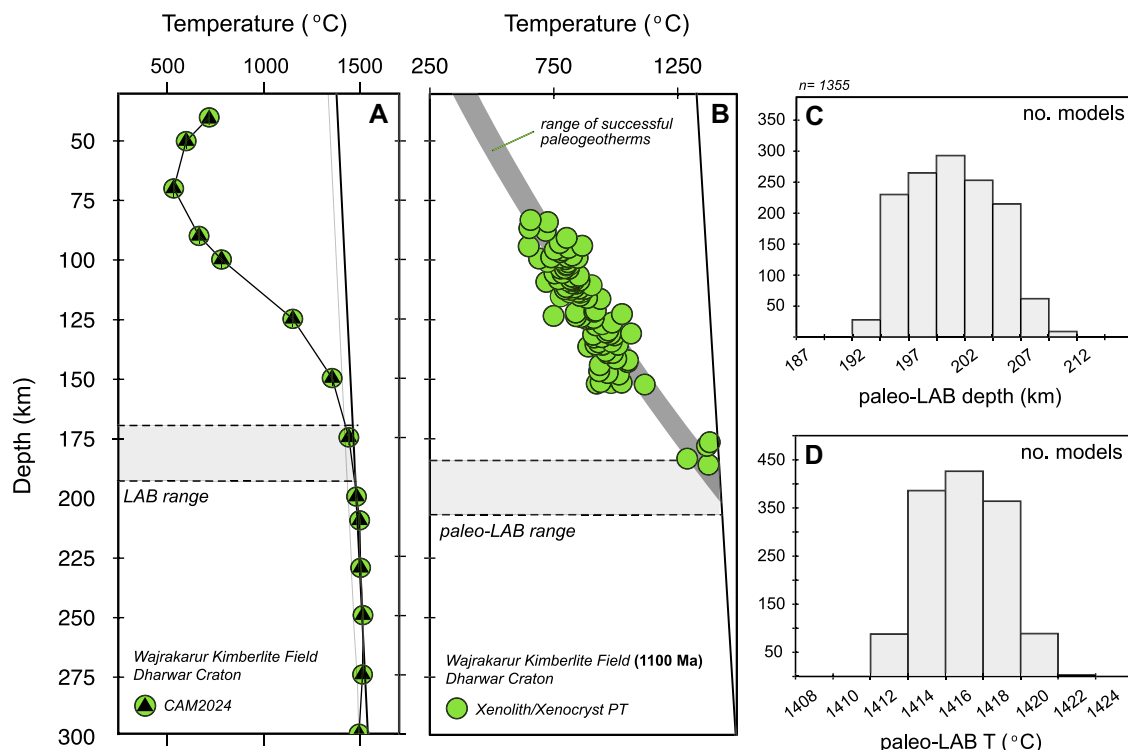


Figure 2. Interpretation of the thermal structure of the cratonic lithospheric mantle based on petrological and seismic datasets. (A) Plot of the temperature-depth profile from the seismological results of Priestley et al. (2024) beneath the Wajrakarur Kimberlite Field. (B) Plot of the equilibration pressure and temperature (P - T) for mantle xenoliths/xenocrysts and successful paleogeotherm models (gray lines). (C) Histogram of the depth range of the lithosphere-asthenosphere boundary (LAB) for successful paleogeotherm models. (D) Histogram of the temperature range of the LAB for successful paleogeotherm models. The temperatures derived from the seismological method are only reliable near the base of the lithosphere, beneath the effects of crustal contamination in the estimated seismic velocities.

results from multiple locations surrounding each kimberlite pipe, and the feature that the conductive section of many temperature-depth profiles shows a range of gradients, means that we take the conservative approach of examining the full spectrum of possible LAB depths and reporting that range (Supplemental Material Table S1; cf. Sarkar et al., 2025). An example of the seismologically determined temperature-depth profile and LAB depth for the Wajrakarur Kimberlite Field is shown on Figure 2. Equivalent results for other locations are reported in Supplemental Material item S2. For all locations, we report an average LAB depth and standard deviation (1σ) based on our intersection method. Our petrological and seismic approaches do not explicitly model a thermal boundary layer at the base of the lithosphere. This exclusion ensures consistency between both methods, allowing for a more reliable comparison of LAB depth estimates. The same conclusions would be obtained if an equivalent thermal boundary layer was included in both methods.

