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Lithosphere–asthenosphere interactions beneath northeast China and the origin of its intraplate volcanism

Anqi Zhang[1,2,3], Zhen Guo[1,3,4]*, Juan Carlos Afonso[2]*, Heather Handley[2], Hongkun Dai[2], Yingjie Yang[2] and Y. John Chen[1,3]
[1]Department of Ocean Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China
[2]ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS)/GEMOC, Department of Earth and Environmental Sciences, Macquarie University, Sydney, NSW 2109, Australia
[3]Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou 511458, China
[4]Shanghai Sheshan National Geophysical Observatory, Shanghai 201602, China

ABSTRACT

Northeast China hosts one of the largest Cenozoic intraplate volcanic regions in the world. However, the mechanisms that generate the volcanism, its spatial-temporal distribution, and compositional signatures remain highly debated due to the lack of high-resolution images of the mantle's thermochemical structure. We jointly inverted new surface-wave dispersion data, surface heat flow, geoid height, and elevation data to image the fine-scale thermal and compositional structures beneath northeast China and infer regions of partial melting in the mantle. Our model reveals a complex circulation pattern in the asthenosphere and a highly variable lithospheric structure. Combining predictions from our model with independent geochemical data from recent basaltic volcanism, we demonstrate that the generation, location, and composition of intraplate volcanism in this region are controlled by the interaction between shallow asthenospheric circulation and lithospheric thickness. The modeling approach and correlations between basaltic composition and mantle state identified in our study are globally applicable to assessing mantle conditions over time in other continental regions.

INTRODUCTION

The origin and spatial distribution of Cenozoic intraplate volcanism in northeast China (NEC) remain highly debated and poorly understood (Liu et al., 2001; Wang et al., 2015; Chen et al., 2017). This basaltic volcanism, which includes four active volcanoes (Changbaishan, Longgang, Jingpohu, and Wudalianchi), is located more than 1000 km west of the Japan Trench (Fig. 1) and therefore its origin cannot be readily reconciled with our current understanding of melt generation at convergent plate boundaries (Davies and Rawlinson, 2014; Yang and Faccenda, 2020). Although previous studies have attributed Cenozoic continental extension, rifting, and deep mantle upwelling to the large-scale mantle circulation induced by the stagnant Pacific slab under NEC (Zhao et al., 2009; Wang et al., 2015; Liu et al., 2017; Guo et al., 2018a), the actual location and geochemistry of the volcanism are more likely affected by shallower and smaller-scale processes near the lithosphere–asthenosphere boundary, none of which are well known.

Intraplate continental basalts in NEC exhibit wide compositional diversity in major element, trace element, and isotope compositions (petrologically, they range from basanites to tholeiitic basalts; Ho et al., 2013). However, the reason for such compositional variations remains controversial, and they are attributed to either mantle source variation, lithospheric contamination, fractional crystallization, variations in lithospheric thickness, or a combination of these factors (Chen et al., 2017; Guo et al., 2020). Recent global analyses (Niu, 2011, 2021; Ball et al., 2021) demonstrated that lithospheric thickness exerts a primary control on basalt composition in all tectonic settings on Earth. What is less clear is whether the same principle, known as the "lid effect," also controls the location and compositional variability of intraplate basalts at the scale of individual basaltic provinces such as NEC. A number of recent studies have evaluated this hypothesis in various parts of mainland China (Liu et al., 2016; Yu et al., 2018; Guo et al., 2020; Sun et al., 2020). Among these, Guo et al. (2020) provided direct evidence of the lid effect; i.e., basaltic compositions show significant correlations with lithospheric thickness. However, that study focused on a limited region of NEC and the samples used spanned ages >20 Ma. Furthermore, estimations of present-day mantle melt fractions and distribution have not been attempted in NEC. Understanding the origin of young intraplate basalts and the associated mantle processes beneath NEC requires detailed information about the thermochemical structure of the lithosphere and sublithospheric upper mantle at a higher resolution over the entire NEC. However, no comprehensive, high-resolution model of the lithospheric thickness, mantle thermal state, and melt distribution is currently available.

