Geodynamics of Anatolia: Lithosphere thermal structure and thickness

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Key points:

1. Lithosphere fragmentation by subduction systems of different ages creates the patchy pattern of lithosphere thermal anomalies in Anatolia

2. Thin (50-75 km) lithosphere of the Menderes Massif, controlled by the Hellenic subduction, includes a block with a 150 km thick lithosphere

3. Thick (80-140 km) lithosphere of the East Anatolian plateau includes continental fragments and teared Neo-Tethyan slab(s)

Length: 30.87 PU

Text: 8934 words (without references, including figure captions)

Figures: 12

Tables: 1

Abstract

We present the first thermal model for the lithosphere in Turkey, which shows a highly heterogeneous pattern associated with mosaics of the Tethyan and modern subduction systems. We calculate regionally average crustal density of 2.90 g/cm^3 consistent with the presence of large volumes of mafic material. The Moho temperature with a regionally average value of $650\text{--}850^\circ\text{C}$ shows strong short wavelength variations. Lithosphere thinning to $50\text{--}75 \text{ km}$ in most of western Anatolia may developed in response to the Hellenic slab roll-back, while the Neoproterozoic block in the Menderes Massif preserves a 150 km deep lithosphere root. In central Anatolia, the lithosphere thickness decreases southwards from $100\text{--}150 \text{ km}$ to $50\text{--}60 \text{ km}$ along a linear belt of young basaltic volcanism, followed by a belt of a 150 km thick lithosphere. We interpret this characteristic pattern by a SE-dipping paleo-slab beneath the western Taurides which may cause to deviate the Cyprus subduction melting zone towards NW and NE. The Eastern Pontides - Lesser Caucasus have $150\text{--}200 \text{ km}$ thick lithosphere roots caused by collisional tectonics. The East Anatolian Plateau is underlain by a $80\text{--}140 \text{ km}$ thick lithosphere which suggests the presence of significant continental fragments; the patchy pattern of its thermal heterogeneity may be explained by teared and fragmented Tethyan slabs. A poor correlation between the lithosphere thermal structure, heat flux, the Neogene volcanic regions, and mantle seismic velocities implies that seismic anomalies are essentially controlled by heterogeneous mantle hydration by subduction systems of different ages and cannot be explained by temperature variations alone.

Keywords: Tethys subduction; lithosphere thickness; Moho depth; Mediterranean; geotherms; slab fragmentation

1. Geodynamic framework

Anatolia, also known as Asia Minor, makes most of Turkey and includes the Western Aegean extensional province and the Central Anatolian Plateau, bordered by the orogenic systems of the Taurides in the south and the Central Pontides in the north, and the East Anatolian Plateau, bordered in the north by the Eastern Pontides and by the Lesser and Greater Caucasus between the Black and Caspian seas (Fig. 1). The region is made of a mosaic of tectonic terranes with the basement ages covering more than 0.5 Ga of the Earth's history. These continental and oceanic fragments have finally been amalgamated in the late Tertiary (Sengör & Yılmaz, 1981).

Most of Anatolia is made of Gondwanaland lithosphere blocks, while western Anatolia north of ca. 40 °N was once a part of Laurasia (Sengör & Yılmaz, 1981). The exposures of the Pan-African basement are very limited: late Precambrian gneisses are known in the southern part of the Menderes Massif (western Anatolia), which is possibly formed by a collage of micro-continental fragments (Robertson et al., 2013), in the eastern part of the Istanbul Zone (Hetzel & Reischmann, 1996), and along the northern side of the East Anatolian Fault (Okay & Tuysuz, 1999) (Fig. 1c).

The modern tectonics of Anatolia has been shaped by the closure of the Tethys oceans. Most of northern Anatolia along the Black Sea coast has been affected in the Permo-Triassic time by a southwards dipping Paleo-Tethys subduction. The Paleo-Tethyan Late Triassic – early Jurassic accretionary complexes are wide-spread in the western part of the Sakarya Zone, Central Pontides, and the Tokat Massif (north-central Anatolia) (Okay & Tuysuz, 1999). Several branches of the Neo-Tethys Ocean existed in central Anatolia; the late Cretaceous to Paleogene closure of the Neo-Tethys created northwards dipping subduction systems across the entire Anatolia roughly at ca. 39 °N and formed the Eastern Pontide magmatic arc in the Jurassic-Cretaceous time (Yılmaz et al., 1997). The associated late Cretaceous to Paleogene Tethyan

ophiolites make a nearly continuous ophiolite belt that runs from Izmir at the Aegean coast to the Lesser Caucasus and Zagros mountains in the east (Fig. 1c). Tethyan ophiolites are also present along the southern margin (and outside) of the Menderes Massif, in the northern part of the Kırşehir Massif, and in the Taurides.