RESULTS AND DISCUSSION

Figures 3A–3D show our petrologically estimated LAB depths plotted against the time of eruption of each sample set. These plots were made using a constant mantle T_p of 1315 °C. Equivalent plots using a change in mantle T_p through time of 50 °C b.y.⁻¹ (Sudholz and Copley, 2025) are reported in Supplemental Material item S2. The largest lithosphere thickness estimates are from cratonic interiors, notably

the Siberian Craton and North Australian Craton (Fig. 1). In contrast, thinner lithosphere is observed in mobile belts and inliers along the margins of cratons, such as the Adelaide Fold Belt (Monk Hill) and Arunta Inlier (Webb). Gradients in the plots of LAB depth against time could result from lateral variations in lithosphere thickness between sites or temporal variations between eruptions due to growth or removal of lithospheric mantle. In some locations, closely spaced sites experienced eruptions over a protracted period of time (e.g., over 0.5–1.5 b.y. in the Kimberley and Yilgarn Cratons on Fig. 3B) with no resolvable changes through time in LAB depth. In contrast, some locations (e.g., the Kaapvaal on Fig. 3A and Siberia on Fig. 3D) show larger variations in LAB depth for roughly coeval eruptions, implying lateral variations in LAB depth. This inference is consistent with the present-day variations in these regions seen on the lithosphere thickness map of Priestley et al. (2024). However, we note that the lateral resolution of the surface wave tomography is ~200 km, so short-wavelength variations are invisible to that method.

Figure 3E shows the comparison between all of our estimated paleo-LAB depths and the present-day estimates for the same locations from the seismological method. A negative value indicates lithospheric thinning since the time of eruption, while positive values indicate thickening. Regardless of age, for the majority of the locations, the xenolith- and seismology-based estimates of LAB depth are within 50 km of each

other. The notable exception is the North China Craton (purple symbols), which shows evidence of significant thinning of the lithosphere since the early Phanerozoic (Fig. 3E). With the exception of North China, the overall similarity in xenolith- and seismology-based estimates of lithosphere thickness implies that over the ~2 b.y. time scale of our dataset, there are no major (i.e., >75 km) and globally systematic changes in lithosphere thickness through time. In other words, there is no significant evidence supporting secular thinning or growth of the CLM on a regional or global scale. The results shown in Supplemental Material item S2, calculated using the maximum change in mantle T_p through time that is compatible with the xenolith dataset (50 °C b.y.⁻¹; Sudholz and Copley, 2025) shows that these patterns hold true even in that case.

Our findings challenge the notion that cratons were significantly thicker in the past, such as recent suggestions that cratons may have reached thicknesses >300 km during the Proterozoic and Archean (Hoare et al., 2022; Kamber and Tomlinson, 2019). Our results also challenge the conclusion of Sarkar et al. (2025), who propose widespread craton erosion over the past 200 m.y. The longevity of cratonic lithosphere as implied from our Figure 3 results is consistent with Re-Os isotopic data for cratonic peridotites, which show that cratons are generally stable over >2 b.y. time scales (i.e., Pearson et al., 1995) and that their destruction and modification is restricted to exceptional circumstances (Carlson et al., 2004). These Re-Os data also

