# Long-distance Asthenospheric Transport of Plume-influenced Mantle

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**Key Points:**

- Upper mantle partial melting prevails beneath the Anatolian Region
- Plume-originated asthenospheric mantle is transported from East Africa to Anatolia while preserving its elevated temperature
- Transport over ~2500 km is facilitated by reduced viscosity due to high temperature and possibly takes only ~10 Myr

**Abstract**

The origin of widespread volcanism far from plate boundaries and mantle plumes remains a fundamental unsolved question. An example of this puzzle is the Anatolian region, where abundant intraplate volcanism has occurred since 10 Ma, but a nearby underlying plume structure in the deep mantle is lacking. We employed a combination of seismic and geochemical data to link intraplate volcanism in Anatolia to a trail of magmatic centers leading back to East Africa and its mantle plume, consistent with northward asthenospheric transport of over ~2500 km distance. Joint modeling of seismic imaging and petrological data indicates that the east Anatolian mantle potential temperature is higher than the ambient mantle (~1420°C). Based on multiple seismic tomography models, the Anatolian upper mantle is likely connected to East Africa by an asthenospheric channel with low seismic velocities. Along the channel, isotopic signatures among volcanoes are consistent with a common mantle source, and petrological data demonstrate similar elevated mantle temperatures, consistent with little cooling in the channel during the long-distance transport. Horizontal asthenospheric pressure gradients originating from mantle plume upwelling beneath East Africa provide a mechanism for high lateral transport rates that match the relatively constant mantle potential temperatures along the channel. Rapid long-distance asthenospheric flow helps explain the widespread occurrence of global intraplate magmatism in regions far from deeply-rooted mantle plumes throughout Earth history.

**Plain Language Summary**

Volcanoes that exist in the middle of tectonic plates are often thought to be produced by plumes of high temperature mantle that originate deep within the Earth, near the core-mantle boundary.

However, while many of these "intraplate" volcanoes share chemical compositions with plume-related volcanism, their close connection to a deep mantle upwelling is not clear for all locations. In this study, we jointly analyze images of the Earth's interior structure from earthquake waves and the chemical properties of erupted magmas to make the case that: 1) the volcanoes in the Anatolia region are fed by a mantle plume that lies beneath the East African Rift system, and 2) upper mantle is transported horizontally over ~2500 km from Africa to Anatolia without significant cooling. We modelled mantle transport driven by a hot upwelling mantle plume and found that it is fast enough to explain the apparent lack of cooling. These results suggest that mantle plumes can affect a much larger volume of the Earth than is commonly assumed.

## 1 Introduction

Intraplate volcanism is widely observed on Earth. Some intraplate volcanoes lie above mantle plumes which potentially bring hot and fertile materials from as deep as the core-mantle boundary to the surface (French & Romanowicz, 2015; Morgan, 1972). These plume-associated volcanic fields often feature chemical compositions that differ from average upper mantle, including elevated source temperatures as well as trace-element and isotopic signatures of recycled and primordial mantle domains (Bao et al., 2022; Herzberg et al., 2007; Hofmann, 2007; Mundl et al., 2017; Putirka, 2005; Trela et al., 2017). However, other intraplate volcanic fields lack a vertical connection to a mantle plume and their origins are debated (Bao et al., 2022; Conrad et al., 2011).

To explain intraplate magmatism that is not located near a mantle plume, horizontal asthenospheric flow over distances of ~1000 km or has been proposed in western Africa (Ebinger & Sleep, 1998) and the Iceland-North Atlantic region (Schoonman et al., 2017), and such flow has also been

63 modelled beneath the Pacific Ocean over distances that exceed 2000 km (Ballmer et al., 2013).
64 However, observationally, uncertainty remains regarding the distances over which material from
65 a mantle plume can permeate the surrounding asthenosphere and the time-scales over which it
66 maintains its elevated temperature (Phipps Morgan et al., 1995). This information is critical to
67 understanding the role of plumes throughout Earth history, including large igneous provinces
68 where magmas sharing a mantle source erupt over massive areas (Madrigal et al., 2016; Marzoli
69 et al., 1999; Stern et al., 2020), and on planets like Venus that lack moving tectonic plates (Smrekar
70 et al., 2010).

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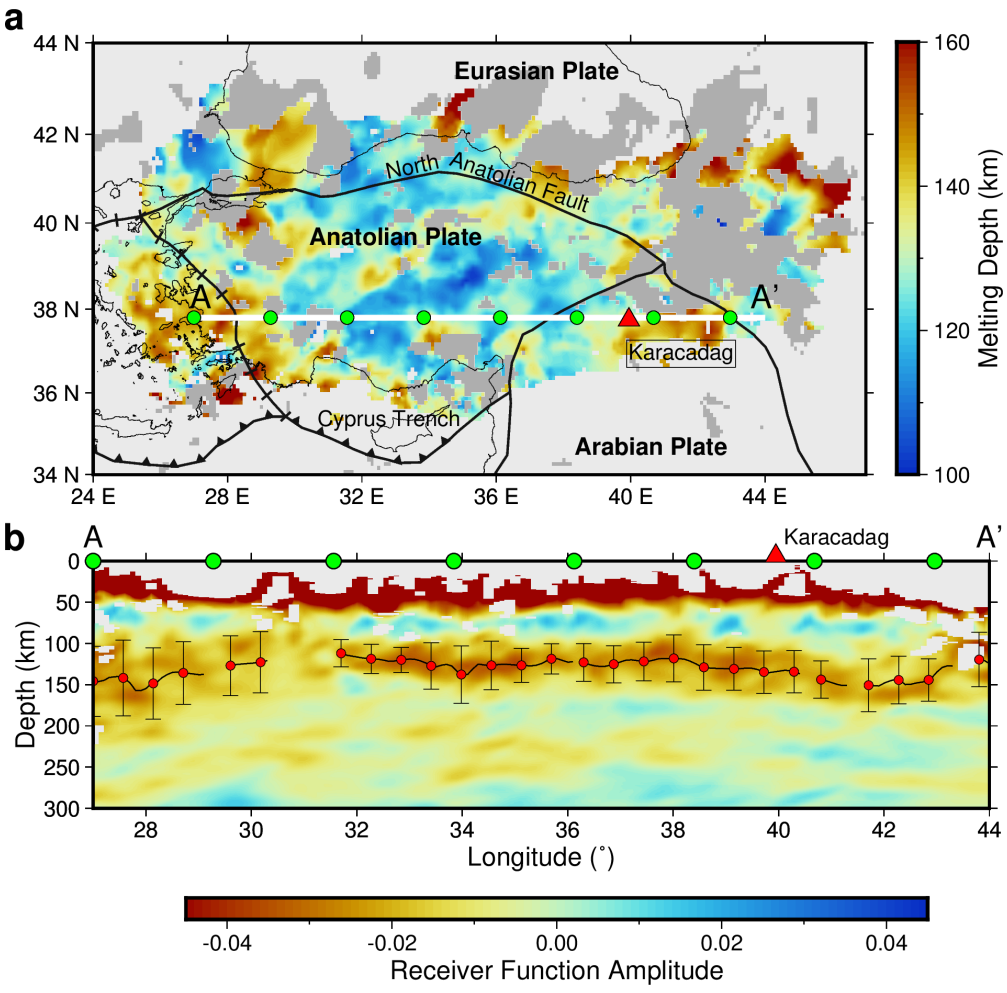


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**Figure 1.** Constraints on seismic velocity gradients and melting onset depths from Sp receiver functions. (a) Melting onset depths in Anatolia inferred from the positive mantle velocity gradient at depths of 100-160 km observed in the Sp common conversion point stack. Colors show positive velocity gradient depths; dark gray regions lack a clear observation of this feature. Profile A-A' location shown by white line with green circles. The Karacadag volcanic field is labelled by the red triangle, and thick black lines show plate boundaries (Bird, 2003). Subduction boundaries are labeled with triangles and divergent boundaries with bars. (b) Sp receiver function common conversion point stack amplitude for profile A-A' (10-100 s bandpass filter). Positive velocity gradient depths picked from the stack are shown by red circles. Error bars (black lines) are the depth ranges spanned by the Sp phase from this gradient, estimated as three times the standard deviation of the receiver function amplitude distributions (e.g. Figure S1a). Positive amplitudes (blue) at depths of 50-90 km represent the lithosphere-asthenosphere boundary. Green circles correspond to markers in (a).

In this paper, we address these fundamental questions by exploring the source of intraplate magmatism in Anatolia and its connection to lower mantle plumes. The tectonically active Anatolian region lies at the northeast edge of the Mediterranean Sea (Figure 1a). To the north, the Anatolian plate is separated from the Eurasian plate by the North Anatolian Fault; to the south, the African plate subducts beneath Anatolia via the Cyprus trench; and to the southeast, the Anatolian plate is compressed by the Arabian plate (Bird, 2003).

Extensive intraplate volcanism exists in Anatolia, and while the erupted basaltic magmas have indicated mantle temperatures and compositions similar to hotspot volcanoes in some areas (McNab et al., 2018; Nikogosian et al., 2018; Reid et al., 2017), this region lacks evidence for a mantle plume that is locally connected to the lower mantle (French & Romanowicz, 2015; Lei et al., 2020). To explain the intraplate magmatism, regional processes within Anatolia have been proposed, including upwelling related to lithospheric extension, lithospheric delamination, and slab rollback and/or fragmentation (e.g. Delph et al., 2017; Göğüş & Pysklywec, 2008; Keskin, 2007; Lynner et al.; Memiş et al., 2020). Although these processes dramatically alter the lithosphere, in most cases they do not result in broad zones with significantly hotter asthenosphere

and elevated mantle potential temperatures, although local temperature increases of tens of degrees may be produced (e.g. King & Ritsema, 2000; Van Wijk et al., 2008). Alternatively, other studies have proposed that hot mantle derived from upwelling beneath the East African Rift (EAR) flows horizontally over thousands of kilometers towards Anatolia (Ershov & Nikishin, 2004; Faccenna et al., 2013; Hansen et al., 2012; Wei et al., 2019). This model is consistent with regional seismic velocity and anisotropy patterns (Wei et al., 2019), and also local seismic tomography results (e.g. Berk Biryol et al., 2011) that suggest that hot mantle material could flow into the Anatolian region through the slab window opened by the Arabian plate-Anatolian plate collision. This type of model provides a possible explanation for high mantle potential temperatures beneath Anatolia. Once in Anatolia, this hotter-than-average asthenosphere could interact with regional processes such as lithospheric extension, delamination, and slab roll-back and break-off.

To systematically test the plausibility of long-distance transport, several questions must be addressed: 1) What are the bounds on mantle potential temperature beneath Anatolia and are they indeed in the range of hotspot regions globally? 2) Does mantle along the transport path record a common mantle source? 3) Is the estimated mantle temperature along the transport path consistent with a single, plume-related, heat source? 4) With reasonable mantle viscosities, is the long-distant transport consistent with constraints from geodynamic models?

In the following sections, we address these questions by joint interpretation of seismic, petrological, and geochemical data, aided by geodynamical modeling, to make the case that rapid lateral transport of high temperature plume-derived asthenosphere from the EAR to Anatolia is possible. To answer question (1), in Section 2 we used novel joint modeling of seismic receiver function phases and basaltic primary magma equilibration conditions to explain the extensive upper mantle melting beneath Anatolia and to constrain upper mantle potential temperature. To

answer question (2), in Section 3 we analyzed multiple seismic tomography models to verify that they are consistent with a channel of high-temperature asthenosphere, and we compared various radiogenic isotope ratios along the transport route. To answer question (3), in Section 4, we obtained mantle potential temperatures at different locations along the path with basaltic magma samples. Finally, to answer question (4), in Section 5, we used a simplified 1D pressure-driven Poiseuille flow model to demonstrate the physical plausibility of rapid long-distance asthenospheric transport.

## 2 Anatolian Mantle Temperatures

### 2.1 Extensive Partial Melting Beneath Anatolia

The Anatolian upper mantle has recently been imaged with Sp receiver function common-conversion point stacking using a new approach that incorporates Sp sensitivity kernels in the spatial functions used to weight the receiver functions as they are summed at each point in the stack (Hua, Fischer, Wu, et al., 2020). The stacking used 23,787 individual receiver functions. Within the upper mantle, in addition to the commonly observed negative velocity gradient (positive receiver function amplitude) that represents the seismic lithosphere-asthenosphere boundary (LAB) (e.g. Figure S1i), the receiver function stack reveals an unusual and widespread asthenospheric positive shear velocity gradient (PVG) at depths of 100-150 km (Figure 1b & S1) that is indicated by negative receiver function amplitudes. To study the depth range over which this gradient extends, similar stacking of Sp receiver functions was performed using seismograms from a range of bandpass filters. This analysis demonstrated that this velocity gradient is gradual in depth (it extends over more than 30 km) and is better characterized with long-period data (Hua,

Fischer, Wu, et al., 2020). Hence, in this study, we used stacks from seismograms with a 10-100 s bandpass filter to study the PVG. The shallower negative velocity gradient (positive receiver function amplitude) associated with the LAB is observed at ~70 km depth (Figure S1) (Hua, Fischer, Wu, et al., 2020). However, due to the thin mantle lithosphere, this phase is clearer at shorter periods (Hua, Fischer, Wu, et al., 2020), so we used stacks from a 2-20 s filter to study this receiver function phase.