Terrane collisions associated with the closure of the Neo-Tethys Ocean also formed the East Anatolian Plateau, most of which is covered by the East Anatolian Accretionary Complex. Its exposed basement is made of late Cretaceous ophiolitic melange and Paleogene flysch sequences and no continental basement has earlier been inferred there (Sengör & Yılmaz, 1981). This interpretation has been recently challenged (Topuz et al., 2017): based on the reported exposures of the pre-Neogene basement with age of 444 ± 9 Ma at the East Anatolian Plateau these authors proposed the presence of a significant component of continental basement beneath the region.

Further deformation of the Central and East Anatolian Plateaux has been controlled by the Arabia-Eurasia collision that started at early Miocene (~ 16 – 23 Ma) and produced more than 1 km of uplift since ca. 11 Ma (McNab et al., 2018) with widespread volcanism starting at ca. 6–7 Ma (c.f. Sengör et al., 2003). Presently, the Central and East Anatolian Plateaux together make the third largest orogenic plateau in the world (Schildgen et al., 2014). Since the Early Pliocene, on-going deformation of Anatolia associated with the Arabia-Eurasia collision is accommodated by the westward escape along two major strike-slip faults, the North and East Anatolian Faults (Bozkurt, 2001).

Deformation in south-western Turkey is controlled by the Hellenic and (still speculative) Cyprus subductions. Western Anatolia is presently experiencing distributed north-south extension, possibly caused by the retreat of the Hellenic trench, and the presence of a series of subparallel rift-type structures is suspected in the Menderes Massif (Jolivet et al., 2012).

It is clear from the brief overview of regional tectonics that an interplay of subduction systems of different ages shapes the geodynamic evolution of Anatolia. While some seismic tomography models suggest that the Tethyan lithosphere may be trapped in the lower part of the mantle transition zone (Biryol et al., 2011), other tomography models image a complex mosaic pattern of seismic velocity anomalies in the upper mantle of Anatolia (see section 3.4). A broad range of regional geodynamic models has been proposed based on seismic models for the crustal and upper mantle structure (Keskin, 2003; Sengör et al., 2003; Hafkenscheid et al., 2006; Göğüş & Pysklywec, 2008; Zor, 2008; Jolivet et al., 2012; Bartol & Govers, 2014; Mahatsente et al., 2018). In most cases, low seismic velocities are interpreted in terms of high mantle temperatures and without considering the hydration effect on seismic velocities. However, Tethyan slabs should have supplied a significant amount of water into the mantle, leading to strong heterogeneity and complexity in regional seismic images, given that the effect of hydration on seismic velocities is comparable to (or even stronger than) the temperature effect. The presence of fluids in the lithosphere is supported by regional magneto-telluric studies (Turkoglu et al., 2008).

The effects of both temperature and hydration heterogeneities, present in seismic images, cannot be separated without additional independent information. Therefore, the existing geodynamic models cannot be assessed in the absence of independent information on the upper mantle thermal regime and the lithosphere thickness, which are at present absent. As a result, interpretations of regional seismic models (Piromallo & Morelli, 2003; Maggi & Priestly, 2005; Hafkenscheid et al., 2006; Lei & Zhao, 2007; Zor, 2008; Biryol et al., 2011) in terms of the present-day lithosphere structure and the associated geodynamic processes are strongly non-unique and controversial.

The purpose of this paper is to present the first regional model for the lithosphere thermal structure in Anatolia. We also include an overview of various regional geophysical models

(sections 2.5 and 3.4). The purpose is two-fold: to identify robust geophysical characteristics of the crust and upper mantle of Anatolia that can be used as basis for regional geodynamic models, and to understand the origin of, perhaps apparent, inconsistencies between different geophysical models for Anatolia. We then present our new model for the lithosphere thermal structure, compare it with geochemical data on the Miocene-Quaternary volcanism (section 3.3), and discuss it within the regional geodynamic framework.

2. Modeling regional average lithosphere density and temperature

2.1. Crustal seismic structure

Crustal-scale seismic reflection-refraction profiles in Anatolia are nearly absent except for the Marmara Sea region (Karahana et al., 2001; Becel et al., 2009). Likewise, the structure of the sedimentary cover is not known in detail and even large-scale features may not be known reliably (Fig. 2a). The crustal thickness in Turkey is now relatively well established from seismic receiver function (RF) studies (Zor et al., 2003; Ozacar et al., 2010; Karabulut et al., 2013; Tezel et al., 2013; Vanacore et al., 2013; Frederiksen et al., 2015). Seismic RF image a highly heterogeneous crustal structure in Anatolia (Fig. 2b), even on a small scale (e.g. Frederiksen et al., 2015). The method is sensitive to the velocity contrast, and it is therefore unknown if the boundary imaged by RF is indeed the Moho, but not an intracrustal boundary. In case of magmatic underplating (Thybo & Artemieva, 2013), the velocity contrast between the underplate and the lower crust may be stronger than between the underplate and the sub-Moho mantle. For example, there is a ca. 10 km difference in the Moho depth imaged by P- and S-RF in central Greenland (Dahl-Jensen et al., 2003; Kumar et al., 2007), and the shallow boundary appears to be the top of the underplated material (Artemieva, 2019a).