In our study, we used a recently developed probabilistic inversion method (Afonso et al., 2013a, 2013b, 2016) to jointly invert multiple geophysical data sets with complementary sensitivities to the fine-scale structure of the lithosphere and sublithospheric upper mantle. Specifically, we jointly inverted normal mode Rayleigh wave dispersion data recently acquired across a dense seismic array (Fan et al., 2021), surface heat flow, geoid height, and absolute elevation data (see the Supplemental Material[1] for details on the data and methods). The output is a three-dimensional model of temperature, bulk density, seismic velocity, melt distribution, and compositional structure of the entire lithosphere and deep upper mantle beneath NEC. This integrated model provides unprecedented

*E-mails: guoz3@sustc.edu.cn; juan.afonso@mq.edu.au

[1]Supplemental Material. Methodology, supplemental Figures S1–S11, and Tables S1 and S2. Please visit https://doi.org/10.1130/GEOL.S.16814314 to access the supplemental material, and contact editing@geosociety.org with any questions.

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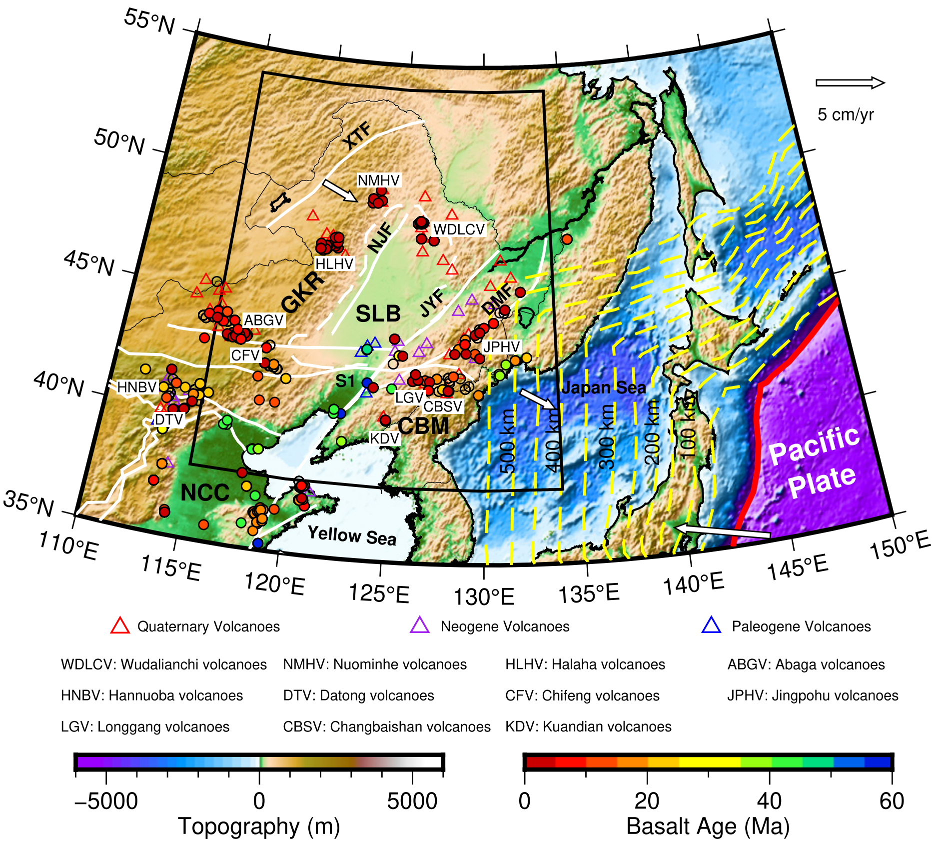

Figure 1. Topographic map of northeast China. White arrows denote velocity vectors of plate motion. Dashed yellow lines indicate depth contours of the present upper boundary of the subducting Pacific slab as estimated from seismicity data (Liu et al., 2017). Colored circles show the spatial and temporal distribution of mafic volcanism (samples are taken from the Geochemistry of Rocks of the Oceans and Continents [GEOROC, http://georoc.mpch-mainz.gwdg.de/georoc/] database). Open circles denote mafic volcanism of unknown age. GKR—Great Xing'an Range; SLB—Songliao Basin (white dashed line); CBM—Changbai Mountain; NCC—North China Craton; XTF—Xiguitu–Tayuan fault; NJF—Nenjiang fault; JYF—Jiamusi–Yilan fault; DMF—Dunhua–Mishan fault; S1—Solonker–Xar Moron–Changchun suture.

information about the thermochemical structure of this region. We combined these results with independent geochemical data to explore the role of lithospheric thickness and upper mantle state in the melting process of continental intraplate volcanism.