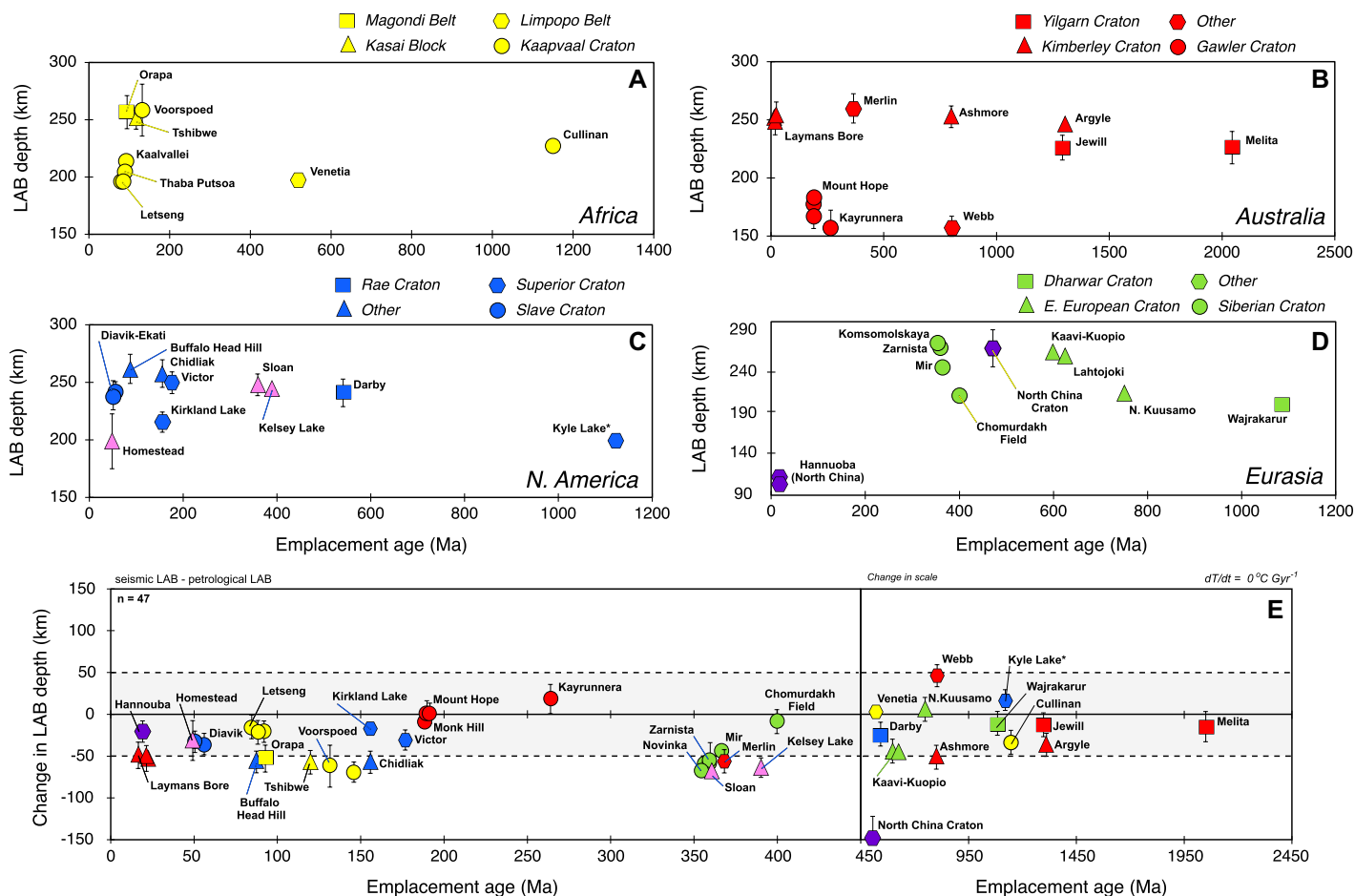


Figure 3. Global trends in cratonic lithospheric mantle thickness from paleogeotherm modeling and seismic tomography. (A–D) Change in paleo-LAB (lithosphere-asthenosphere boundary) depth through time for the locations on Figure 1. (E) Comparison between the present-day LAB depth and paleo-LAB depth for our global dataset. The values for ΔLAB were calculated as present-day LAB minus paleo-LAB (km). The standard deviation values were calculated as the sum of the squares of the petrological and seismic errors on the LAB estimates. Pink symbols are data for the Wyoming Craton and adjacent mobile belts (i.e., Cheyenne Belt). Purple symbols are data for China.