Crustal thickness in Anatolia has also been studied seismically by Rayleigh wave phase velocities (Cinar & Alkan, 2017) and ambient noise tomography (Delph et al., 2015), and the results are generally consistent with the RF models. We further use a recent regional RF crustal model for the entire Anatolia (Vanacore et al., 2013) which is largely consistent with RF models for western Turkey (Karabulut et al., 2013) and the East Anatolian Plateau (Zor et al., 2003; Ozacar et al., 2010). The RF model is merged with a European crustal seismic model EUNaseis (Artemieva & Thybo, 2013) and is manually filtered to remove stations with local structural complexity (Vanacore et al., 2013) and with Moho depth values inconsistent with local data from near-by stations (Fig. 2b).

In general, the crust is 30-35 km thick in western Turkey and beneath the Kırşehir Massif, increases to ca. 40 km in the Central Pontides and Taurides, and is 45-50 km thick (with large, up to 10 km, short-wavelength variations) at the East Anatolian Plateau. Sparse seismic data suggest that the Moho depth may increase to 50 km and more beneath the Lesser and the Greater Caucasus. Seismic RF suggest strong heterogeneity of the crust as reflected by a highly variable V_p/V_s ratio (Fig. 2c). However, the V_p/V_s anomalies are poorly correlated with tectonics, although some regions of young basaltic volcanism have low V_p/V_s values. In the absence of classical seismic reflection/refraction profiles in Turkey, the inner structure of the crust (including the structure of the sedimentary cover) remains unknown. This precludes gravity modeling for the upper mantle density heterogeneity since the gravitational effect of the crust cannot be properly calculated (e.g. Herceğ et al., 2016).

2.2. Mantle contribution to topography

Most of Anatolia is close to isostatic equilibrium, but the equilibrium is incomplete with free air anomalies being slightly positive (+20 to +50 mGal) in most of the region (Fig. 3a). Notable exceptions where the lithosphere is uncompensated and free air anomalies are $>+100$

mGal include the mountain ranges of the Central and Eastern Pontides in the north, the Lesser and Greater Caucasus in the east, and the Anatolides in the south.

Regional studies of the gravity-topography relationship suggest that mantle flow produces free air gravity anomalies of ca. +50 mGal for 1 km of topography and the gravity/topography ratio is ca. 30 mGal/km for oceans (Crosby et al., 2006; Molnar et al., 2015). This may suggest that for most of western-central Anatolia with a 0.5-1.0 km elevation and free air anomalies of ca. +25 mGal, mantle convection contribution to topography (dynamic topography) may be around 0.5 km, and it may be double (ca. 1.0 km) in eastern Anatolia (Fig. 1a, 3a). However, these estimates are based on the assumption on an infinite depth of isostatic compensation (Molnar et al., 2015), and the wavelength of free air anomalies suggests that their origin may be in the shallow mantle. Modeling of residual topography in eastern Anatolia (assuming an Airy-type compensation at the Moho) indicates that the non-isostatic part of topography is ca. 0.7 km with local peaks of ca. 1.0 km at the East Anatolian Plateau and the Caucasus (Komut, 2014). We therefore, examine the cases of dynamic topography DT=0 km, 0.5 km, and 1 km in our further modeling (section 3.1).

The presence of a low density lithosphere material, associated either with a thick crust, or with a low density (hot?) upper mantle, or with a combination of both beneath the East Anatolian Plateau, the Taurides and Zagros is expected from strong negative (-50 to -120 mGal, locally down to less than -200 mGal) Bouguer anomalies (Fig. 3b). The anomalies decrease in amplitude westwards, but still remain negative in all Anatolia, except for the Aegean and the Black Sea coastal zones.

Residual Bouguer anomalies reflect the sub-Moho density anomalies, such as associated with a hot mantle material or the presence of cold dense slabs in the upper mantle. We calculate residual Bouguer anomalies (Fig. 3c) by subtracting gravity anomalies predicted from the Moho

depth variations (as deviation from a typical continental crustal thickness of 40 km) from the true Bouguer anomalies. In the absence of geophysical data on the intracrustal structure, we assume a uniform bulk crustal density. Additionally, the correlation between the Bouguer anomalies (BA) and the Moho depth (Fig. 4a) allows for calculating, what we call, Bouguer anomalies deviation (Fig. 3d) by subtracting, from the true BA, gravity anomalies predicted from the regional BA-Moho depth relationship (Fig. 4a).