RESULTS AND DISCUSSION

Lithospheric Thickness and Melt Distribution

Direct geophysical constraints on lithospheric thickness in NEC are scarce and highly debated, and estimates range from as thin as 40 km to more than 120 km (Zhang et al., 2014; Peng et al., 2020). Given the significant influence that temperature has on the physical properties of mantle rocks, we adopted the thermal definition of the lithosphere–asthenosphere boundary (LAB). Specifically, we identified the LAB as the depth to the 1250 °C isotherm, consistent with results from numerical simulations using realistic viscosities (e.g., Afonso et al., 2008).

The predicted LAB is shown in Figure 2A as the mean of the posterior probability density function (see the Supplemental Material); the associated uncertainty is shown in Fig. S5 in the Supplemental Material. We imaged a very thin (∼65 km depth) lithosphere beneath the Changbai Mountain region (CBMR), the Jiamusi-Yilan fault (JYF) and the Dunhua-Mishan fault (DMF) zones. There is an overall increase in lithospheric thickness toward the Great Xing'an Range (LAB ∼95 km depth) with a few localized thin regions, the most prominent of which coincides with the Halaha volcanic and Abaga volcanic areas. Figure 2A also shows the locations of intraplate basalts with ages younger than 5 Ma, taken from the Geochemistry of Rocks of the Oceans and Continents (GEOROC, http://georoc.mpch-mainz.gwdg.de/georoc/) data set and additional references (e.g., Zou et al., 2003; Zhao and Fan, 2012; Ho et al., 2013; Kuritani et al., 2013; Wang et al., 2017; Yu et al., 2018). There is a clear correlation between the location of these intraplate basalts and regions of relatively thin lithosphere (<70 km) and anomalously hot (>1350°C) sublithospheric mantle (Figs. 2A and 3). The thermobarometric information collected from mantle xenoliths for the Nuominhe volcanoes and Halaha volcanoes (Figs. 2C and 2D) provides representative comparisons with our thermal LAB.

During the inversion, we estimated total melt fractions and their effects on seismic velocities based on the models of Katz et al. (2003) and Clark and Lesher (2017), respectively (see the Supplemental Material). As seen in Figure 2B, our predicted melt distribution coincides remarkably well with the locations of recent basaltic volcanism; i.e., along the north side and flanks of the Songliao Basin. All predicted melts are located in the sublithospheric mantle, mostly within the depth range of 60–110 km (Fig. S6). We note that while the highest melt fractions in the model occur in the region between the Changbaishan volcanoes and Jingpohu volcanoes, the melt is generated at deeper levels and under thicker lithosphere than exists in the surrounding area (Fig. S6). We emphasize here that these predictions are true outcomes of the inversion, as our method does not include the location of volcanic centers as input information; the inversion is completely driven by the joint fit to only the four inverted data sets.

Beneath the Changbai Mountain region, partial melt is widespread and shows high absolute values (*5%). This result is encouraging, as the Changbai Mountain region hosts a large number of young volcanic centers. More interesting is the observation that the Dunhua–Mishan fault zone seems to be exerting significant control on the spatial distribution of partial melting in the mantle, despite both regions being characterized by a relatively thin lithosphere. We also imaged smaller regions of low-degree partial melting beneath the northern and western flanks of the Songliao Basin, as well as beneath the Nuominhe volcanic and Halaha volcanic areas. These patterns are not a coincidence and highlight a clear link between the location of recent volcanism with anomalous temperatures in the sublithospheric mantle and thin lithosphere. Importantly, while the sublithospheric mantle beneath these regions is anomalously hot (Fig. 3), the LAB is generally deeper than in the Changbai Mountain region. This provides a unique opportunity to determine the role the lid effect plays on the origin of intraplate basalts and their evolution. However, we note that ∼3% partial melting is predicted beneath the central–east Songliao Basin, where there is no surface evidence of recent volcanism (Fig. 2B; see details in the Supplemental Material).