To quantify the depths of the PVG and LAB, these receiver function phases were picked with an algorithm (Hua et al., 2018, see Supporting Information Text S1 for details) that assumes the phase amplitude at a given depth is proportional to the probability that the velocity gradient is located at that depth (Figure S1a). This assumption is reasonable given that the common-conversion point stacked receiver function amplitude is proportional to the intensity of the velocity gradient (Hua, Fischer, Mancinelli, et al., 2020). The depth of the phase is defined as the expected depth for the distribution, and the depth extent of the phase is characterized by one and half the standard deviation of the distribution. The phase depth picking indicates that the PVG is present primarily at depths of 100-150 km beneath most of the Anatolian region (Figure 1a), while the LAB phase exists mainly at depths of 60-85 km (Figure S1h).

To assess the potential origins of the PVG, we compared its depth to two full-waveform tomography models (Blom et al., 2020; Fichtner et al., 2013). Both velocity models contain a widespread layer of low seismic velocity above the 100-150 km depth of the receiver function PVG, consistent with an interpretation where the PVG is a depth-localized lower boundary to this layer (Hua, Fischer, Wu, et al., 2020). This result is illustrated in Figure 2a for the location of the Karacadag volcanic field. To assess whether partial melt could exist within the low velocity layer, the velocity models were transformed to temperature assuming different mantle conditions and

transform relationships (see Supporting Information Text S2). For the case shown in Figure 2, the velocity models were converted to temperature based on the relationship in Yamauchi and Takei (2016) and the shear modulus from Priestley and McKenzie (2013) assuming 100 wt. ppm water in the mantle (Figure 2b), but the direct effects of an unconstrained melt fraction on velocity are not accounted for in the calculation. Temperatures exceed the inferred mantle solidus over most of the low velocity layer, starting at depths of 120-160 km and continuing to depths of 50-60 km. In this depth range, calculated temperatures reach unrealistically high values. However, at supra-solidus conditions, the presence of partial melt will likely also reduce shear wave velocity, resulting in more reasonable mantle temperatures. We tested this result using different mantle conditions as well as a different velocity-temperature relationship (Jackson & Faul, 2010). While these cases result in different estimated mantle temperatures (Figure S2), the estimated geotherm consistently starts to exceed the solidus at depths close to where the PVG is observed, and unrealistically high mantle temperatures are calculated above these depths (Figure S2). Overall, these comparisons overall support the conclusion that the PVG could represent the base of a layer containing partial melt and lies at the depth where the upper mantle starts to melt. The LAB phase is consistent with a negative velocity gradient at the top of this melt-bearing layer.

We emphasize that the calculated temperature profiles are highly dependent on the chosen conversion relationship between shear wave velocity and temperature and assumptions about other mantle parameters such as water content (Figures 2 and S2). We therefore do not use this type of velocity-temperature scaling to infer mantle temperatures for the remainder of this paper. Rather, we have developed a new approach, described in the next two sections, which relies on the depths of the PVG and LAB phases and constraints on mantle temperatures from the major element compositions of erupted basalts.

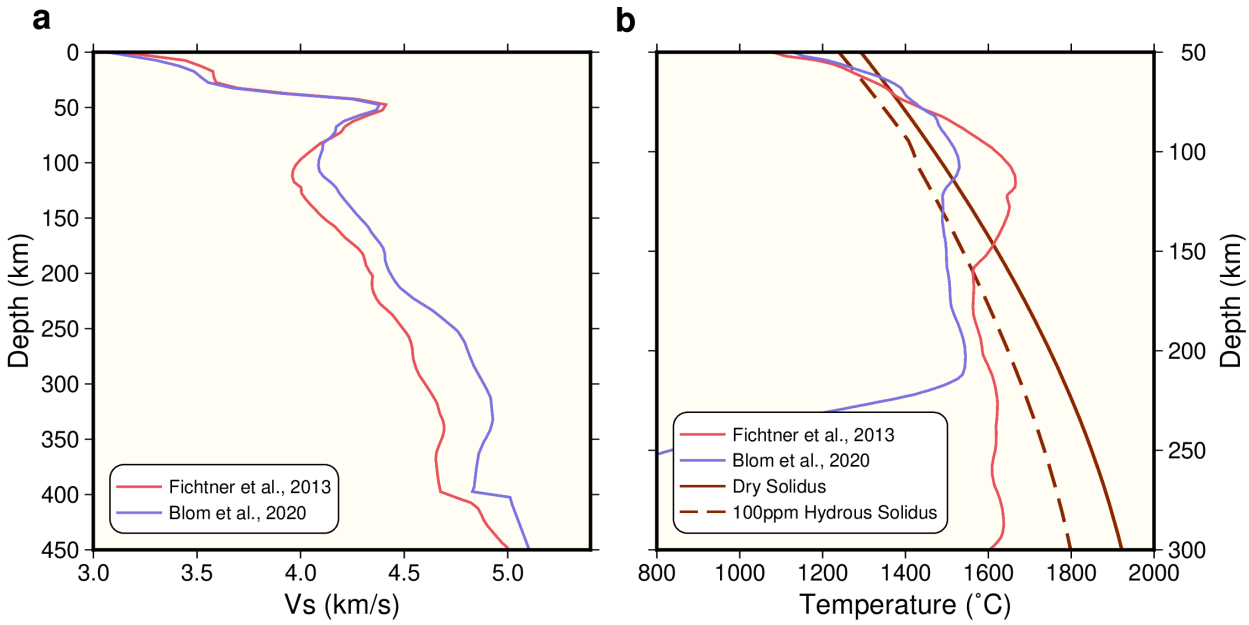


**Figure 2.** $V_S$-temperature conversion for two velocity models. These examples demonstrate that the positive velocity gradient at depths of 100-150 km indicated by the Sp phases can be interpreted as the lower boundary of a layer containing partial melt. However, these loosely constrained converted temperatures are not used otherwise in our analysis. (a) 1D $V_S$ profiles from local (Fichtner et al., 2013) and regional (Blom et al., 2020) models at 38.9°N, 33.2°E. (b) Temperature converted from $V_S$ in (a); cases for a dry and 100 wt. ppm hydrous solidus (Hirschmann et al., 2009) are shown by solid and dashed dark red lines. Conversions are based on the $V_S$-temperature relationship from Yamauchi and Takei (2016), assuming 100 wt. ppm of mantle water, and the modulus estimated based on Priestley and McKenzie (2013).

## 2.2 Primary Magma Equilibration Pressure and Temperature (P-T) Conditions

To provide independent constraints on the mantle geotherm from major element compositions of erupted basalt samples, we first picked reliable basalt samples from the Karacadag volcanic field (Figure 1a). We also estimated the temperatures and pressures of last mantle equilibration from basalts in other Anatolian volcanic fields, but the Karacadag field was the only location where a sufficient number of asthenospheric samples were found. In this study, all samples in the GEOROC database till 2020 (http://georoc.mpch-mainz.gwdg.de/Georoc) from 37° to 38°N and

212 39° to 40.5°E were classified as being from Karacadag (Supporting information Data Set S1).
213 The FeO and $Fe_2O_3$ weight percentages were first converted to $FeO_{total}$ to represent the total iron
214 weight percentage. Then we calculated the sum of the weight percentages for major elements,
215 and only samples with summed weight percentage between 98% and 102% were used. For these
216 samples, the major element weight percentages were normalized to make their sum equal to
217 100%. We only used samples that follow an olivine control trend based on major element (FeO,
218 $TiO_2$, CaO, $Al_2O_3$, $CaO/Al_2O_3$, $Na_2O$, etc.) variations with MgO, and limiting the samples to
219 those with MgO higher than 8 wt. %, and $SiO_2$ higher than 45 wt. % to be consistent with
220 experiments done with peridotite sources that are the basis for modeled primary magmas FeO-
221 MgO thermometers (Herzberg & Asimow, 2008; Lee et al., 2009). The average location for the
222 117 selected samples is 37.58°N, 39.83°E. The Sp PVG phase at this location (Figure S1a) is
223 centered at 138 km depth with a phase depth extent of 28.5 km (defined as 1.5 times the
224 distribution standard deviation), as obtained from the receiver function phase picking.

225 Primary magma equilibration pressure-temperature (P-T) conditions for the basaltic magma
226 samples were calculated based on the Lee et al. (2009) parameterization (Figure 3a). Starting from
227 the major element compositions of the collected melt samples, this method first adds olivine
228 increments in equilibrium with the instantaneous melt composition back to the melt until the melt
229 reaches equilibration with the suggested ambient mantle composition (explaining why only
230 samples in an olivine control trend can be used); the corresponding melt composition represents
231 the primary magma. Then, the primary magma equilibration P-T conditions are estimated from the
232 primary magma major element compositions using an experimentally-defined empirical
233 relationship (Lee et al., 2009). A more recently calibrated empirical relationship also exists (Plank
234 & Forsyth, 2016), based on the same experimental data used by Lee et al. (2009); the resulting T-

235 P estimates are similar (Plank & Forsyth, 2016). We therefore chose to continue using the well-
236 established thermobarometer in Lee et al. (2009).

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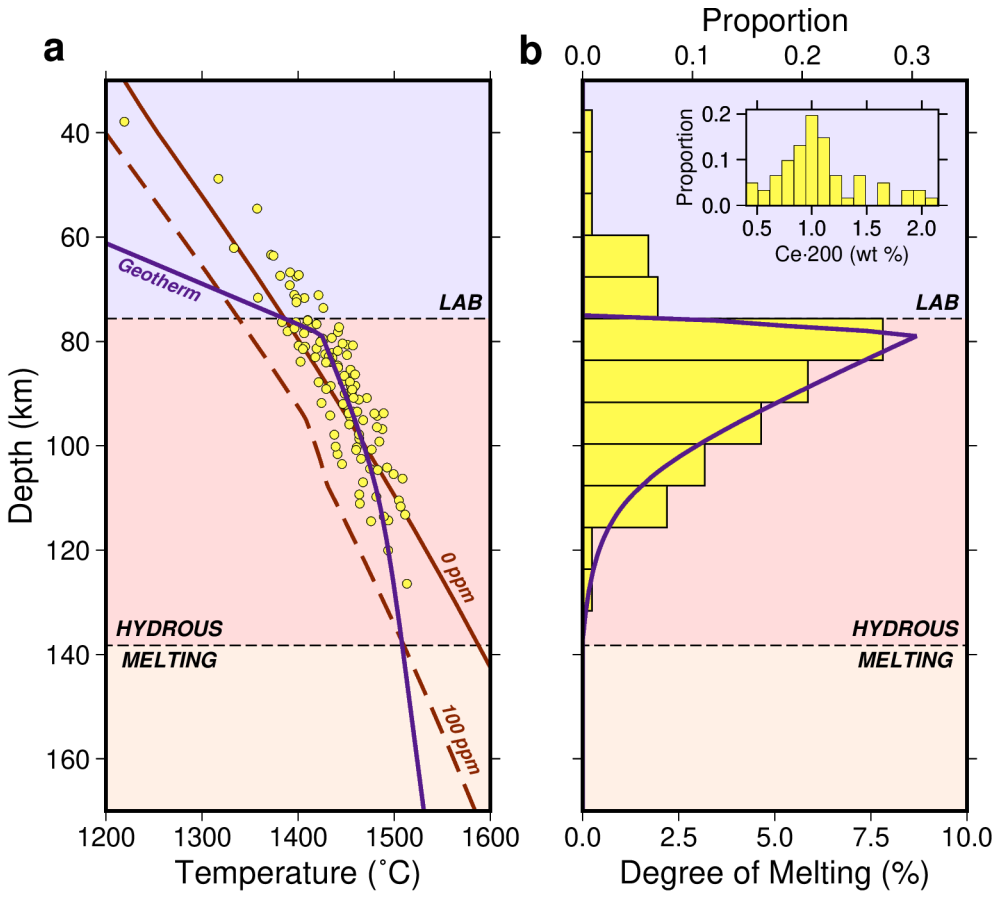


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239 **Figure 3.** Mantle $T_P$ determination with Karacadag samples. (a) The geotherm (purple line) that
240 best fits primary magma equilibration P-T conditions (yellow dots) and melting onset depth from
241 the Sp stack (lower black dashed line) beneath the Karacadag volcanic field. The dry solidus and
242 100 wt. ppm water solidus (Hirschmann et al., 2009) are shown by the red solid and dashed lines.
243 The upper dashed line indicates the lithosphere-asthenosphere boundary from the Sp stack. (b)
244 Degree of melting predicted for the mantle conditions in (a) (purple line). The vertical histogram
245 shows the distribution of basalt sample equilibration depths. The histogram in the inset shows the
246 distribution of 200 times Ce for samples as a proxy for water in the melt sample.