The results (Fig. 3cd) indicate the presence of a heavy mantle material (slabs?) beneath the Greater Caucasus and the Eastern Pontides, and light (hot?) mantle beneath western Anatolia and the Central Anatolian Plateau. In contrast, no anomaly is present beneath the East Anatolian Plateau, indicating that its high topography is supported largely by the crust, without any significant contribution from the mantle. This contradicts an earlier hypothesis on the cause of the high topography of the East Anatolian Plateau. It has been argued, based on a comparison with the Ethiopian Plateau and without including gravity data into the analysis, that the crust beneath the East Anatolian Plateau is, on average, 5-10 km thinner than normal isostatic compensation requires (assuming it is achieved at the Moho), and that therefore a high topography of the East Anatolian Plateau is supported by a hot mantle in the absence of lithosphere mantle (Sengör et al., 2003). This conclusion (based chiefly on data on the crustal thickness) is not supported by our results (Fig. 3c). It is also in contradiction with a clear correlation between the Bouguer anomalies and the Moho depth (Fig. 4a) which suggests that variations in crustal thickness play a major role in negative Bouguer anomalies in Turkey, including eastern Anatolia (Fig. 3d). A recent geodynamic modeling of topography evolution in eastern Anatolia predicts a less than 0.5 km dynamic contribution to the East Anatolian Plateau topography (Komut, 2014), despite unrealistically high mantle temperatures constrained by a conversion of a P-wave global seismic tomography model (which yield sub-Moho temperatures

of ca. 1500 °C). This suggests that a model with a more realistic colder mantle may not require any significant contribution of the mantle to the topography of eastern Anatolia, which can therefore be largely explained by the crustal structure.

2.3. Regional average crustal and lithosphere mantle densities

The slope of the Moho depth – Bouguer anomalies (BA) correlation (Fig. 4a) depends on the contrast between bulk crustal density and average in situ density of the lithosphere mantle (Fig. 5a), assuming an Airy-type isostasy. Similarly, the slope of the Moho depth – topography correlation (Fig. 4b) also depends on the density contrast between the crust and the lithosphere mantle (Fig. 5b). The system of two equations with two unknowns allows for the unique determination of the average in situ crustal and lithosphere mantle densities (Fig. 5c,f).

The approach ignores a possible dynamic topography and lithosphere flexure, which are likely to contribute to regional topography in the complex regional geodynamic setting affected by paleo-subduction systems and the on-going Arabia-Eurasia collision. However, the latter is presently accommodated by the westward lithosphere escape along the North and East Anatolian Faults (Bozkurt, 2001), and the compressional component of deformation (<10 mm/y) is present only in the eastern part of Anatolia (east of ca. 40 °E) with near-zero values in the Eastern Pontides (Reilinger et al., 2006). A dynamic effect of mantle flow heterogeneity on regional topography is hardly possible to evaluate in the absence of a unique regional geodynamic interpretation of the upper mantle heterogeneity. We therefore consider our estimate as an end-member evaluation of mantle density heterogeneity.

Regional correlations for the entire Anatolia (Fig. 4ab), with the Moho-BA slope of -0.07 km/mGal and the Moho-topography slope of 8.5 km/km correspond to regional average crustal density of 2.90 g/cm³ (Fig. 5c) and regional average in situ lithosphere mantle density of 3.24 g/cm³ (Fig. 5f). A typical density of continental crust is around 2.80 g/cm³ (Artemieva & Shulgin,

2019). Therefore, an unusually high average density of the Anatolian crust (averaged for the entire on-shore study region) suggests that the sedimentary cover is thin, while the basaltic crustal layer is thick. The latter is expected in regions affected by volcanic and magmatic activity and with a widespread presence of ophiolites. In the absence of seismic reflection/refraction profiles, the inner structure of the Anatolian crust remains yet unknown, and we therefore cannot test our model predictions by seismic models of the crust.

2.4. Regional average lithosphere temperatures

Making an assumption that average density structure is controlled by thermal heterogeneity alone (therefore ignoring lithosphere compositional and structural density heterogeneity), average density anomalies in the crust and lithosphere mantle can be converted to average lithosphere temperature anomalies for the known value of thermal expansion. Theoretical curves (Fig. 5d,e) are calculated for the Bouguer plate approximation assuming mantle density of 3.37 g/cm³ at SPT conditions (at room pressure and temperature); this value is typical of Phanerozoic fertile mantle composition (Gaul et al., 2000).

The results suggest that the regional average temperature of the lithospheric mantle (in the layer between the Moho and the LAB) in the entire continental Anatolia is ca. 1100 °C (Fig. 5d,e). For the LAB temperature of 1300 °C, it provides a regional average temperature at the Moho depth in the entire Anatolia of ca. 900 °C. Importantly, this regionally average value (with strong short wavelength variations everywhere in Anatolia) corresponds to different depths, because the Moho depth varies from ca. 30 km in western Anatolia to ca. 45-50 km in its eastern part (Fig. 6). We further show (section 3.2) that most of western Anatolia has a hot mantle, while in eastern Anatolia the mantle is typically colder (although still hot). Therefore the regionally averaged Moho temperature is similar for western, central, and eastern Anatolia due to the combined effect of the Moho depth variations anticorrelated with lithosphere temperatures.

Lithosphere geotherms constrained by the Moho temperatures (Fig. 6) suggest regional average surface heat flux of $>100 \text{ mW/m}^2$ in western Anatolia and $60\text{-}80 \text{ mW/m}^2$ in eastern Anatolia and imply that the lithosphere can be $40\text{-}50 \text{ km}$ thick in western Anatolia and $70\text{-}90 \text{ km}$ thick in eastern Anatolia, in case all topography is caused by the lithosphere isostasy without dynamic contribution of the mantle. The detailed modeling of regional temperature variations in the lithosphere and the lithosphere thickness is presented in section 3 below, where the effect of dynamic topography is also included in the analysis. Here we first compare the calculated regional average heat flux predictions with observations.