Lithospheric Controls on the Compositions of Continental Basalts

To explore lithospheric controls on the compositions of erupted basalts in NEC, we averaged the imaged LAB depths and the composition of basalts within specific areas of interest (red rectangle in Fig. 2A). The basalt samples used here are all younger than 5 Ma (to make comparisons with the present-day LAB valid)

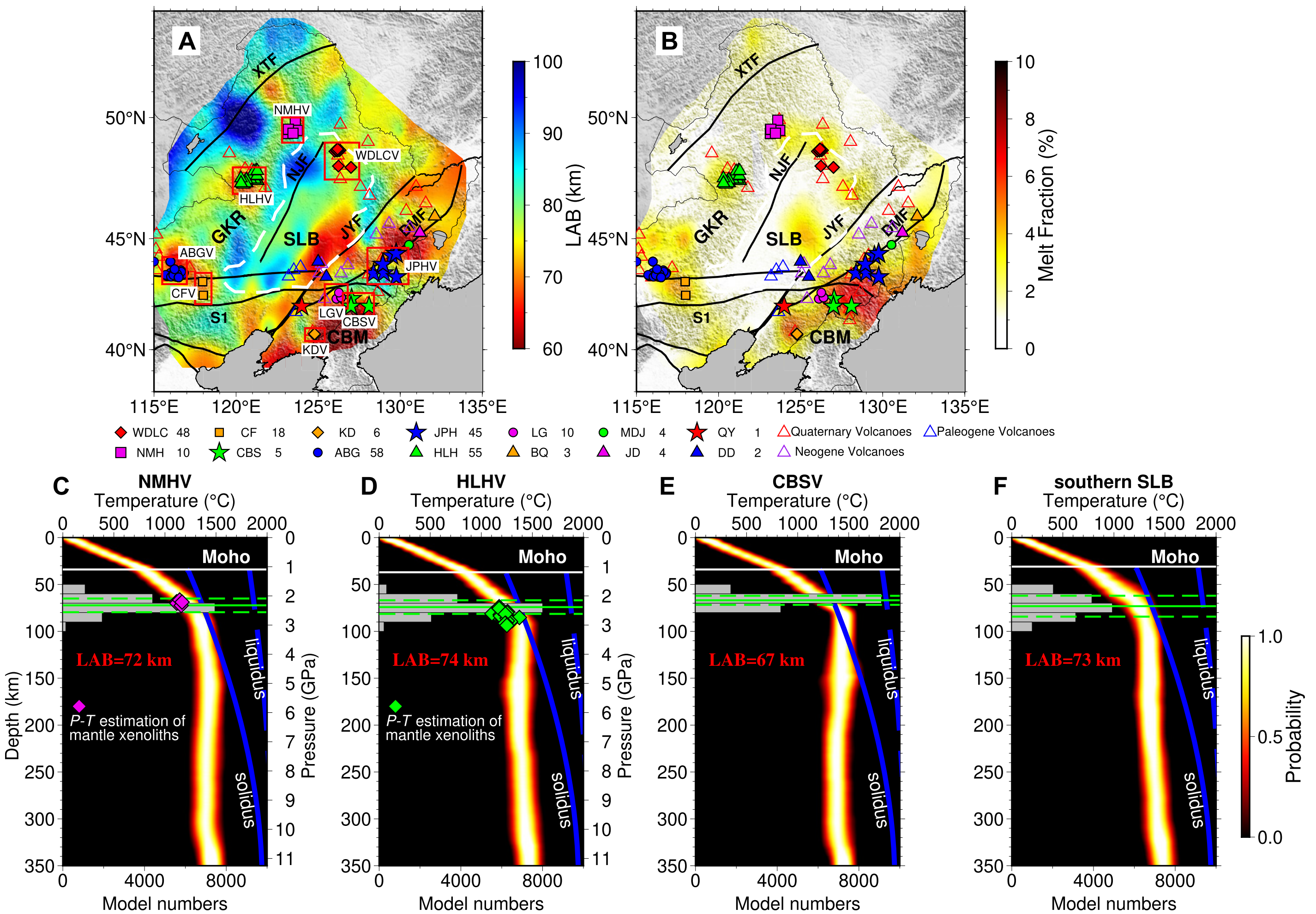

Figure 2. (A) Predicted lithosphere–asthenosphere boundary (LAB) depth. (B) Melt fraction in the asthenosphere. (C–F) The 1-D columns at four locations show geotherm probability density and posterior distribution of LAB depths. Basaltic samples shown in A and B (filled symbols) are younger than 5 Ma, and the number of samples available for each volcanic cluster is given in the key. Pressure-temperature (*P-T*) estimation of mantle xenoliths in C and D are from Guo et al. (2018b). BQ—Baoqing; MDJ—Mudanjiang; JD—Jidong; QY—Qingyuan; DD—Dadun; NMHV—Nuominhe volcanoes; HLHV—Halaha volcanoes; CBSV—Changbaishan volcanoes; WDLCV—Wudalianchi volcanoes; ABGV—Abaga volcanoes; JPHV—Jingpohu volcanoes; LGV—Longgang volcanoes; CFV—Chifeng volcanoes; KDV—Kuandian volcanoes. Other abbreviations are as found in Figure 1.