247

248 The estimated final P-T equilibration conditions also depend on the assumed water weight
249 percentage in the melt sample, oxidation state (represented by $Fe^{3+}/Fe^{Total}$) and source mantle
250 forsterite content (Fo) (Figure 4a-4c). We assumed the 1 wt. % water in the melt, a typical value

for primitive intraplate basalts (Dixon & Clague, 2001; Plank & Forsyth, 2016). This value is also in the range of water contents in olivine hosted melt inclusions that were collected at a volcano ~300 km away from Karacadag (Özdemir et al., 2011). To further validate the assumed water content, the Ce abundances of these basalt samples were used as a proxy (Dixon et al., 2002). Ce values were multiplied by 200 (Dixon et al., 2002) to obtain the estimated water content (inset in Figure 3b), which is also distributed around 1 wt. %. If the actual water in the melt is not approximately the assumed value, this parameter could introduce a ~30°C difference in the calculated mantle equilibration temperature (e.g. Figure. 4a). For the other two factors, the effects from $Fe^{3+}/Fe^{Total}$ and Fo are nearly identical (Figure 4d), so we fixed Fo to be 90% and only solved for bounds on the value of $Fe^{3+}/Fe^{Total}$.

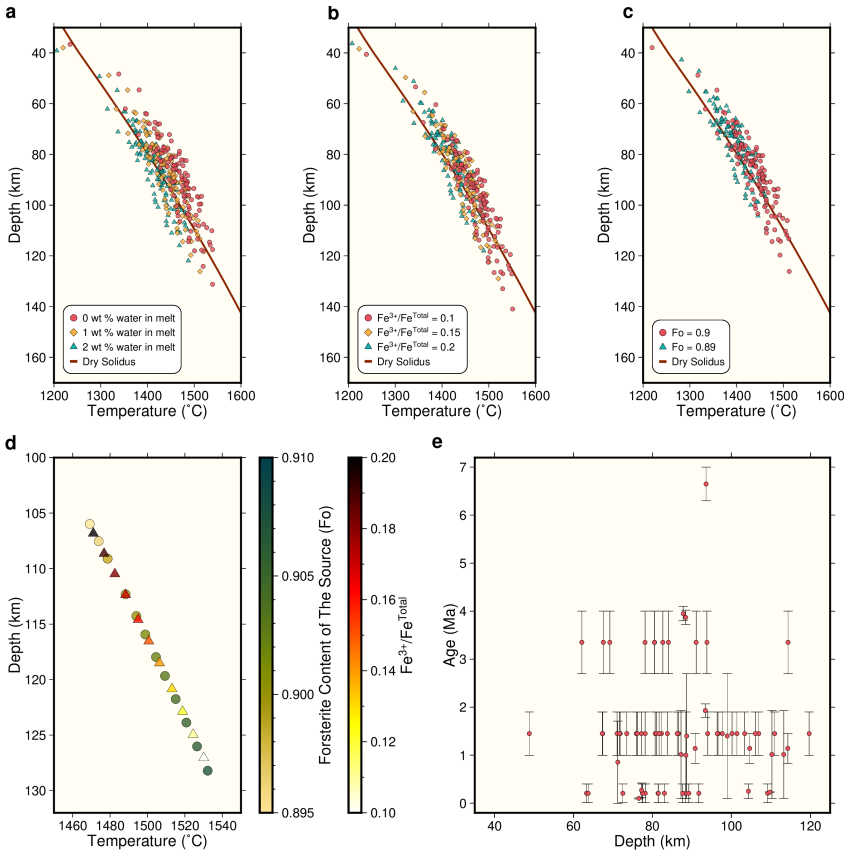


**Figure 4.** Primary magma equilibration P-T conditions for Karacadag samples. In (a)-(c), we test the effect of wt. % water in melt, $Fe^{3+}/Fe^{Total}$ and Fo on the estimated melt equilibration conditions. Red lines in (a)-(c) show the dry solidus (Hirschmann et al., 2009). (a) The equilibration conditions with varying water in the melt (labelled in legends); shifts in temperature are larger than shifts in pressure. (b) The equilibration conditions with varying oxidation state ($Fe^{3+}/Fe^{Total}$); shifts in pressure are larger than shifts in temperature. (c) The equilibration conditions with different forsterite content (Fo). (d) The effect of changes in Fo and $Fe^{3+}/Fe^{Total}$ on the equilibration conditions for a single sample (Sample ID 3983 in Supporting Information Data Set S1). (e) Equilibration depth versus sample age for the estimated and assumed parameters (1 wt. % water in melt, Fo equal to 0.9 and $Fe^{3+}/Fe^{Total}$ equal to 0.1615). Error bars show age uncertainties from published studies.

To constrain $Fe^{3+}/Fe^{Total}$, we used the depth of the smoothed Sp receiver function LAB phase (Figure S1h). $Fe^{3+}/Fe^{Total}$ primarily affects the estimated equilibration pressure but also has a smaller effect on equilibration temperature (Figure 4b). Assuming the equilibration P-T conditions represent the geotherm, the distribution of the sample equilibration depths should be similar in shape to variation in the degree of melting with depth, as depths with a higher degree of melting are more likely to have generated melt that is extracted to the surface and collected, especially for a volcanic field with an abundant number of samples in a small region like Karacadag. Since the LAB phase represents the upper boundary of the low velocity layer in which partial melt is expected to be concentrated, the degree of melting is expected to increase abruptly with depth across the seismically defined LAB, so we expect the number of samples equilibrated beneath the LAB depth to be much greater than the number equilibrated above this depth. In practice, we performed a grid search over $Fe^{3+}/Fe^{Total}$ values from 0.05 to 0.3 with an interval of 0.001 to find the $Fe^{3+}/Fe^{Total}$ values that result in the largest difference between the number of samples in the 10 km depth range beneath the LAB (75-85 km depth) and the number of samples in the 10 km depth range above the LAB (65-75 km depth) (Figure 3b). The 10 km interval is used as it is the standard deviation of the picked LAB depth distribution for this region. Since $Fe^{3+}/Fe^{Total}$ values between 0.16 and 0.163 produce the maximum difference in number of samples equilibrated above and

below the LAB depth, we set $Fe^{3+}/Fe^{Total}$ to 0.16 for the remaining analyses. This value is consistent with high temperature upper mantle conditions, as shown by samples from other intraplate locations like Hawaii and Iceland that also indicate similar $Fe^{3+}/Fe^{Total}$ values (Moussallam et al., 2019).

With these parameters, we calculated the equilibration P-T conditions of the Karacadag melt samples (Lee et al., 2009) (Supporting Information Data Set S1). To convert equilibration pressures to depths, we used the pressure-depth relationship obtained in the $V_S$-temperature conversion section assuming the local velocity model (Fichtner et al., 2013) for 70 s, a mantle with 100 wt. ppm of water, the $V_S$-temperature relationship of Yamauchi and Takei (2016), and the shear modulus dependence of Priestley and McKenzie (2013) (Supporting Information Text S2).

### 2.3 Joint Modeling of Receiver Function and Primary Magma Equilibrium Conditions

With both the Karacadag melting onset depth at 138 km from the Sp receiver function PVG phase and the estimated primary magma equilibration P-T conditions from the 117 reliable Karacadag basalt samples, both the mantle potential temperature ($T_P$) and the water content of the Karacadag volcanic field are constrained through joint modeling. We first assumed that the primary magma P-T conditions represent the actual mantle conditions, and the asthenospheric geotherm follows an adiabat. Values of $T_P$ and mantle water content were then obtained by requiring that the corresponding mantle geotherm approximates the equilibration P-T conditions, and that the geotherm intersects the hydrous solidus for the given water content (Hirschmann et al., 2009) such that the onset of melting matches the seismically-observed (PVG) melting depth (Figure 3a).

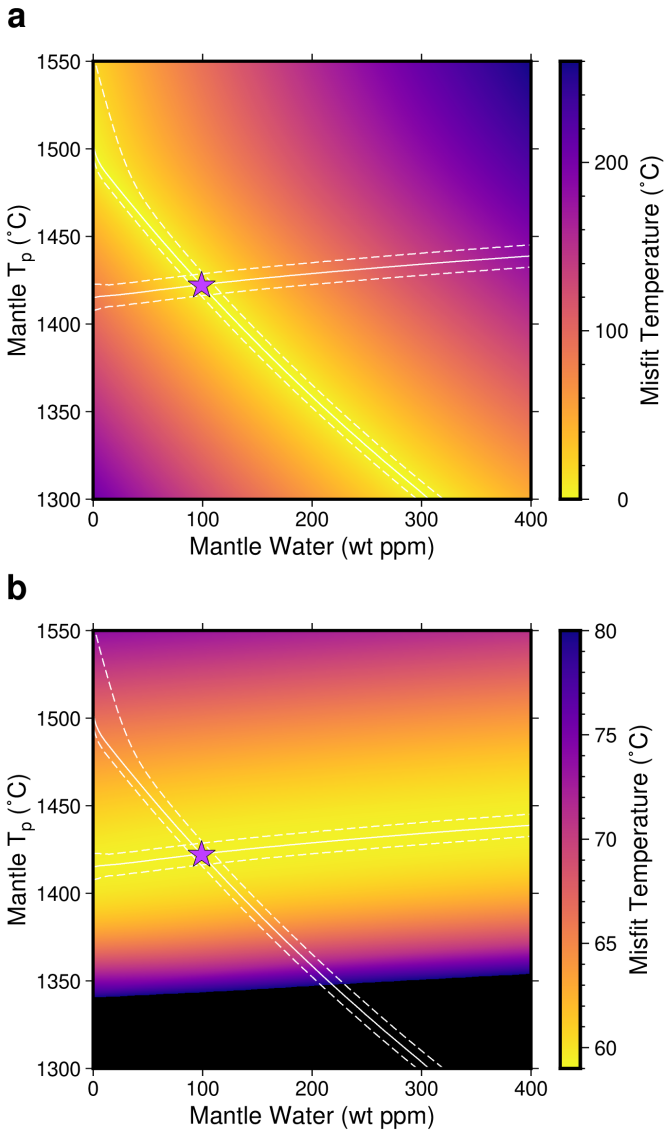



**Figure 5.** Joint modeling results of Sp-based melting onset depth and basalt equilibration P-T conditions. Misfit values are shown as colored surfaces for (a) melting depths and (b) basalt sample P-T values. White solid lines show $T_P$ and water content values that result in minima for both misfit functions, and white dashed lines show twice the standard deviation for the solid lines. The purple star shows the best fitting $T_P$ and water content values for Karacadag samples. Black regions have misfits beyond the upper limit of the color bar.

In practice, a grid search of $T_P$ and mantle water content values was employed for the modeling (Figure 5). We tested $T_P$ from 1300°C to 1550°C, and water from 0 to 400 wt. ppm. For each tested $T_P$-water combination, we estimated two misfits between model predictions and conditions based

on either the observed melting depth from the Sp stack or the basalt samples. One misfit is $\left|T_{soli} - T_{geo}\right|$ (Figure 5a), where $T_{soli}$ is the hydrous solidus temperature at the observed melting depth from the PVG with the assumed water content, and $T_{geo}$ is the predicted geotherm temperature at the same depth for the values of $T_P$ and water (see Supporting Information Text S3 for how we construct geotherms). The misfit between the predicted geotherm and the basalt equilibration P-T conditions is characterized as $\left\|T_{sample} - T_{geo}\right\|_2$ (Figure 5b), where in this L2-norm misfit function, $T_{sample}$ represents the primary magma equilibration temperature at its equilibration depth, while $T_{geo}$ represents the predicted geotherm temperature at that equilibration depth. Each of the misfit functions reaches a minimum value along a curve that reflects trade-offs in the effects of $T_P$ and water (Figure 5). However, the intersection of the two misfit minima curves resolves the $T_P$ and water conditions that satisfy both seismic and basalt data. The best-fitting values for the Karacadag basalts are 1420°C for $T_P$ and 100 wt. ppm for mantle water content.

To further test the estimated values of $T_P$ and mantle water content, we predicted the degree of melting for the inferred geotherm (Hirschmann, 2010; Hirschmann et al., 2009; Katz et al., 2003) (see Supporting Information Text S3). The predicted degree of melting correlates with the observed equilibration depth distribution of the basaltic samples (Figure 3b). Since melt is more likely to be extracted at depths with higher degrees of melting, this agreement validates the $T_P$ and mantle water content estimates and the assumption that P-T conditions represent the geotherm. An alternative interpretation for the equilibration P-T values from the basalts is that they always represent re-equilibration of the magmas at the base of the lithosphere (Gazel et al., 2012b; Plank & Forsyth, 2016), and that the distribution of equilibration depths (Figure 3b) is caused by

lithospheric thinning. However, this interpretation requires that magma samples equilibrated at shallower depths be younger than those from deeper depths, which is not evident in the basalt data (Figure 4e).