2.5. Comparison with geophysical data

Surface heat flux measurements (open access database of the International Heat Flow Commission) in Anatolia are concentrated in few zones (Fig. 7a) and do not provide even regional coverage. Many boreholes are shallow (Fig. 7b) and data quality may be questioned. This also results in a large heterogeneity of the measured values, which are affected by shallow temperature perturbations associated with faults and groundwater circulation. Basically, reliable heat flux measurements are very limited (Fig. 7b). Available data indicate, in general, a high heat flow ($>80 \text{ mW/m}^2$) in most of Anatolia, especially in regions of crustal extension in the Menderes Massif, supporting our estimate of high regional lithosphere temperatures (Fig. 6). Few reliable measurements in the East Anatolian Plateau provide values $60\text{-}100 \text{ mW/m}^2$ and even $<50 \text{ mW/m}^2$ south of Lake Van, in support of our results.

Measured heat flux does not correlate with Pn and Sn velocity anomalies (Fig. 8ab). Importantly, the region with the highest measured heat flux in the Menderes Massif ($>100 \text{ mW/m}^2$) has normal Pn ($8.0\text{-}8.1 \text{ km/s}$) and Sn (ca. 4.5 km/s) velocities. This confirms our conclusion that seismic velocity anomalies cannot be explained solely by mantle temperature anomalies. Pn- (Al-Lazki et al., 2004; Toksoz et al., 2008; Gans et al. 2009; Mutlu & Karabulut,

2011) and Sn tomography (Gok et al. 2003; Toksoz et al., 2008) show a very patchy pattern of the upper mantle velocity anomalies, and Pn and Sn velocities are poorly correlated (Fig. 8ab). In general, Neogene volcanoes are associated, as expected, with low Pn; however not with low Sn, which is very surprising and suggests significant anisotropy of the upper mantle. Surprisingly, the volcanic region in the East Anatolian Plateau has fast Sn velocities. Both Pn and Sn anomalies also show poor correlation with tectonic terranes, crustal structure and topography. These observations preclude interpretation of Pn and Sn in terms of mantle temperatures alone. We emphasize this important observation, because as mentioned earlier, the presence of numerous paleosubduction systems in Anatolia suggests the presence of water in the mantle, which may be distributed highly heterogeneously. The Vp/Vs ratio at the top of the mantle, that is the Pn/Sn ratio (Fig. 8c), is thought to be more sensitive to fluids and composition than to temperature variations. However, the general pattern of the anomalies is also poorly correlated with tectonics, although young volcanic fields in general have $Vp/Vs < 1.73$. It implies that if Pn and Sn velocities cannot be explained by temperature anomalies, seismic tomography images also cannot be interpreted in terms of mantle temperature anomalies alone.

Commonly, the Curie depth is considered as proxy for the lithosphere thermal state. For Anatolia, such interpretation is supported by a spatial correlation between the regions with the shallow Curie depth (<12 km) and the Neogene volcanoes. Furthermore, a highly extended crust with the anomalously high heat flux in western Turkey has the shallowest Curie depth. As for heat flux, there is no correlation between the Curie depth and the Pn- and Sn velocity anomalies. This may not be surprising, because the Curie depth (Fig. 7c) variations between <10 km to ca. 25 km (Aydin et al., 2005) indicate that in Anatolia the magnetic layer extends neither into the deep crust nor into the upper mantle. Pure magnetite has a Curie temperature of 580 °C and this temperature is commonly accepted to determine the Curie point depth. However, it has long been

noted (Gasparini et al., 1979) that while magnetite is likely to control the Curie depth in the mantle, ferrimagnetic minerals with a Curie temperature as low as 300-400 °C are responsible for the magnetisation of crustal rocks (McElhinny & McFadden, 2000). Note that representative geotherms for eastern and western Anatolia (Fig. 6) predict the same range of the Curie depth values (from <10 km to 25-30 km) as determined by magnetic surveys (Fig. 7c).

3. Lithosphere thermal structure

3.1. Thermal isostasy method

An overview of geophysical models for Anatolia demonstrates that the existing data on the lithosphere thermal structure are highly controversial and do not support regional interpretation of seismic models in terms of mantle temperature anomalies alone. Seismic tomography images are very heterogeneous and complex (see section 3.4), and all interpretations of seismic velocity anomalies are driven by regional geodynamic history, when the presence of slabs in the mantle is expected from geological data. At the same time, one should expect that the upper mantle that hosted slabs of oceanic and, possibly, of continental origin should also have a strong heterogeneity in water distribution in the mantle and some chemical heterogeneity as well. The latter may be insignificant in case no ancient cratonic mantle material is present (Gaul et al., 2000).