with a minimum sample population per area of 5. To retain the less evolved (most primitive) samples from the whole data set, we restricted our data set to samples with MgO contents >6%. Figure 4 and Figure S9 show plots of several trace element ratios and $(Na_2O + K_2O)/SiO_2$ versus LAB depth. These ratios are considered to be sensitive to the degree of melting of the source (Niu, 2011; Guo et al., 2020). For instance, partial melts produced by low degrees of mantle melting are usually enriched in highly incompatible elements (e.g., La and K_2O) and thus show high La/Sm and $(Na_2O + K_2O)/SiO_2$ ratios. The observed correlation of average whole-rock composition with LAB depth (Fig. 4) suggests that lithospheric thickness exerts a first-order control on the geochemistry of NEC intraplate basalts. More specifically, because the lithospheric lid impedes the upwelling and further decompression melting of the mantle, basalts erupted through thin lithosphere are characterized by geochemical signatures that are indicative of low pressure (lower Y/Yb and $(Na_2O + K_2O)/SiO_2$) and a higher extent of melting (lower La/Sm and La/Yb), whereas basalts that erupted through thick lithosphere exhibit characteristics that are indicative of lower degrees of melting and higher-pressure signatures (Niu, 2011). Although the absolute values of melt fractions predicted by our inversion can only be taken as a first approximation, we also observe clear correlations between composition and predicted melt fraction (Fig. S10). The effects of other factors such as contamination and source heterogeneity, which are considered to be secondary factors, on the composition of basalts are evaluated in the Supplemental Material.

The Deep Thermal Structure and Geodynamic Evolution of NEC

Davies et al. (2015) recently provided evidence that lithospheric thickness has a dominant influence on the volume and chemical composition of plume-derived magmas in eastern Australia, which is one of the world's most extensive intraplate volcanic regions. The case is different in NEC. Helium isotope studies and whole-mantle seismic tomography infer that the contribution of large mantle plumes to the volcanism in NEC seems unlikely (Huang and Zhao, 2006). Moreover, recent seismic tomography studies and geodynamic simulations suggest that the main mantle upwelling beneath NEC likely originates at mantle transition zone depths (Tang et al., 2014; Guo et al., 2018a; Yang and Faccenda, 2020; Xu et al., 2021). Our inverted three-dimensional (3-D) temperature structure shown in Figure 3A shows three large-scale, interconnected, high-temperature anomalies beneath the Changbai Mountain region, the central–north Songliao Basin, and the Abaga volcanic area, respectively. These upwellings interact with the base of the lithosphere and produce a small-scale, complex, upwelling-downwelling circulation pattern that is responsible for the melting of the shallow sublithospheric