## 2.4 The Uncertainty of the Calculated Mantle Conditions

We quantified the uncertainty of our grid search method for determining $T_P$ and mantle water content. For uncertainties related to the seismically-inferred melting onset depth, a Monte Carlo method was used. Since the melting onset depth is defined as the center of the receiver function PVG phase, to calculate its uncertainties we randomly perturbed the stacked Sp receiver function at Karacadag based on an estimated covariance matrix, whose elements represent the covariance between receiver function amplitudes at different depths. This operation was repeated 60,000 times, and the picked depth of the perturbed receiver function PVG phase was recorded. We used twice the standard deviation of the 60,000 PVG depths as the PVG depth uncertainty (±9.7 km). To construct the covariance matrix used in this operation, the variance of the Sp stacked amplitudes at Karacadag (Hua, Fischer, Wu, et al., 2020) was used to form the diagonal terms. The off-diagonal terms, which reflect the covariance between different depths, were based on the Gaussian shape functions that were used in the time-domain deconvolution of the receiver functions; these Gaussians have a standard deviation equal to the S-wave wavelength at 1 s (Hua, Fischer, Wu, et al., 2020). The PVG depth uncertainty (±9.7 km) was transferred to the uncertainty of the melting depth trade-off curve in Figure 5. For the uncertainty related to the basalt samples, we bootstrapped the 117 samples 500 times. Each time the corresponding trade-off curve was recorded, and twice the standard deviation of that curve was used as its uncertainty (Figure 5).

Based on the uncertainties in the seismically-constrained melting depth and the basalt sample trade-off curves, the resulting estimates of $T_P$ and mantle water content have two-standard deviation uncertainties of ±6.4°C, and ±17 wt. ppm. The resulting $T_P$ value of 1420±6.4°C for the Karacadag field is consistent with the 1420°C $T_P$ estimate from Reid et al. (2017), obtained with a different method. It also falls within the range of elevated $T_P$ values for eastern Anatolia from a previous study (McNab et al., 2018). However, our calculated uncertainties depend strongly on our interpretation of the PVG phase, i.e. that the center of the phase represents the melting onset depth. In addition, the depth uncertainty of 9.7 km represents the uncertainty of the picked center of the PVG phase, which is different from the previously described PVG depth extent. The latter is represented by 1.5 times the standard deviation of the receiver function amplitude distribution (28.5 km, Figure S1a) where the receiver function amplitudes are treated as the probability distribution for the depth of the PVG phase. Similarly, the bootstrapping result for the geotherm determined from the basalt samples represents the uncertainty for the representative geotherm that is closest to all of the samples. However, if geotherms that pass through calculated equilibration conditions for each individual sample are considered, their variation would be much bigger (as evident from the spread of samples in Figure 3a).

To make sure the temperature estimation is not biased by our interpretation of the observed Sp receiver function PVG phase, we also tested two alternative scenarios. In the first scenario, we considered the possibility that the depth of the center of the PVG phase corresponds to 0.5% of melting instead of incipient melting (Figure 6a & 6b) since a small amount of melt could be present at greater depths due to $CO_2$ (Dasgupta et al., 2007). The joint modeling in this case produces a $T_P$ of 1430°C and a water content of 185 wt. ppm. In the second scenario, we assumed that the lower boundary of the positive velocity gradient Sp phase was taken as the melting onset depth.

In other words, the center depth of the phase plus the depth extent (1.5 times standard deviation for the PVG phase distribution 28.5 km) was assumed to define the melting onset depth (Figure 6c & 6d). This case yields a $T_P$ of 1425°C and a water content of 155 wt. ppm. Overall, both cases introduce little change in $T_P$ estimation but have a larger effect on inferred values of mantle water content.

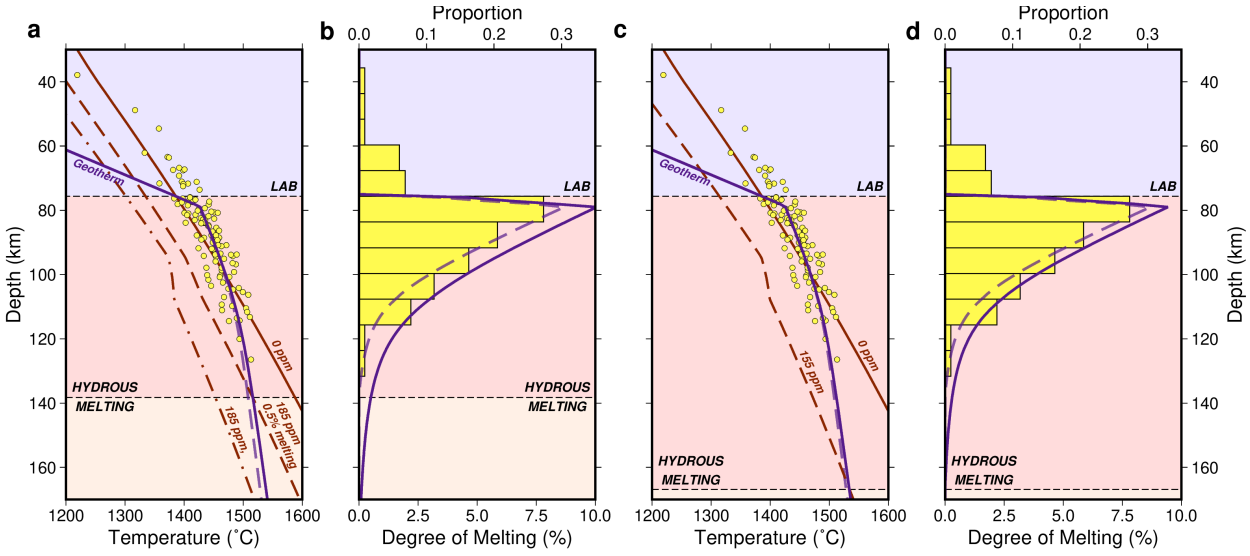



**Figure 6.** Alternative scenarios for mantle $T_P$ determination for Karacadag. (a)/(b) The scenario where the positive velocity gradient Sp phase represents 0.5% of melting (Hirschmann, 2010) instead of incipient melting, and 185 wt. ppm water is the best-fitting value. a) The solid purple line shows the final determined geotherm that best fits primary magma equilibration P-T conditions (yellow dots) and melting onset depth from the Sp stack (lower black dashed line) beneath the Karacadag volcanic field. The dashed red line shows the 185 wt. ppm water mantle 0.5% melting conditions, and the dotted dashed line shows the 185 wt. ppm hydrous solidus. b) Degree of melting predicted for the mantle conditions in (a) (purple line). The vertical histogram shows the distribution of basalt sample equilibration depths. (c)/(d) The scenario where the bottom of the positive velocity gradient is the melting depth, and 155 wt. ppm water is the best-fitting value. The solid purple line shows the final determined geotherm (c) and degree of melting (d). In (c), the dashed red line shows the 155 wt. ppm hydrous solidus. Otherwise, these plots are similar to Figure 3 except without the inset Ce histogram, and with additional purple dashed lines that show the geotherm or degree of melting which are the solid purple lines in Figure 3.

413

414 2.5 Mantle Conditions beneath other Regions of Anatolia

415 Mantle $T_P$ values were also estimated for other regions of Anatolia. We first assumed the solidus
416 for a mantle source with 100 wt. ppm of water (Hirschmann et al., 2009), consistent with our
417 analyses of the Karacadag basalts with the assumption that the center of the PVG defines the
418 melting onset depth (Figure 3). Then we determined $T_P$ across the region by requiring that its
419 corresponding geotherm intersects the solidus at the depth of the local seismically-determined
420 PVG, again associated with the onset of mantle melting. The resulting $T_P$ distribution for Anatolia
421 ranges from 1350°C to 1450°C (Figure S3a).

422 To further illustrate that $T_P$ estimates are relatively insensitive to how the PVG phase is interpreted,
423 Anatolia-wide $T_P$ values were also calculated using scenarios where the PVG corresponds to 0.5%
424 of melt (Figure 6a and 6b) or that melting starts at the lower bound on PVG depth (Figure 6c and
425 6d), while assuming the previously-determined water contents beneath Karacadag for these
426 scenarios (185 wt. ppm and 155 wt. ppm, respectively). The resulting $T_P$ maps are similar to those
427 calculated assuming that the center of the PVG defines the melting onset depth (Figure S3). These
428 results show that although the estimated water content depends strongly on how we interpret the
429 PVG phase, since the mantle $T_P$ is mainly constrained by the basalt samples, its value is not
430 strongly influenced by the choice of PVG interpretation. However, since mantle water content is
431 not directly constrained in the Anatolia-wide $T_P$ maps, we base the following analyses related to
432 elevated Anatolian temperatures on the well-constrained value of 1420±6.4°C beneath Karacadag.

433

### 2.6 Mantle Conditions beneath Karacadag Relative to Ambient Mantle

Based on Herzberg and Gazel (2009), the $T_P$ of normal ambient mantle ranges from 1300°C to 1400°C. If we use the set of adiabat-related parameters used in that study (Iwamori et al., 1995), the estimated $T_P$ in Karacadag would be 1435°C, higher than the value of 1420°C that is based on parameters from Katz et al. (2003) we used here. Therefore, Karacadag is at least ~35°C hotter than the upper bound for a normal ambient mantle. The Karacadag $T_P$ does overlap the higher end of the mid-ocean ridge $T_P$ ranges of some previous studies (Bao et al., 2022; Courtier et al., 2007; Dalton et al., 2014; Putirka, 2008). However, differences in $T_P$ measurement methods make it difficult to directly compare the Karacadag $T_P$ values to some of these studies, e.g. the $T_P$ values inferred from seismic velocities in Bao et al. (2022). In addition, when determining ambient mantle $T_P$ ranges, the use of basalt samples that are close to active mantle plumes or do not lie on an olivine control trend would obscure ambient mantle conditions (Herzberg & Asimow, 2008; Herzberg et al., 2007; Madrigal et al., 2016). Hence, we choose to put more weight on the comparison of the Karacadag $T_P$ values to Herzberg and Gazel (2009), where accounting for differences in $T_P$ estimation is straightforward.

## 3 The Source of the High Temperature Anatolian Upper Mantle

### 3.1 Potential Lower Mantle Roots

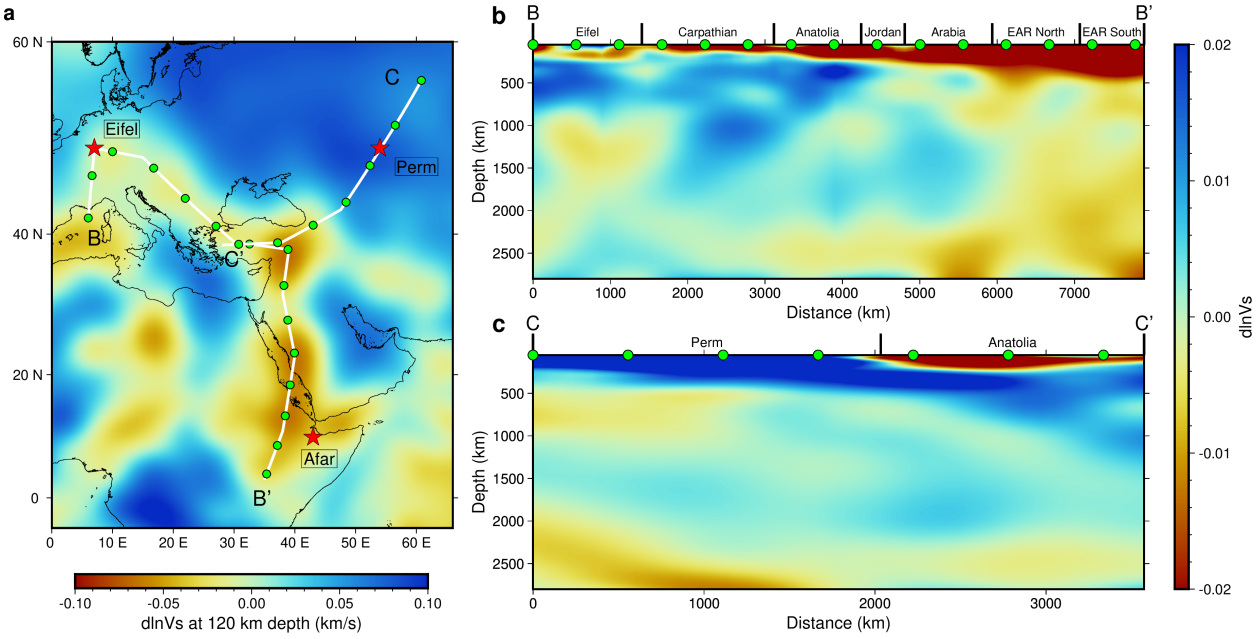
To test the idea that the elevated $T_P$ beneath Karacadag reflects high temperature mantle that flows into the upper mantle beneath Anatolia, we searched for the signatures of potential heat sources in multiple global and regional mantle seismic velocity models (Figure 7, S4 & S5), including

455 SEMUCB_WM1 (French & Romanowicz, 2015), GLAD_M25 (Lei et al., 2020),
456 S362WMANI+M (Moulik & Ekström, 2014), EAV09 (Chang et al., 2010), CAM2016 (Ho et al.,
457 2016), 3D2018_08Sv (Debayle et al., 2016), Africa.ANT.Emry-etal.2018 (Emry et al., 2019) and
458 CESM_Europe (Fichtner et al., 2018). Based on these models, no low velocity mantle plume
459 structure coming from the lower mantle is evident beneath Anatolia, and the closest low velocity
460 anomalies that connect to the lower mantle include plume structures beneath the East African Rift
461 system (Afar hotspot) and the Eifel hotspot, as well as the lower mantle Perm Anomaly (Figure 7
462 & S5) (French & Romanowicz, 2015; Lei et al., 2020). However, all of these regions are more
463 than 2000 km away from Anatolia. Although the Perm Anomaly is the closest low velocity lower
464 mantle body, no obvious low velocity anomaly connects it to the Anatolian upper mantle (Figure
465 7c & S5b). In contrast, the EAR region, which lies above a broad plume of low velocity mantle
466 extending from the core-mantle boundary to the upper mantle, is connected to Anatolia through a
467 pronounced channel of low velocity upper mantle (Figure 7, S4 & S5). While a low velocity upper
468 mantle anomaly also connects the Eifel region to Anatolia (Figure 7b and S5a), this anomaly is
469 weaker and shallower than the EAR-Anatolia channel, and the Eifel region is less obviously
470 connected to a deeply-rooted mantle plume. We therefore focus on the mantle plume beneath the
471 EAR as a potential source for the high temperature mantle beneath Anatolia, although we also
472 evaluate the Eifel region.