It is therefore, timely to provide an independent constraint on regional lithosphere thermal structure to tighten geodynamic interpretations of seismic models. We use the thermal isostasy method to calculate lithosphere temperatures and thermal thickness (Fig. 9). We refer the reader to the original publications (Artemieva, 2019ab) where the method is described in detail, including the uncertainty analysis, and present here a brief summary. The method assumes regional isostasy with density heterogeneity extending down to the lithosphere base (LAB). As

discussed above (section 2.2), weakly positive free air anomalies over most of the region (Fig. 3a) indicate some deviation from the isostatic equilibrium, which is likely to be caused by a mantle dynamic contribution and lithosphere flexure. These possible components to topography cannot be directly estimated, and our results provide a maximum estimate of lithosphere temperatures and a minimum estimate of the lithosphere thickness, if the contribution of the dynamic topography (DT) is assumed to be zero. However, based on the discussion in section 2.2, we also include into the analysis the cases of DT=0.5 km and DT=1.0 km. As mentioned above, the observed values of free air anomalies suggest that mantle contribution to topography (dynamic topography) may be around 0.5-1.0 km in most of Anatolia.

Isostatic topography variations are caused by variations in the thickness and density of the crust and the lithospheric mantle (LM). Densities of both the crust and the LM are affected by temperatures and composition. Crustal density heterogeneity (both thermal and compositional) is reflected in the Moho depth - topography plot (Fig. 4b). By neglecting compositional density heterogeneity of LM (unknown in Anatolia), we can calculate density anomalies in the LM caused by temperature variations. Further, knowledge of lithospheric geotherms allows for calculating the lithosphere thermal thickness (e.g. Fig. 6).

We first calculate anomalous topography (Fig. 9, 10a) as deviation of the true topography from the predicted topography based on the correlation in Fig. 4b. The Airy-type crustal isostasy links topography to the crustal thickness (Fig. 4b) through the density contrast between the crust and the upper mantle (Fig. 5), and therefore one can predict isostatic topography from the known crustal thickness (Fig. 3b). In general, in western and central Anatolia the topography is ca. 0.5-1 km higher than predicted from the crustal isostasy (“hot” lithospheric mantle), while in the Eastern Pontides, the Caucasus region and in the northern Arabian Shield it is depressed by ca. 1 km (“cold” lithospheric mantle) (Fig. 10a). This suggests the presence of a hot mantle material in

regions with a positive anomalous topography and the presence of a cold, high-density material in the mantle (e.g. subducting slabs) where the anomalous topography is negative. Importantly, the interpretation of “cold” and “hot” lithospheric mantle is not in the absolute values, but with respect to the regional average defined by the regional relationship between topography and the crustal thickness (Fig. 4b). As discussed in section 2.4, the entire Anatolia has high mantle temperatures (Fig. 6), so that even “cold” Anatolian mantle may be warmer than typical continental.

Next, assuming that anomalous topography is all caused by temperature anomalies within the lithosphere mantle (due to density heterogeneity caused by thermal expansion), we calculate these temperature anomalies with respect to a reference location with zero anomalous topography. Lithosphere geotherms control lithosphere thermal thickness, and we next calculate the lithosphere thermal thickness, assuming that the latter is known at a location where the anomalous topography is zero (these values can be determined from independent data). Here we assume that the lithosphere thickness in locations with zero anomalous topography (Fig. 10a) is 100 km. It is close to the lithosphere thickness values based on seismic RF (Kind et al., 2008). The choice of a different geotherm and the lithosphere thickness at a zero anomalous topography location will systematically shift all results, without changing the pattern (e.g. Artemieva, 2019a). In particular, a change in the reference lithosphere thickness by 50 km will shift the results by ca. 20-25 km only, due to a strongly non-linear relation between the anomalous topography and the lithosphere thickness (Fig. 9).

Mantle temperature anomalies, assuming no compositional density variations, may also be calculated from gravity data, if the crustal structure is known (Shulgin & Artemieva, 2019). However, this requires independent information on the lithosphere thickness in order to calculate

the gravitational effect of temperature-induced density variations in the lithosphere mantle.

Unfortunately, such information does not exist for Anatolia at present.

3.2. Lithosphere thermal structure: Results

The patchy pattern of lithosphere thermal anomalies and lithosphere thickness variations is the major characteristics of Anatolia. We interpret this pattern by lithosphere fragmentation, in agreement a small (ca. 10 km) thickness of elastic lithosphere in Anatolia (McNab et al., 2018). We present results as temperatures at the Moho depth (Fig. 10bcd) and the lithosphere thickness (Fig. 11) for three values of dynamic topography (DT=0 km, 0.5 km, and 1.0 km). In our further discussion we focus on the models with DT>0, as supported by slightly positive regional free air anomalies (Fig. 2a), gravity interpretations (Molnar et al., 2015), free-board considerations (Artemieva & Vinnik, 2016), and regional numerical modeling (e.g. Komut, 2014; Howell et al., 2017). Note that our results are poorly constrained for the off-shore areas due to limited data on the crustal thickness (Fig. 3b, 4b).