support our rejection of the possibility of a time-varying LAB depth that repeatedly returns to the same value for sampling by sporadically erupted xenoliths, and to be imaged seismologically at the present day. Such a situation is probabilistically highly unlikely and would involve reset Re-Os ages during regular episodes of CLM thinning and growth. Superimposed upon the overall pattern of limited changes in LAB depth are variations of up to 50 km between the two methods of estimating LAB depth. The two possible interpretations of these differences are (1) changes in LAB depth through time, and (2) short-wavelength variations in LAB depth that are sampled by the xenoliths but not the seismicological method.

We attribute the long-term stability of the CLM to the relatively constant mantle T_p since the Proterozoic (Sudholz and Copley, 2025), as well as the highly depleted composition of the CLM beneath most cratons. The limited changes in mantle T_p through time means that the thermal structure of cratons has remained mostly unchanged. The addition of volatiles into the base of the CLM may contribute toward rheo-

logical weakening and to lowering the melting temperature (Foley, 2008). However, the volume of these melts is likely too small to contribute to large changes in lithospheric density structure through time, as implied by the observation that low-volume melts make up an extremely small portion of the melts derived from cratons, both spatially and temporally (Tappe et al., 2018).

The Wyoming and North China Cratons are commonly thought to have experienced significant shallowing of the LAB through time (Wu et al., 2019; Dave and Li, 2016). The North China Craton (purple symbols on Fig. 3) is the only location in our dataset with a large (>100 km) difference between the present-day and paleo-LAB depth. The information from the Wyoming Craton and adjacent mobile belts (i.e., Cheyenne Belt; pink symbols) is more ambiguous and potentially implies thinning of 50–75 km since the Devonian, although this value is small enough to be poorly constrained. Both regions have spent large amounts of time (>100 m.y.) immediately overriding subducting slabs (Pacific and Farallon plates), and both are in regions experiencing current or geologically

recent extension. These findings imply that the conditions necessary to destroy the geological longevity of thick cratonic roots are (1) hundreds of millions of years of volatile input in a supra-subduction setting, and (2) subsequent extensional stresses that are able to stretch, and thin, the volatile-rich and weaker lithosphere. However, in the case of these exceptional circumstances, whether the necessary weakening to allow extension occurs in the crust or mantle portions of the lithosphere, or both, is dependent upon lithosphere rheology (Burov, 2011; Jackson et al., 2021).

CONCLUSION

Our results indicate that the thickness of the CLM was not significantly greater during the Precambrian. Comparison between paleo-LAB estimates with present-day observations shows that there have been no secular trends in lithosphere growth and/or destruction since at least the mid-Proterozoic. The rare exceptions to this pattern require the geologically noteworthy history of long periods of subduction-induced volatile input followed by significant extensional stressing.

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ERRATUM: Long-term evolution, stability, and thickness of cratonic lithosphere

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Errors were made in the pre-issue publication version of this paper, first published online on 19 September 2025. The sentence “The LAB depth from the seismological results is only reliable near the base of the lithosphere, beneath the effects of crustal contamination in the estimated seismic velocities.” should read “The temperature estimates from the seismological results are only reliable near the base of the lithosphere, beneath the effects of crustal contamination in the estimated seismic velocities.” There was an equivalent error in the caption to Figure 2. The sentence “Our analyses of the LAB depth from the seismological results are only reliable near the base of the lithosphere, beneath the effects of crustal contamination in the estimated seismic velocities.” should read “The temperatures derived from the seismological method are only reliable near the base of the lithosphere, beneath the effects of crustal contamination in the estimated seismic velocities.”

The correct text now appears in the final published version of the paper to which this erratum is appended.