473 We also acknowledge that other models are possible, for example that a plume connected to the
474 lower mantle actually exists directly beneath Anatolia but has not been imaged, or that some
475 fortuitous combination of regional scale processes (such as extension or delamination in the upper
476 plate lithosphere, or slab roll-back and break-off (Delph et al., 2017; Göğüş & Pysklywec, 2008;
477 Keskin, 2007; Lynner et al.; Memiş et al., 2020)), has contributed to the high Anatolia $T_P$.

478 However, our focus is to assess whether lateral flow of high temperature asthenosphere over
479 thousands of kilometers from the EAR is plausible, rather than disproving other scenarios.

480




481

482 **Figure 7.** Shear velocity structure between Anatolia and potential lower mantle roots based on
483 SEMUCB_WM1 (French & Romanowicz, 2015). (a) Shear velocity perturbation at 120 km depth.
484 Red stars show surface projections of low-velocity anomalies related to the Afar and Eifel hotspots
485 (Courtillot et al., 2003) and the lower mantle Perm anomaly (Lekic et al., 2012). Locations of
486 cross-sections shown in (b) and (c) are indicated by white lines with green markers. The color
487 scale is shown at the bottom of the panel. (b) and (c) are mantle $V_S$ perturbation cross-sections for
488 B-B' and C-C' in (a). Geochemical sample geographic group ranges and the surface projections
489 of the Eifel hotspot and Perm anomaly are labelled at the top. Green symbols correspond to the
490 same symbols in (a). The color scale for (b) and (c) is on the right side.

491

492 Prior studies have supported the idea that asthenosphere mantle flows from the EAR to Anatolia
493 based on geochemical data (Ershov & Nikishin, 2004; Faccenna et al., 2013), anisotropy in seismic
494 wave velocities (Faccenna et al., 2013; Wei et al., 2019), and geodynamical modeling in which
495 driving forces from plume upwelling and pull from Mediterranean slabs draw upper mantle from

496 the EAR to Anatolia (Faccenna et al., 2013). In addition, this type of flow is also evident in global
497 mantle flow models (e.g. Conrad & Behn, 2010). In this study, we test the possibility of upper
498 mantle transport from the EAR to Anatolia using isotopic data and $T_P$ estimates for basalts erupted
499 along the low velocity channel.

500

501 3.2 Radiogenic Isotope Ratios

502 Radiogenic isotope ratios from 1,004 samples were used to assess whether basalts erupted along
503 the proposed EAR-Anatolia transport channel share a common mantle isotopic composition
504 (Figure 8, S6 & S7). The ratios were obtained from the GEOROC database from all studies
505 including regions from the EAR to Anatolia published between 1990 and 2020. Maximum and
506 minimum ages for the samples were obtained from their original publications (Supporting
507 Information Data Set S2).

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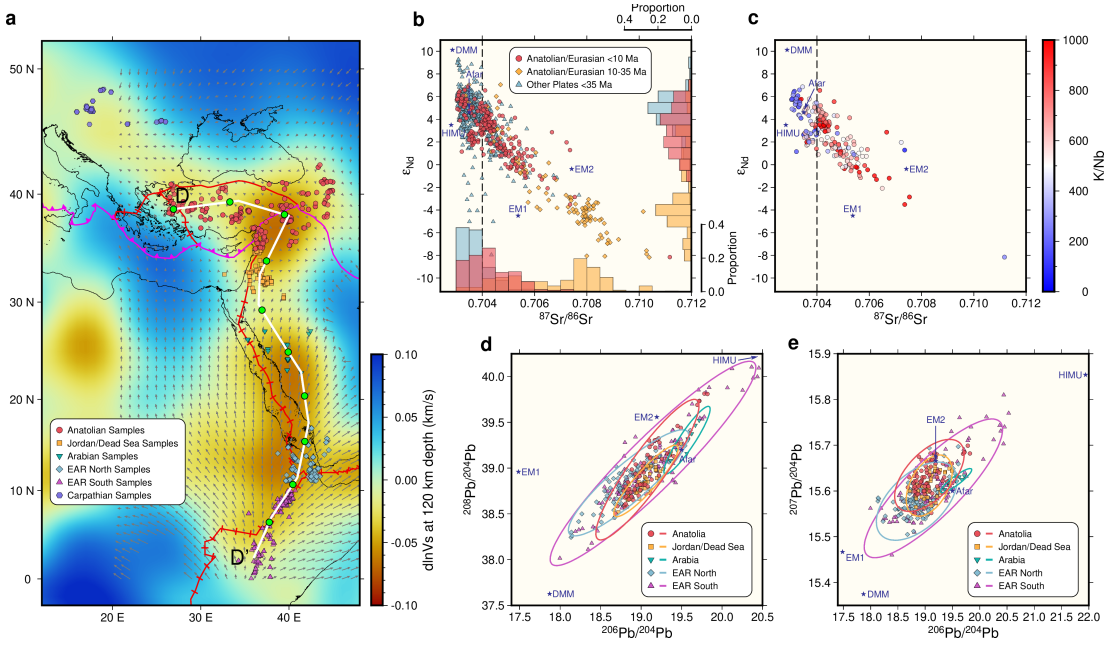


509

**Figure 8.** Common isotopic signatures for Anatolian and EAR mantles. (a) $V_S$ perturbations at 120 km depth (French & Romanowicz, 2015) show a channel of low velocity mantle that connects the EAR region to Anatolia. Locations of all samples used by Figure 8 & 9 are shown by symbols colored by geographic group. Plate boundaries (Bird, 2003) related to the group division in (b) are in pink (Anatolian/Arabian, Anatolian/African, Eurasian/Arabian and Eurasian/African) and others in red. Subduction boundaries are marked with triangles and divergent boundaries with bars. The white line indicates profile D-D' in Figure 10. Grey arrows show negative horizontal pressure gradients based on the stress field from a global mantle flow model (Conrad & Behn, 2010). (b) $^{87}Sr/^{86}Sr$ vs. $\varepsilon_{Nd}$ from samples grouped by age and tectonic plate (locations in Figure S6a). Histograms show distribution of points in each group. (c) $^{87}Sr/^{86}Sr$ vs. $\varepsilon_{Nd}$ for the Anatolian plate samples < 10Ma in (b), color coded by the K/Nb. (d) $^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$ from different geographic groups; ellipses show 95% confidence (locations in Figure S6c). (e) Similar to (d) but for $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ from different geographic groups (locations in Figure S6d). Stars in (b)-(e) are mantle endmembers (Hofmann, 2007), and the Afar plume composition (Rooney et al., 2012).

We first analyzed $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotopes. For this analysis, $^{143}Nd/^{144}Nd$ is represented by its relative deviation $\varepsilon_{Nd}$ which was calculated based on the present-day chondritic value of 0.512638 (Hofmann, 2007), and only mafic samples with maximum ages within 35 Ma were used. Values of $\varepsilon_{Nd}$ versus $^{87}Sr/^{86}Sr$ for all samples from the Arabian plate to the EAR for ages less than 35 Ma are clustered closely (Figure 8b), consistent with a common source that overlaps suggested values for the Afar plume (Rooney et al., 2012). However, samples from Anatolia on the Eurasian/Anatolian plate (Bird, 2003) show age-dependent results consistent with the region's tectonic evolution (Figure 8b & S6a). Anatolian samples with minimum ages older than 10 Ma, when the Anatolian plate was separated from the Arabian plate by a subducting slab (Cosentino et al., 2011), show high $^{87}Sr/^{86}Sr$ and negative $\varepsilon_{Nd}$ (Figure 8b), consistent with a large contribution from continental sediments that were potentially related to prior subduction (White, 2020). In contrast, Anatolian samples with maximum ages younger than 10 Ma show isotopic ratios that are similar to other regions along the EAR-Anatolia channel, consistent with EAR-sourced mantle entering the asthenosphere beneath Anatolia following the Arabia-Anatolia collision and slab break-off (Cosentino et al., 2011; Faccenna et al., 2013; Wei et al., 2019) (Figure 8b). A similar

shift in isotope ratios was also reported in McNab et al. (2018). Some Anatolian samples with ages less than 10 Ma still show $^{87}Sr/^{86}Sr$ values higher than 0.704, but similar to what was documented in McNab et al. (2018), most of these samples also show high K/Nb ratios (Figure 8c), which suggests that part of the Anatolian mantle could also be influenced by subduction-modified or lithospheric sources (Class et al., 1998; Gazel et al., 2012a) involved in post-collision processes like lithospheric delamination (Keskin, 2007).

We also analyzed Pb isotopes for samples that are not strongly influenced by lithospheric sources to verify mantle source similarity along the EAR-Anatolia channel (Figure 8d & 8e). For the Pb isotope analyses, in addition to the $SiO_2$ filter, we also required $^{87}Sr/^{86}Sr$ to be between 0.7028 and 0.7040 to make sure the source compositions based on $^{87}Sr/^{86}Sr$ were similar and crustal and sea water influences were eliminated (White, 2020). We also calculated the 95% confidence ellipse for Pb isotope distributions ($^{206}Pb/^{204}Pb$ , $^{207}Pb/^{204}Pb$ & $^{208}Pb/^{204}Pb$, Figure 8d & 8e), assuming a normal distribution for all Pb isotope ratios in each geographic group. To avoid outliers in the Pb isotope analyses, samples outside of the 99.9% confidence ellipse were removed; this operation was conducted iteratively until all samples were within the 99.9% confidence ellipse. In what follows, we limited our analysis of samples south of the boundaries between the Anatolian/Arabian plates, Eurasian/Arabian plates and Anatolian/African plates (pink lines in Figure 8a) (Bird, 2003) to those with maximum ages of less than 35 Ma, and limited our analysis of samples north of the boundaries to those with maximum ages less than 10 Ma. Samples along the channel between the EAR and Anatolia were divided into five geographical groups (Figure 8a & S6): the EAR South group contains samples within 0° to 10°N and 30° to 45°E; the EAR North group contains samples within 10° to 20°N and 38° to 45°E; the Arabian group contains samples within 20° to 30°N and

563 35° to 45°E; the Jordan/Dead Sea group contains samples within 30° to 35°N and 30° to 45°E; and
564 the Anatolian group contains samples within 35° to 43°N and 30° to 45°E;

565 Based on the filtered samples, both the Anatolian group and the Jordan/Dead Sea group have Pb
566 isotope ratios similar to those observed in the EAR system (Figure 8d & 8e), similar to what was
567 found in Faccenna et al. (2013). A few Arabian samples have slightly more radiogenic $^{206}Pb/^{204}Pb$,
568 but the values are still within the 95% confidence range of samples from the southern EAR, while
569 overlapping the Anatolian 95% confidence range. Therefore, the similarity of Sr, Nd and Pb
570 isotopes from different locations along the transport channel, the data from Anatolia since 10 Ma,
571 and the shift in isotope ratios in Anatolia at the 10 Ma Eurasia-Arabia collision (when mantle from
572 the EAR region could more easily reach Anatolia), are all consistent with the hypothesis that
573 asthenospheric mantle beneath Anatolia is derived from a low velocity channel originating from
574 the EAR upper mantle.

575

576 **4 Thermal Evolution During Asthenospheric Transport**

577 If the plume rising beneath the EAR region is the main heat source for material flowing towards
578 Anatolia, $T_P$ values should not increase along the proposed path of upper mantle transport from
579 the EAR towards Anatolia. To estimate $T_P$, basaltic primary magma equilibration P-T conditions
580 for 771 volcanic rock samples with major element abundance measurements from the GEOROC
581 database (Supporting Information Data Set S1) along the channel (Figure S6f) were calculated
582 (Lee et al., 2009) with the same method and parameters that were used for the Karacadag samples
583 (Figure 9a). The samples were divided into the same geographic groups that were used for the
584 isotopes applying the same age requirements. The culling operation based on major element

585 composition that was used for Karacadag samples for the $T_P$ modeling was also applied to these
586 samples, and we assumed the same magma water content (1 wt. %) and oxygen fugacity
587 ($Fe^{3+}/Fe^{Total}$ = 0.16). Since the assumed water content in the melt influences the inferred $T_P$ (e.g.
588 Figure 4a), to justify the 1 wt. % assumption, the Ce abundances of the samples along the channel
589 were analyzed (Figure 9b). These values demonstrate that 1 wt. % is a good estimate of water
590 content. 1 wt. % also agrees with the water abundance from olivine hosted melt inclusions from
591 samples in Ethiopia and Eritrea (Donovan et al., 2018; Field et al., 2012; Iddon & Edmonds, 2020).