Moho temperatures (Fig. 10bcd) show a strongly heterogeneous mosaic pattern, which reflects regional variations in both the crustal thickness and lithosphere geotherms. The model without dynamic topography predicts average temperatures similar to those estimated in section 2.4 (Fig. 6) with Moho temperatures around 800-900 °C in most of Anatolia (Fig. 10b). When dynamic topography is included, lithosphere geotherms reduce significantly, especially in eastern Anatolia (Fig. 10d), e.g. by ca. 200 °C at the Moho depth in case of DT=1 km (Table 1). We favor the models with dynamic topography of 0.5-1.0 km (section 2.2) which predict Moho temperatures around 650-850 °C in most of Anatolia. All regions of young volcanism have high temperatures at the Moho and often appear as localized thermal anomalies.

Likewise, lithosphere thermal thickness shows significant regional variations with many short wavelength anomalies (Fig. 11). The general features of our thermal model are: (i) a patchy pattern of lithosphere thermal structure in most of Anatolia, (ii) the presence of a thin and hot lithosphere in most of western and central Turkey with embedded fragments of a thick lithosphere, and (iii) lithosphere thickening beneath the East Anatolian Plateau with a thick lithosphere beneath the Caucasus region and the Eastern Pontides (Fig. 11). This pattern is in the overall agreement with the depth to Curie point (Fig. 7b) and with a global tomography model (Schaeffer & Lebedev, 2013), which shows the presence of a ca. 150 km thick lithosphere beneath the Eastern Pontides and the East Anatolian Plateau. Our results are also similar in pattern to the tomography model of Piromallo & Morelli (2003) at a 150-200 km depth (Fig. 12a). We briefly summarize them here and compare with geochemical data from young volcanic provinces of Anatolia and with seismic tomography models (sections 3.3-3.4).

- The rifted part of the western Menderes Massif and the Antalya Block have an anomalously hot and thin (50-75 km) lithosphere, that may be related to the Hellenic subduction and a possible slab roll-back (Fig. 11) (Jolivet et al., 2012).
- The Kirsehir Massif has a heterogeneous lithosphere thermal structure. The south-central part has a 50-70 km thick lithosphere, in agreement with seismic receiver function studies (Vinnik et al., 2014). The belt of thin lithosphere corresponds to a linear belt of the Neogene volcanoes where mantle melting at ca. 60-80 km depth (a typical depth for magma generation in subduction systems (Lee et al., 2009)) may be expected. Our result for a 50-70 km thick lithosphere is also consistent with the melting depth estimate in a recent study of the Anatolian basaltic volcanism which concluded that mantle melting across Anatolia occurs at a ca. 60 km depth at mantle potential temperature of 1400 °C (McNab et al., 2018).

- The belt of thin lithosphere in the southern Kirsehir Massif is followed by a near-linear belt of a ca. 150 km thick lithosphere beneath the western Taurides (Fig. 11bc). The pattern of the deepening lithosphere base combined with the volcanic belt suggests the presence of a SE-dipping paleosubduction system (Fig. 11d).
- The NE part of the Kirsehir Massif includes a block with a cold and thick (150-175 km) lithosphere, which corresponds to the Tethyan ophiolites (Fig. 1c) and therefore may represent a remnant of the Tethyan slab.
- The East Anatolian Plateau has lithosphere thickness of 80-140 km with strong short wavelength variations. The smallest values tend to be associated with the Neogene volcanoes (Fig. 11) and are similar to the lithosphere thickness (60-80 km) determined by receiver functions (Angus et al., 2006; Ozacar et al., 2008). Lithosphere thermal thickness is close to the estimate of 62-74 km thickness of the lithospheric mantle (that is ca. 110-130 km for the entire lithosphere, including the crust), based on gravity modeling constrained by seismic tomography and RF (Mahatsente et al., 2018). The patchy pattern of lithosphere thickness suggests the presence of slab windows associated with slab tearing, fragmentation and a possible interplay of multiple paleosubduction systems.
- The lithosphere beneath the Eastern Pontides orogenic belt and the Lesser Caucasus is 150-200 km thick and is probably also associated with the presence of the Neo-Tethys slabs (Eyuboglu et al., 2014). The presence of lithospheric root beneath the Central Pontides is less certain, and the lithosphere there is ca. 100-150 km thick.

3.3. Comparison with geochemical data on young volcanism

Miocene-Quaternary volcanics are wide-spread in western, central and eastern Anatolia (Fig. 1b). The origin of this abundant magmatism is debated with a variety of processes, such as lithosphere delamination, anomalously hot mantle, and subduction-related magmatism proposed

to explain its origin. Clearly, the relative roles of these processes may be very different across Anatolia.