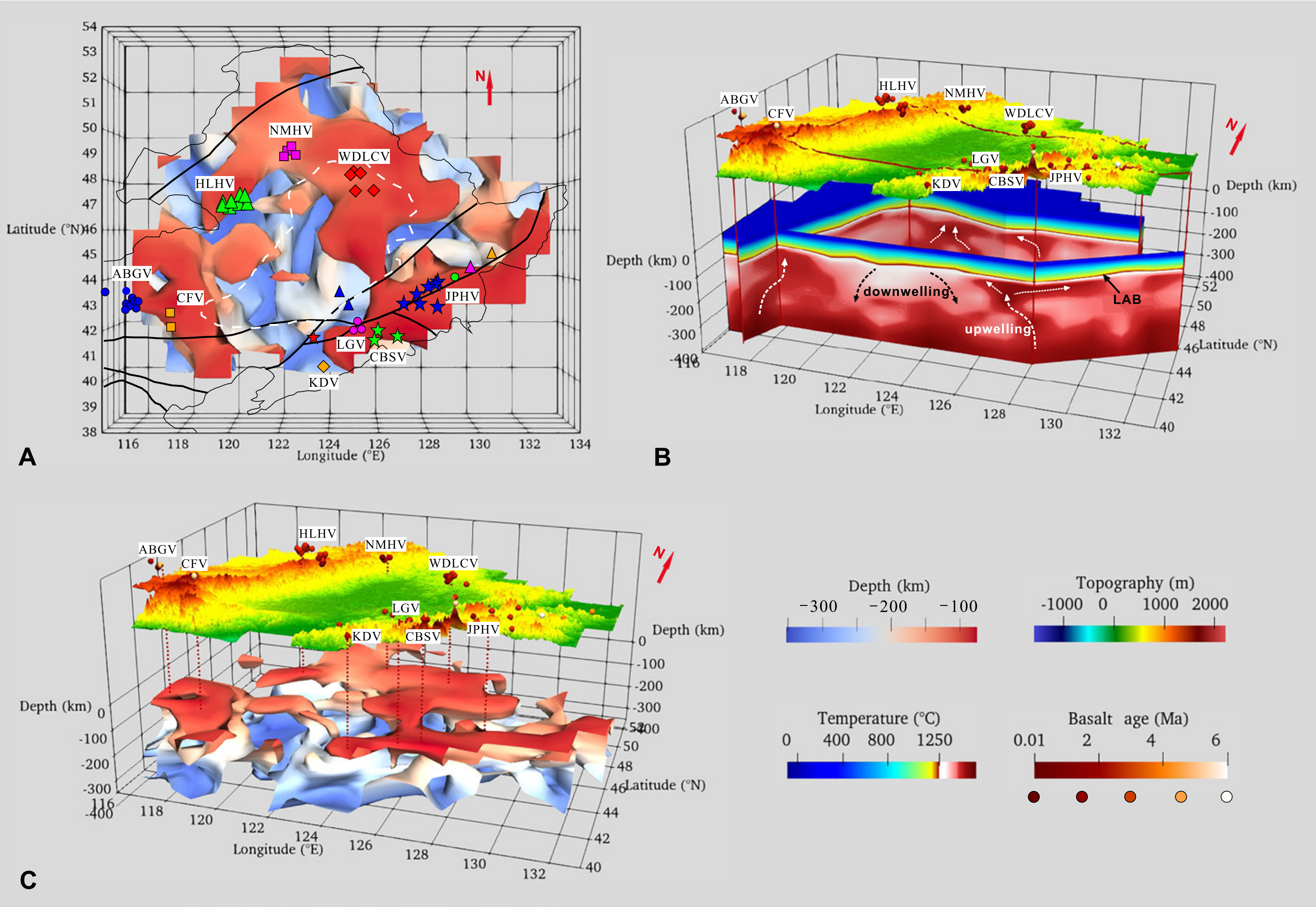

Figure 3. Three-dimensional rendering of the thermal field beneath northeast China. The isosurface in panels A and C includes temperatures >1405 °C and is colored as a function of depth. Hot upwellings originating at depths >350 km break into smaller cells at shallower depths and are focused beneath regions of recent volcanism. LAB—lithosphere–asthenosphere boundary; other abbreviations are as found in Figure 2.

mantle, with lithospheric structure modulating the localization of volcanism. More specifically, the high-temperature structure beneath the Changbai Mountain region indicates that the mantle upwelling may originate in the deep upper mantle or transition zone and then extend up to a depth of ~60 km, where it interacts with the base of a thin lithosphere (Fig. 3B). This process produces relatively high degrees of partial melting that preferentially migrates along the preexisting Dunhua-Mishan fault zone (Fig. 2B). Based on their shear wave velocity model, Guo et al. (2016, 2018a) suggested that the mantle upwelling beneath the Changbai Mountain region may be coupled to a return downwelling beneath the southern Songliao Basin. The significant low-temperature anomaly imaged beneath the southern Songliao Basin (Fig. 3B) supports this view. This sublithospheric downwelling also provides a plausible explanation for the volcanic cessation inside this region since ca. 28 Ma (Liu et al., 2001) and the subsequent migration of the volcanism toward the edges of the Songliao Basin. In this scenario, the recent intraplate basalts in the Wudalianchi, Nuominhe, and Halaha volcanic areas are derived from low-degree partial melting associated with small-scale upwellings that are either triggered or reinforced by the downwelling in the southern Songliao Basin region (Fig. 3). Taken together, our results suggest a very active sublithospheric circulation beneath NEC that couples several small-scale upwellings and downwellings in the shallow sublithospheric mantle.