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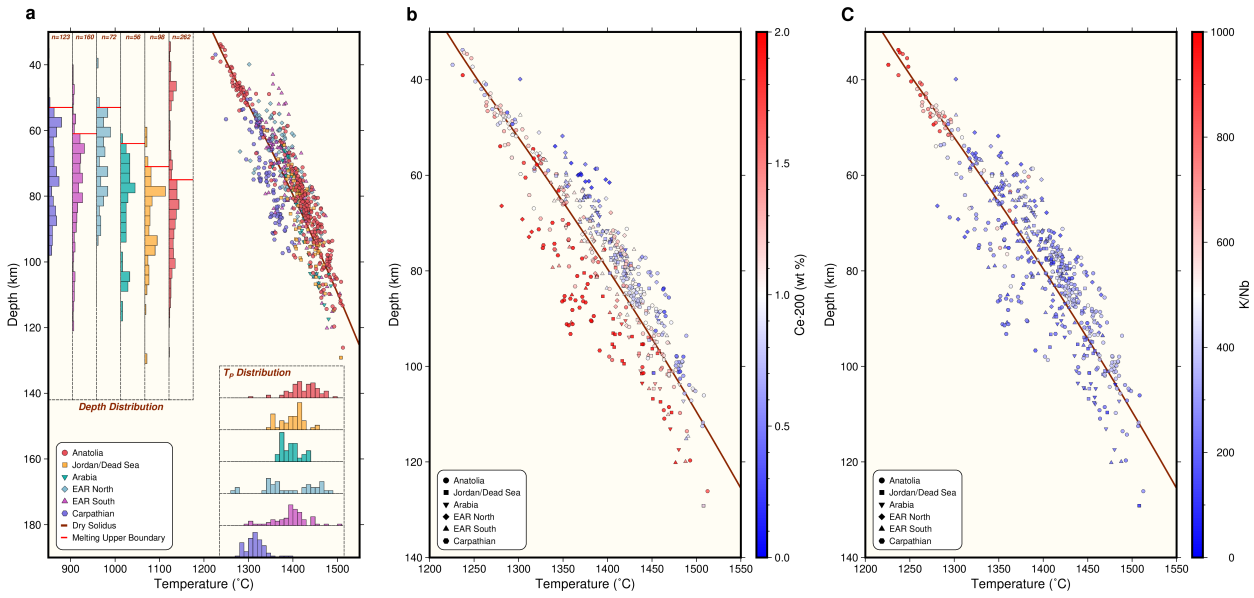



593

594 **Figure 9.** Primary magma equilibration along the channel. (a) Primary magma equilibration
595 conditions from different geographic groups (dots). $T_P$ distribution for each group shown in lower
596 right histograms, and equilibration depth distribution shown in the upper left histograms, using the
597 same axes as the main plot. Red bars are the upper limit of melting defined from the equilibration
598 depth distribution. Red line is the dry solidus (Hirschmann et al., 2009). (b) Primary magma
599 equilibration conditions color coded by 200 times Ce for basaltic magma samples as a proxy for
600 the water content. (c) Similar to (b), but color coded by sample K/Nb.

601

602 To ensure that melt equilibration P-T values represent the asthenosphere, we estimated LAB
603 depths for each geographic group by analyzing the distribution of melt equilibration depths (Figure
604 9a), and defining the LAB as the depth where the number of samples in the 10 km beneath it most
605 outnumbers the number of samples in the 10 km above it (similar to what we did for the Karacadag
606 samples). Because samples in each group are not from the same volcanic field and LAB depths
607 for different sample locations may differ, to avoid samples from regions with deeper LAB and thus
608 affected strongly by the lithosphere, we only used samples with equilibration depths more than 15
609 km below the estimated overall LAB depth for each group to estimate mantle $T_P$ (Figure 9a).

610 Equilibration P-T conditions were again assumed to represent the geotherm, and for samples at
611 depths that are not strongly affected by lithospheric conduction, the corresponding adiabatic
612 geotherms and $T_P$ values were estimated through a grid search of mantle adiabats with $T_P$ from
613 1300°C to 1550°C with an interval of 5°C, following the approach in section 2.3 (Figure 9a, lower
614 inset). Samples from the two EAR groups, the Arabian Peninsula and the Jordan/Dead Sea region
615 produced distributions of $T_P$ values that overlap the $T_P$ values from Anatolia (Figure 9a). Some
616 samples from the Anatolian group are clustered at shallower depths, but as noticed before (McNab
617 et al., 2018), these central Anatolian samples share a high K/Nb value, indicating the potential
618 influence of a different geodynamic process that involves water (Figure 9c). The observed elevated
619 mantle $T_P$ over ambient mantle values in these regions is also consistent with the low sodium found
620 in basalts erupted at the Red Sea mid-ocean ridge (Gale et al., 2014). However, although we tried
621 to add basalt samples from the Red Sea to our primary magma analyses, none of them passed the
622 compositional filter. The distribution of $T_P$ values from Anatolia has more samples at slightly
623 higher values than the other regions (Figure 9a), but given potential uncertainties in water content,
624 these minor temperature differences are not significant. We also tested the effect of only including

the 394 samples with normalized MgO higher than 9 wt. % (Figure S8) instead of 8 wt. % (Figure 9a), but the main conclusions about $T_P$ do not change.

The relatively constant $T_P$ values among the different geographic groups along the potential channel are consistent with upper mantle flow from the EAR to Anatolia. However, they also require that only a limited amount of conductive cooling occurs within the channel during the transport, despite the ~2000-3000 km distance.

To test whether or not Eifel could be the heat source for the Anatolian mantle, we also analyzed samples from the Carpathian region within 42° to 50°N and 14° to 30°E. If upper mantle was flowing from the Eifel region to Anatolia, along the weaker low velocity channel that connects these zones, it would pass through Carpathian-Pannonian volcanic fields (Figure 7a & S6). Although recent Carpathian samples show isotopic signatures similar to Anatolian samples (Figure S7), consistent with the same mantle source, their $T_P$ values are significantly lower than the basalts erupted on the EAR-Anatolia channel (Figure 9a). This result argues against flow from the Eifel region to Anatolia, because the mantle $T_P$ trend would require an additional heat source en route. If flow from the EAR to Anatolia continues on to the Carpathians, the lower Carpathian $T_P$ would suggest that the effects of cooling become more obvious at these longer transport distances.

## 5 A Potential Mechanism for the Long-distance Transport

As has been demonstrated in the previous sections, data from different regions along the potential transport channel from the EAR to Anatolia are consistent with a shared mantle source and similar mantle temperatures. These observations can be explained if asthenospheric material

can flow laterally over 2000 km distance without much cooling. In this model, as shown in Figure 10, hot mantle materials would rise upwards within the mantle plume beneath the EAR system, but after reaching the upper mantle, this hot material would flow towards Anatolia creating a low seismic velocity channel (Figure 8a) that lies beneath the Red Sea, the western edge of the Arabian Peninsula, and the eastern edge of the Mediterranean Sea, then finally reaching Anatolia.

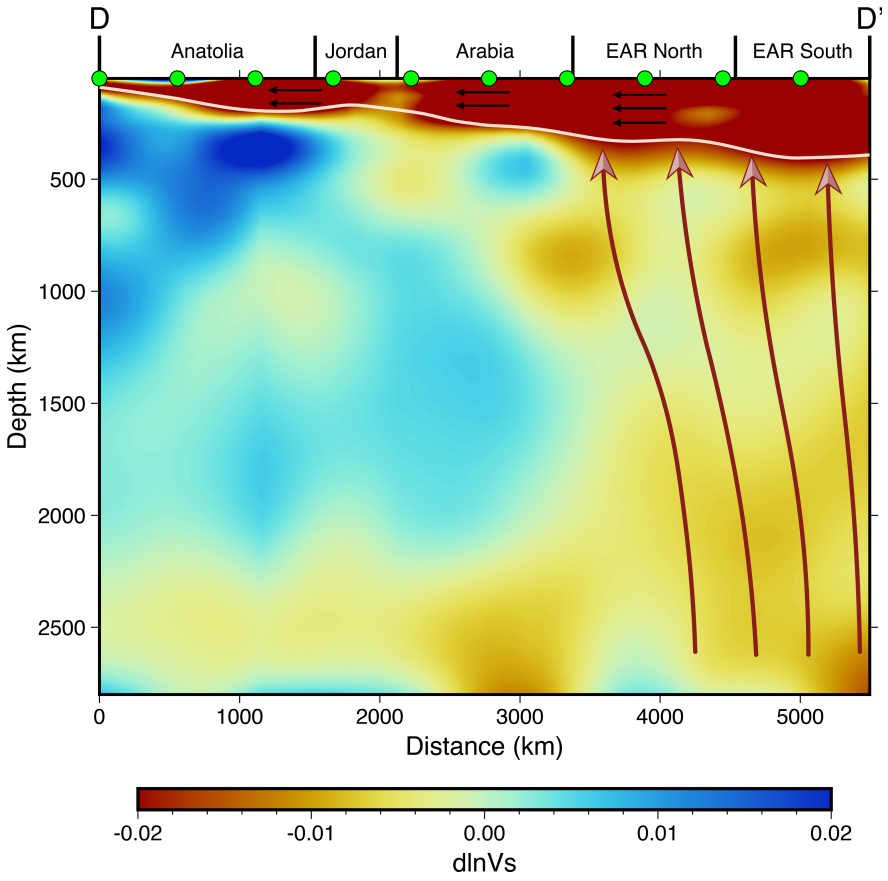



**Figure 10.** Mantle transport from Africa to Anatolia. $V_S$ perturbation (French & Romanowicz, 2015) is shown for cross-section D-D' (Figure 8a). Red arrows show potential paths of deep mantle upwelling. Black arrows show transport in the asthenosphere through the low velocity channel from the EAR region to Anatolia. White line shows the estimated maximum channel depth corresponding to a $dlnV_S$ of -0.02. At the top, green symbols match the positions of similar symbols on the map in Figure 8a, and black bars are boundaries of geographic groups.

660

661 The preservation of high mantle temperatures during transport along this asthenospheric channel
662 from the EAR to Anatolia may seem surprising. Since northward plate motion along the channel
663 since 20 Ma is only 2-5 cm/yr (Seton et al., 2012), the asthenosphere driven by plate motions
664 would move slowly enough that it would likely have lost significant heat before reaching
665 Anatolia. However, flow driven by lateral pressure gradients acting on the low-viscosity
666 asthenosphere in the channel due to buoyancy forces provides an alternative mechanism.

667 Here, we develop a 1D model of northward pressure-driven asthenospheric flow to test whether
668 flow rates can be high enough to explain the relatively constant $T_P$ values from the EAR to
669 Anatolia. The presence and geometry of a low viscosity athenospheric channel are inferred from
670 the seismic velocity profiles shown in Figures 8 & 10, and we assume that the channel has
671 already been completely developed, as supported by various seismic tomography models (Figure
672 7a & S4), and that flow is in steady-state.

673

674 5.1 Pressure Gradients Between the EAR and Anatolia

675 Pressure-driven flow in the direction from the EAR to Anatolia could be viewed in two ways.
676 From the global mantle convection perspective, whole mantle buoyant flows that originate from
677 large-scale density variations (over the whole depth of the mantle) could result in a horizontal
678 pressure gradient within the asthenosphere. For the region of this study, buoyancy forces driving
679 the upwelling mantle plume beneath the EAR would produce a horizontal pressure gradient that
680 pushes hot, low-viscosity material towards Anatolia. Such a northward gradient has been

681 demonstrated in global flow models (Conrad & Behn, 2010; Natarov & Conrad, 2012) (e.g.
682 Figure 8a).

683 From a regional observational perspective, a horizontal asthenospheric pressure gradient could be
684 caused by variations in the thickness of hot asthenospheric material and surface uplift to maintain
685 overall isostatic balance. As plume material upwells beneath the EAR system, it generates uplift,
686 i.e. the observed residual topography high (Yang & Yang, 2021). This upwelling and uplift would
687 produce an excess in upper mantle pressure which pushes hot mantle materials away from the
688 surface expression of the plume (e.g. Bercovici & Lin, 1996; Olson, 1990). The thickness of the
689 buoyant plume-derived asthenosphere would decrease in the direction of mantle flow, as
690 corroborated by seismic velocity structure (French & Romanowicz, 2015) (Figure 10). The
691 northward gradient in the thickness of the channel and its accompanying surface topography would
692 produce a northward pressure gradient. Hence, by evaluating the thickness variation of hot
693 asthenopheric materials from EAR to Anatolia, we could obtain the pressure gradient caused by
694 the thinning of this low-viscosity, low-density asthenospheric layer.

695 In the simple model of Olson (1990), mantle flow at the top of the plume could spread to form a
696 disk of asthenosphere. Alternatively radial outflow at the top of the mantle plume could be
697 concentrated in relatively narrow fingers due to the Saffman-Taylor instability (Schoonman et al.,
698 2017), instead of distributed uniformly and radially in all directions. Fingering could occur because
699 the upwelling mantle would have a much lower viscosity than the ambient mantle due to its higher
700 temperature. For example, as shown in Figure 7a, while the seismic velocities suggest that hot
701 upper mantle materials are concentrated along the channel from the EAR to Anatolia, the hot
702 mantle is also evident along the Gulf of Aden, and a potential finger extends westward as well.
703 Hot material from the plume could thus flow in other than a purely northward direction with a

geometry that is even time-dependent. However, our goal in the following discussion is to simply estimate the northward component of flow speed by balancing viscous shear stresses on horizontal planes with the northerly pressure gradient described below. Therefore, the exact geometry of low viscosity fingers and potential east-west horizontal inflows and outflows from/to the channel will not affect the following interpretation, and we are able to ignore flow perpendicular to the channel and treat the flow as 1D to the north. To further validate the 1D flow assumption, we also checked asthenospheric pressure gradients from the global mantle flow model of Conrad and Behn (2010), which also indicates a consistent northward pressure-driven flow in region of the EAR-Anatolia channel (Figure 8a).

Asthenospheric pressure gradients and resulting flow velocities between the EAR and Anatolia based on either the large-scale buoyant flow or regional asthenosphere thickness variations were estimated from both global flow models and the observed regional asthenosphere thickness variation. To quantify the horizontal pressure gradient from global buoyant flow, we took the pressure field at 150 km depth from the stress tensors in Conrad and Behn (2010) (Figure 11b; this global mantle flow model includes plate-driven flow, lithosphere net-rotation-driven flow, and buoyant flow driven by density anomalies beneath 325 km depth. To be consistent with the following analyses, these pressure values were smoothed by taking the average of all locations within ± 556 km of the path (Figure 11b), but the smoothed profile is nearly identical to the original one. The pressure gradient was estimated as the pressure difference between the starting point at 3750 km (the north edge of the EAR region) and the ending point at 1150 km (near Karacadag) on D-D' (~17.3 MPa) divided by the total distance of 2600 km, resulting in a pressure gradient of 6.64 Pa/m (Figure 11b). We chose this starting point since it is north of the upwelling plume (Figure 8a & 10), allowing us to ignore vertical flow and focus only on the northward flow in

following analyses. Instead of using the great circle distance, we chose to use the path distance on the D-D' profile that passes through the various volcanic fields. This choice makes the estimates of possible mantle flow velocities more conservative since a higher pressure gradient would be obtained if the great circle path was used.

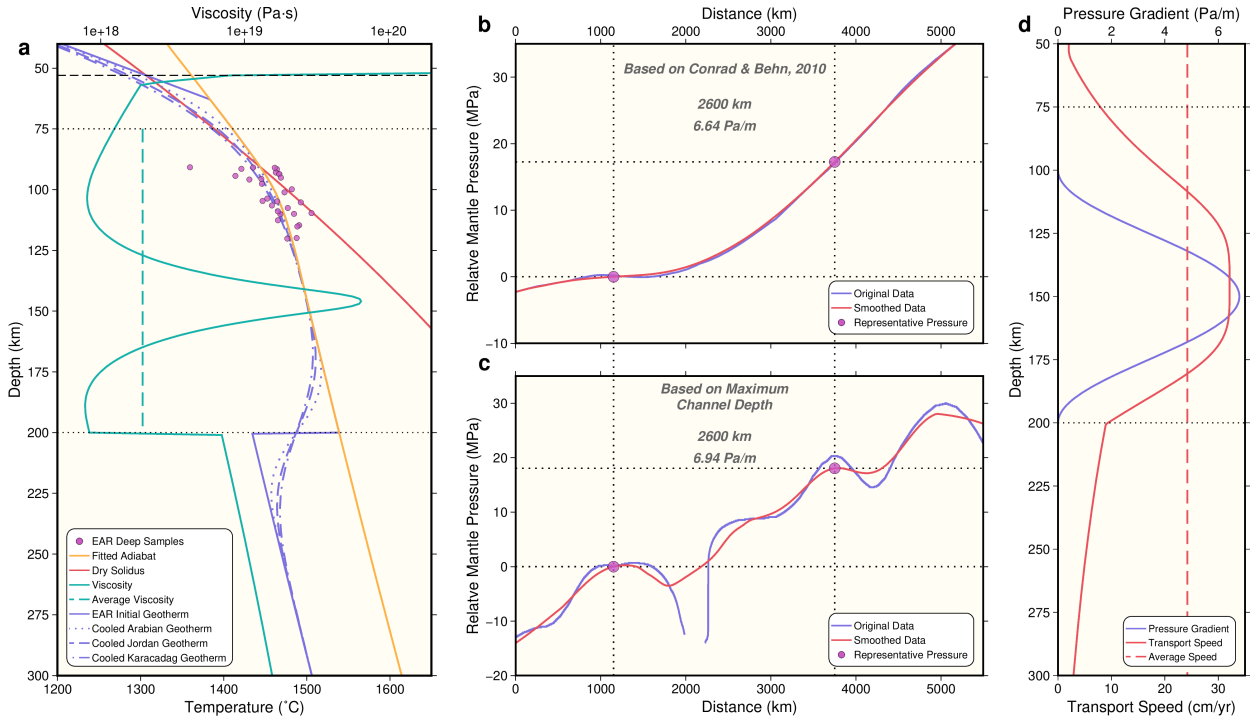



**Figure 11.** Thermal evolution during mantle transport from the EAR to Anatolia. (a) The initial geotherm at the EAR before transport (solid blue line); cooled geotherms after transport to Arabia for ~4 Myr (blue dotted line); cooled geotherms after transport to Jordan for ~8 Myr (blue dashed line); and cooled geotherms after transport to Anatolia for ~10.74 Myr (blue dotted-dashed line). The initial geotherm is constructed from the EAR adiabat (yellow line) estimated from deep EAR primary magma equilibration conditions (dots). The red solid line shows the dry solidus. The black dashed line shows the LAB depth defined by the north EAR samples (upper melting limit; Figure 9a). The equivalent viscosity profile for the initial geotherm is shown by the green solid line with its scale labeled at the top of the panel, and its averaged log-scale value between the depths of two black dotted lines is shown by the green dashed line. (b) Relative pressure gradient with respect to the transport end point in Anatolia at 1150 km (left dotted line) from Conrad and Behn (2010). The original value is shown by the blue line, and the smoothed gradient averaged over length-scales of ±556 km is shown by the red line. The representative pressure drop (magenta dots) obtained from the starting point in the EAR at 3750 km (right dotted line) and the end point. The transport length and estimated values for pressure gradient are labelled in gray. (c) Similar to (b) but for the pressure gradient estimate based on the maximum channel depth. (d) The estimated

749 transport flow speed based on the stress-dependent rheology (red solid line) and its average value
750 between 75 and 200 km depths (red dashed line) with the scale at the bottom. The pressure gradient
751 profile (blue line) with the scale at the top.

752

753 To quantify the pressure gradient based on variations in the asthenospheric channel thickness, we
754 estimated the bottom depth of the potential transport channel as defined by the shear wave velocity
755 structure (Figure 11c). After the upwelling plume impinges on the surface, horizontal mantle flow
756 would form a disk of high-temperature mantle which thins radially (Olson, 1990). Horizontal flow
757 within this layer reflects the balance between the horizonal pressure and the vertical gradient in
758 viscous shear stresses on horizontal planes. If the horizontal mantle flow is concentrated within
759 this disk and not beneath it, vertical buoyancy forces are balanced by surface topography, resulting
760 in a radially uniform pressure and isostasy beneath the disk. Therefore, since pressure is
761 approximately uniform beneath the channel, and the hot plume-affected material has a lower
762 density than the ambient mantle, the slope of the lower boundary of the channel ($dz_b / dx$) can be
763 translated into a pressure gradient as $\Delta\rho g \cdot dz_b / dx$ (Olson, 1990) within the channel, where $\Delta\rho$
764 is the density difference between hot plume material and ambient mantle, and $g$ is gravitational
765 acceleration. We defined the bottom of the channel on profile B-B' as the depth where $dlnV_S$
766 (Figure 10) equals -0.02, and smoothed these values within ±556 km (white line in Figure 10). We
767 chose the value of -0.02 because it defines the lower boundary of the channel just above where
768 $dlnV_S$ is zero (Figure 10). This choice captures depths where little to no partial melt exists, avoids
769 depths where temperatures are much higher than the solidus and $dlnV_S$ may be significantly
770 affected by variations in melt fraction, and more accurately reflects where mantle temperature
771 exceeds ambient conditions. In addition, since the estimated pressure gradient depends primarily
772 on the slope of the lower boundary, the absolute $dlnV_S$ value chosen to represent the boundary

773 does not actually have a significant impact. We assumed that the temperature difference across
774 the channel boundary is 100°C, which is reasonable for mantle material rising from the lower
775 mantle (e.g. Bao et al., 2022), and conservative relative to potential temperature changes associated
776 with a $d\ln V_S$ value of -0.02 (Lee, 2003). With the same solid thermal expansion coefficient that
777 was used for calculating mantle adiabats (Katz et al., 2003) and a reference mantle density of
778 $3.4\times10^3$ kg/m$^3$, the corresponding density difference across the channel boundaries $\Delta\rho$ would be
779 13.6 kg/m$^3$, which translates into a pressure gradient of 6.94 Pa/m (Figure 11c). This value is
780 similar to the pressure gradient calculated from the large-scale buoyant flow (6.64 Pa/m).

781 Although estimated differently, the pressure gradients from large-scale buoyant flow and
782 asthenospheric channel thickness variation could play a similar role in pushing upwelled material
783 away from the plume. For the global model of Conrad and Behn (2010), a rigid boundary condition
784 is imposed at the surface, which provides the required horizontal mantle pressure gradients for the
785 channel flow. However, if a more realistic traction-free boundary condition is assumed at the
786 surface, and both lithospheric uplift and the asthenospheric channel are included, then instead of
787 the rigid boundary condition, the variations in topography and channel thickness would provide
788 the pressure gradients. Hence, these two estimates of pressure gradients could act similarly to drive
789 horizontal asthenospheric flow. However, because density variations at the depths of the channel
790 are not included in Conrad and Behn (2010), and pressure estimates based on channel thickness
791 do not include dynamic pressures, it would be difficult to judge whether pressure gradients
792 estimated in these two ways are completely equivalent. In any case, we regard these two values as
793 independent pressure gradient estimates, and because their values are similar (0.30 Pa/m
794 difference), we use an intermediate value (6.79 Pa/m) as the reference pressure gradient in the
795 following steps of the 1D flow calculation.

796 Based on the EAR-Anatolia pressure gradient constraints, we constructed a conservative depth
797 profile for the pressure gradient (Figure 11d). In the profile, non-zero pressure only exists between
798 depths of 100 and 200 km, so that the lower boundary is above the base of the channel as defined
799 by the shear-wave velocities in Anatolia (Figure 10). The maximum pressure gradient is the EAR-
800 Anatolia estimate of 6.79 Pa/m, and pressure is represented by a cosine shape function (Figure
801 11d), so the average pressure gradient within the channel is only half of the maximum. This
802 conservative approach is supported by the findings of Natarov and Conrad (2012), who found that
803 the pressure gradient inferred from the asthenospheric infinite strain axis is smaller than the values
804 directly taken from the flow model (Conrad & Behn, 2010). In addition, if the temperature
805 difference between the mantle inside and outside of the channel is less than 100°C, the estimated
806 pressure gradient from the second approach would also be smaller.

807

808 5.2 Thermal Evolution Along the Channel

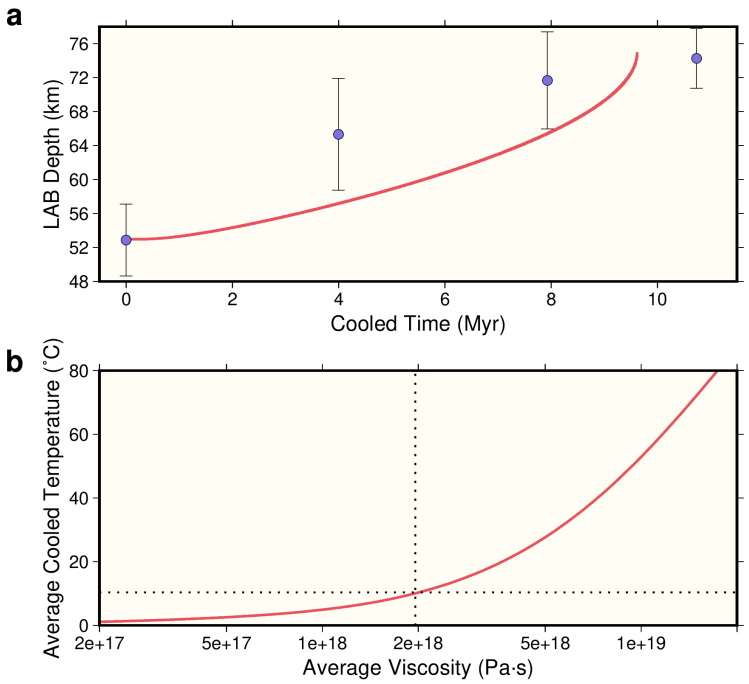
809 The initial EAR mantle geotherm was first estimated based on primary magma equilibration P-T
810 conditions for magma samples from the two EAR groups with equilibration depths below 90 km
811 (Figure 11a). Only these deep samples were employed since these depths are less influenced by
812 the lithosphere and the less well-constrained latent heat of melting. The corresponding EAR
813 adiabat (Figure 11a) was obtained by assuming a mantle water content of 100 wt. ppm (as found
814 in Karacadag) and by searching for the best-fitting mantle $T_P$ with the grid search approach similar
815 to that used in section 2.3 that minimizes $\left\| T_{sample} - T_{geo} \right\|_2$. The resulting EAR $T_P$ value is 1408°C.