CONCLUSION

Our model of the lithosphere and sublithospheric upper mantle beneath NEC is obtained from the joint inversion of newly acquired Rayleigh wave dispersion data, surface heat flow, geoid height, and absolute elevation data using a thermodynamically constrained probabilistic inversion approach. Our model bridges the important gap between the deep, large-scale mantle structure inferred from body-wave tomography and the local geochemical studies on erupted basalts. The model reveals a complex and very active 3-D circulation pattern in the shallow asthenosphere with several small-scale upwellings that join near the LAB and promote forced downwellings in the surroundings. We demonstrate that the location and composition of recent basaltic volcanism correlate well with regions of anomalously hot asthenosphere, but most importantly, with shallow LAB. This highlights the dominant role of lithospheric structure in controlling the location and nature of intraplate volcanism in NEC and in continental settings in general. The results from our study should be applicable to other regions with intraplate magmatism that is unrelated to large mantle plumes, and set the stage for developing new joint geophysical-geochemical inversion approaches to image the thermochemical state of the mantle and improve our understanding of the evolution of global intraplate volcanism.

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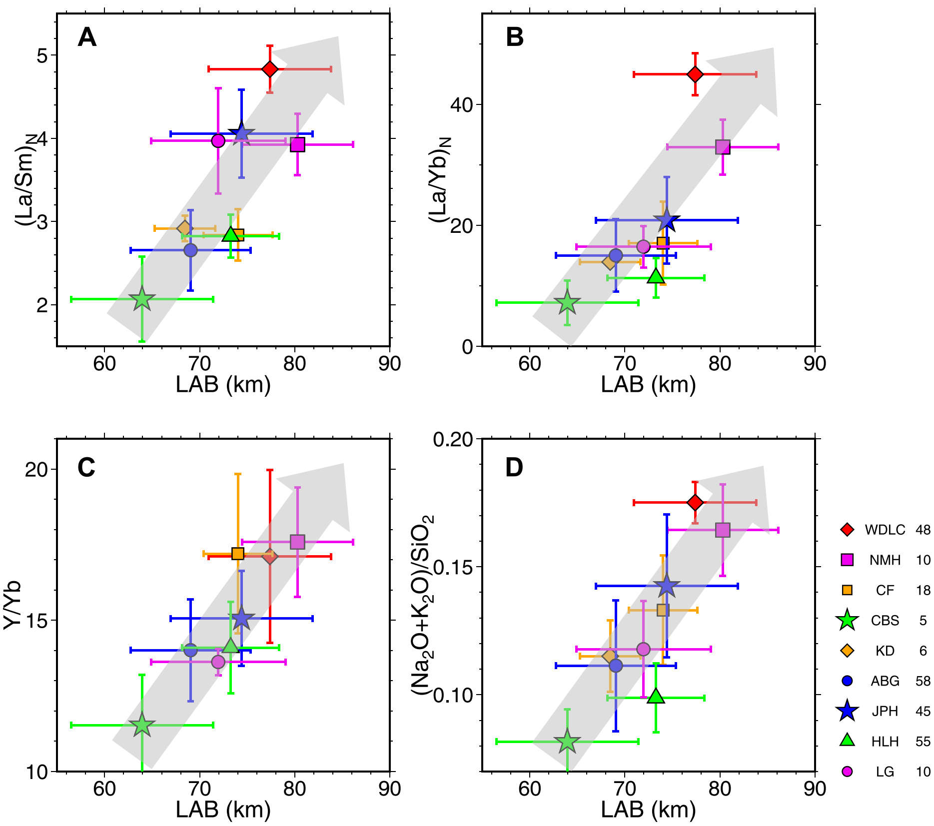

Figure 4. Trace element ratios (A–C) and total alkali versus silica (D) plotted with lithosphere–asthenosphere boundary (LAB) depth for samples younger than 5 Ma. Uncertainties are calculated within the red rectangles in Figure 2A for each volcanic cluster. Gray arrows highlight the general trend between lithospheric thickness and geochemical proxies of the degree of melting. Abbreviations are as found in Figure 2.

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