816 We used a semi-analytical method to solve for the depth distribution of flow speed, assuming a
817 stress-dependent mantle rheology that considers both dislocation and diffusion creep (Hirth &
818 Kohlstedt, 2003) and calibrations of FTIR data in olivine (Bell et al., 2003). The details of the
819 rheology and flow calculations are in Supporting Information Text S4. The resulting
820 asthenospheric flow as a function of depth is shown in Figure 11d. Between the overall LAB depth
821 from Anatolian basalt samples (75 km, Figure 9a) and the lower boundary of the channel in
822 Anatolia (200 km, Figure 10), the average flow speed is 24.2 cm/yr. This rate, while high, is
823 comparable to upper mantle flow rates estimated in the South Pacific (Ballmer et al., 2013), within
824 the range estimated near North Atlantic Ridges (Parnell-Turner et al., 2017), and lower than the
825 estimated rates in another North Atlantic study (Hartley et al., 2011). With a 24.2 cm/yr
826 asthenospheric flow rate, mantle materials would travel the 2600 km distance from the EAR to
827 Anatolia in 10.74 Myr.

828 Given the estimated transport time from the EAR to Anatolia, we modeled thermal evolution
829 within the channel to evaluate whether cooling in the channel is small enough to be consistent with
830 the minimal variation among observed mantle potential temperatures along the transport path. For
831 the initial geotherm at the beginning of the transport in EAR, a conductive geotherm for the
832 lithosphere was used to link the adiabatic temperature in the asthenosphere to 0°C at the surface.
833 We also required that this geotherm crossed the dry solidus at 53 km depth in accordance with the
834 LAB (upper melting limit) inferred from the basalt samples in the northern EAR group (Figure
835 9a). At depths below 200 km, a 100°C temperature decrease from the adiabat defined by the EAR
836 deep samples was imposed so that the mantle beneath the channel is at a typical ambient mantle
837 temperatures (purple line in Figure 11a). Details for how the initial geotherm was parameterized
838 appear in Supporting Information Text S4.

839 To estimate cooling along the transport path, the initial geotherm was allowed to cool over time
840 intervals corresponding to the transport times to the Arabian volcanic fields (~4 Myr), the
841 Jordan/Dead Sea volcanic fields (~8 Myr) and to Anatolia (near Karacadag; 10.74 Myr) (Figure
842 11a). While the shallower part of the geotherm cools significantly over these time-scales,
843 temperatures at depths greater than 75 km are largely unchanged, especially for depths over 100
844 km. Since the mantle $T_P$ values are based on the basalt samples with equilibration depths greater
845 than 75 km, the cooling models explain how similar mantle $T_P$ values can be observed in the
846 different regions along the EAR-Anatolia transport channel.

847




848

849 **Figure 12.** Cooling related tests. (a) LAB deepening with cooling. Blue dots show the LAB depth
850 determined from the distribution of basalt equilibration depths (the upper limit of melting) (Figure
851 9a) for the north EAR (0 Myr), Arabia (~4 Myr), Jordan/Dead Sea (~8 Myr) and Anatolia (~10.74
852 Myr). Error bars show twice the standard deviation of the LAB depths. The red line shows the
853 depth where the upper part of the cooled geotherm crosses the dry solidus (Figure 11a) which
854 could indicate the upper limit of melting, for different cooling times. (b) The average temperature
855 at the depths of the Anatolian basalt samples after transport to Anatolia (~10.74 Myr of cooling)

856 with respect to the average equivalent viscosity between 75 and 200 km depths. Black dotted lines
857 mark the value for the case in Figure 11.

858

859 To further test the cooling during channel flow model, we compared the LAB depths inferred from
860 the basalts (Figure 9a, upper inset) with LAB depths predicted by the cooling. In the cooling model,
861 as lithospheric conduction and cooling progress, the upper intersection of the geotherm and the
862 dry solidus moves to deeper depths (Figure 11a). The shallowest depth at which primary magmas
863 could equilibrate thus gets deeper as well. This prediction (red line in Figure 12a) is broadly
864 matched by the deepening of the basalt-inferred LAB (Figure 12a) along the channel from the
865 northern EAR to Anatolia. The uncertainty of the basalt-inferred LAB was obtained by
866 bootstrapping the basalt samples in each group that were used for determining that LAB depth
867 (Figure 12a). The overall trends in predicted and observed depths are similar, and given
868 uncertainties in the initial geotherm (which depends strongly on the assumed water content in the
869 melt), local tectonic histories, and calculation of pressures of last equilibration, misfits at specific
870 cooling times can easily be accounted for. The overall match between predicted and observed
871 depths provides support that the cooling model is plausible for transport along the EAR-Anatolia
872 channel.

873 Since actual mantle rheology may differ from the experimentally-constrained rheology assumed
874 in the flow model, we also tested the effect of different viscosity models on flow rates and potential
875 cooling of the asthenosphere along the EAR-Anatolia channel. In the experimentally-constrained
876 case discussed so far, the equivalent viscosity for the stress-dependent rheology is calculated as
877 the shear stress ($\tau$) divided by the strain rate ($dv/dz$), where $v$ is the horizontal flow speed, and
878 $z$ is depth (solid green line in Figure 11a). The very high equivalent viscosity near 150 km depth
879 is due to the very small strain rate (evident from the flow speed profile in Figure 11d) and the

880 stress-dependent nature of dislocation creep. In the first alternative viscosity model, we instead
881 used the average value of the log-scaled viscosities between 75 and 200 km depths to represent the
882 overall viscosity, which is ~$2\times10^{18}$ Pa·s (dashed green line in Figure 11a). We also systematically
883 varied the magnitude of viscosity between 75 and 200 km depth by varying the pre-factors of the
884 dislocation and diffusion creep flow laws (Supporting Information Text S4). For each of these
885 new viscosity profiles, we calculated the average viscosity between 75 and 200 km depths and the
886 EAR-Anatolia transport time and the degree of cooling. Cooling was measured by the average
887 temperature decrease at the depths corresponding to Anatolian basalt samples (deeper than 90 km).
888 For the average viscosity of ~$2\times10^{18}$ Pa·s, the overall cooling is only ~10°C (Figure 12b), and for
889 viscosities less than $5\times10^{18}$ Pa·s, cooling is still small enough to be consistent with the observed
890 $T_P$ distributions. This comparison shows that asthenospheric flow rates fast enough to match the
891 modest cooling evident in the $T_P$ distributions along the transport channel are possible, but only
892 for relatively low asthenospheric viscosities, as would be expected for the elevated $T_P$ values from
893 EAR to Anatolia. In other words, this type of fast asthenospheric transport is plausible in high
894 temperature regions of the mantle, but probably not globally.

895 Compared with published mantle viscosities estimated with different methods, the viscosities
896 assumed in the flow rate calculations at or above $5\times10^{17}$ Pa·s are reasonable. They are higher
897 than the lower bound for asthenospheric viscosity of $5\times10^{17}$ Pa·s constrained by seasonal
898 deformation (Chanard et al., 2018), within the range of the mantle viscosity suggested from
899 postseismic deformation beneath Indian Ocean as (0.5-10)$\times10^{18}$ Pa·s (Hu et al., 2016), and lower
900 than the upper bound for asthenospheric viscosity of $10^{19}$ Pa·s estimated from the geoid variation
901 across an ocean basin fracture zone (Craig & McKenzie, 1986). However, we also recognize that

902 the different time-scales of these processes need to be taken into account when making viscosity
903 comparisons (e.g. Lau et al., 2021).

904

905 **6 Conclusions and Implications**

906 In this study, we demonstrated that a wide range of seismic and geochemical observations are
907 consistent with a model in which hot asthenosphere beneath Anatolia is fed by long-distance lateral
908 transport of upper mantle from East Africa, with the lateral flow being driven by pressure gradients
909 created by the buoyancy of the African mantle plume. These conclusions are based on a series of
910 analyses.

911 1. We determined the mantle potential temperature beneath the Karacadag volcanic field in
912 eastern Anatolia to be ~1420°C, higher than typical of ambient mantle, based on joint modeling
913 of primary magma equilibration pressure-temperature conditions from basalt samples and a
914 seismic velocity gradient imaged by Sp receiver functions that is consistent with the onset of
915 partial melting.

916 2. Tomographic models show that no obvious deep mantle plume exists beneath Anatolia, but
917 they consistently show a channel of low seismic velocity upper mantle that connects Anatolia
918 and the East African Rift, as has been proposed by prior studies (Ershov & Nikishin, 2004;
919 Faccenna et al., 2013; Wei et al., 2019).

920 3. In a chain of magmatic field along the proposed transport path from the East African Rift
921 system to Anatolia, we assessed available radiogenic isotope ratios in basalt samples, including

922 $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$, $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$, and found they are consistent
923 with a shared mantle source.

924 4. To evaluate thermal evolution along the transport channel, we analyzed primary magma
925 equilibration P-T conditions from the basalts, and found that any decreases in mantle potential
926 temperature are minimal, indicating little cooling within the asthenospheric channel.

927 5. To assess whether the observed mantle potential temperatures are physically consistent with
928 flow over thousands of kilometers in the channel, we modelled potential mantle transport time
929 from East Africa to Anatolia for pressure-driven flow, created by the African plume, and a
930 stress-dependent rheology. With conservative assumptions, asthenospheric mantle from East
931 Africa could reach Anatolia in 11 Myr. By modeling conductive cooling of the geotherm for
932 ~11 Myr, we found that while the shallowest asthenosphere is significantly cooled, leading to
933 an increase in the depth of the LAB that is matched by basalt sample constraints, temperature
934 changes in the deeper asthenosphere are small, consistent with the observed elevated mantle
935 potential temperatures all along the channel. In addition to the horizontal pressure gradient
936 provided by the mantle plume, another factor needed to enable this type of rapid asthenospheric
937 flow is a low viscosity, as would be expected for the elevated temperature of plume-affected
938 mantle.

939 The type of rapid pressure-driven asthenospheric flow over length-scales of thousands of
940 kilometers supported by this study (Figure 10) has important implications for heat and material
941 transport in the Earth. The 2000-3000 km length-scale from East Africa to Anatolia exceeds some
942 previously inferred cases of long-distance transport of hot plume materials from their plume roots
943 (Ebinger & Sleep, 1998; Schoonman et al., 2017), and rivals others (Ballmer et al., 2013). Rapid

944 asthenospheric flow from plumes and the preservation of high mantle temperatures that it enables
945 help to explain massive Large Igneous Provinces earlier in Earth history, such as the Central
946 Atlantic Magmatic Province (Marzoli et al., 1999) and in the Pacific (Madrigal et al., 2016; Stern
947 et al., 2020). While the inferred rates of asthenospheric flow from the EAR to Anatolia are higher
948 than regional plate velocities, they are actually comparable to the pressure-driven asthenospheric
949 flow velocities implied by the age-progression of volcanic chains from the Pacific superswell
950 towards the southern East Pacific Rise (Ballmer et al., 2013) and in the North Atlantic (Hartley et
951 al., 2011; Parnell-Turner et al., 2017). Mantle flow driven by plume-related pressure gradients are
952 relevant to understanding the distribution of magmatism on terrestrial planets such as Venus which
953 have plume-like upwellings (Smrekar et al., 2010) in the absence of plate tectonics. Overall, the
954 results of this study indicate that high temperature plume-influenced materials can reach much
955 farther in the upper mantle and over larger volumes of the Earth than commonly assumed.

956

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964

## Open Research

The Sp receiver function common-conversion point stack is available upon request. Geochemical and petrological data were downloaded from GEOROC (http://georoc.mpch-mainz.gwdg.de/Georoc) and are provided in the supporting information. Velocity model SEMUCB_WM1 was downloaded from the Berkeley Global Seismology Group (http://seismo.berkeley.edu/wiki_br/Main_Page). Velocity model GLAD_M25 was obtained from E. Bozdag, the velocity model in (Blom et al., 2020) from N. Blom, and the velocity model in (Fichtner et al., 2013) from A. Fichtner; other velocity models are from the IRIS archive (https://ds.iris.edu/ds/products/emc-earthmodels/). All computer codes used for data processing, analysis, and plotting are available upon request. All the figures are generated with the Generic Mapping Tools (Wessel et al., 2019).

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