In western Anatolia, wide-spread mafic volcanism has been ascribed to oceanic subduction (Aldanmaz et al., 2006; Ersoy et al., 2010), fragmentation (Agostini et al., 2007) and tearing (Prelevic et al., 2015) of subducted slab, or slab stretching associated with the slab rollback beneath (Innocenti et al., 2005). It has also been proposed that the Late Miocene to Pleistocene basalts of western Anatolia may mark the transition between subduction-related and intraplate activity, where composition of the older basalts indicates the presence of slab fluids in a mantle source, while the younger basalts indicate the involvement of both MORB-like (mid-ocean-ridge basalt) and OIB-like (ocean-island basalt) components (Agostini et al., 2007). The transition from subduction-related calc-alkaline magmatism to intraplate alkaline magmatism in western Anatolia (McNab et al., 2018) is in accordance with our conclusion on the presence of an anomalously thin (ca. 50 km thick) lithosphere in much of western Anatolia, with local preservation of small slab fragments or fragments of cratonic lithosphere where the lithosphere thickness may reach a 100-150 km depth (Fig. 11).

Similarly, the transition from Eocene-Oligocene andesitic lava flows to Miocene basaltic dykes is documented for volcanics in the southern part of the Eastern Pontides (NE Turkey). One of the interpretations of this magmatism includes lithospheric delamination, which led to the partial melting of the subduction-metasomatized enriched lithospheric mantle source of the Neoproterozoic age (Aslan et al., 2014). The geochemical results on shallow mantle melting are in agreement with our model, which for the same region (ca. 39.5 °E, 40.5 °N) indicates the presence of a local anomaly with a ca. 50-60 km thin lithosphere surrounded by a cratonic-type, thick and cold lithosphere (Fig. 11).

In central Anatolia (the southern part of the Kirsehir Massif, ca. 34 °E, 38 °N) composition of widespread basaltic volcanism indicates melting of a subduction-related component and intraplate mantle (Reid et al., 2017). This volcanism was explained by mantle decompression melting at maximum mantle potential temperatures of <1350 °C at a depth of ca. 40-55 km in response to the rollback of the Cyprian slab (Reid et al., 2017), which has led to a nearly complete removal of the lithosphere mantle (McNab et al., 2018). These conclusions are supported by our results which indicate the presence of an anomalously thin (ca. 50 km) lithosphere beneath the volcanic region in central Anatolia (Fig. 11). We favor geodynamic interpretation which includes tearing of the Tethyan lithosphere as a possible response to the corner flow associated with the Cyprian subduction (Fig. 11d).

In eastern Anatolia, the Miocene (11 Ma) to present day volcanism has a striking compositional variability that has been attributed to a northward subducting oceanic lithosphere with slab fragmentation and breakoff, which resulted in lithosphere thinning to ca. 50 km beneath the southern margin of the East Anatolian Plateau (ca. 42-44 °E, 38-39 °N) (Keskin, 2003). Our results are consistent with the depth of the mantle melting source, but indicate that the shallow melting anomaly is limited to the volcanic region, while the lithosphere of eastern Anatolia is highly variable in thickness (Fig. 11). This patchy pattern is better explained by a complicated geometry of slab fragmentation and tearing beneath the East Anatolian accretionary complex, possibly including several slabs, and is inconsistent with the model of a wide-spread lithosphere delamination (Pearce et al., 1990).

It has recently been proposed, based on the analysis of young basaltic magmas, that temperatures in asthenospheric mantle across Anatolia may be somewhat higher in its eastern part (McNab et al., 2018). Our results neither prove, nor disprove this hypothesis, since our modeling assumes a constant temperature of 1300 °C at the lithosphere-asthenosphere boundary

for the entire region ([section 3.1](#)). We further note that while our results clearly indicate lithosphere thinning to a typical depth of basaltic magma generation (ca. 60 km) beneath all Anatolian Miocene-Quaternary volcanic regions, the overall pattern of lithosphere thermal structure indicates, on average, thicker (80-140 km) and colder lithosphere beneath eastern Anatolia with a, generally, thinner (50-80 km) and hotter lithosphere beneath most of the Western Aegean extensional province ([Fig. 11](#)). We speculate that melting anomalies in the sublithospheric mantle, responsible for basaltic volcanism and possibly associated with a complex geometry of subduction systems of different ages and heterogeneous mantle hydration, may have short wavelengths to be reflected in geophysical data. We further note that our geophysical model provides a complete spatial coverage of Anatolia, while basaltic magmatism samples possible melting anomalies and regional generalizations based on the Nature's sampling carry with them sampling limitations.

3.4. Comparison with upper mantle velocities and seismic lithosphere

A comparison of our results with regional seismic models shows no correlation between the lithosphere thermal structure ([Fig. 10](#)) and S_n velocities ([Fig. 8](#)), in support of our earlier conclusion that temperature variations alone cannot explain all seismic velocity anomalies, although in some regions the thermal model correlates with P_n velocities. Therefore, upper mantle velocity anomalies, especially S_n , may be controlled by the water content in the mantle and therefore some of low- S_n , high P_n/S_n anomalies may mark paleoslabs in the mantle.

Anatolia has been covered by a large number of regional seismic tomography models ([Maggi & Priestly, 2005](#); [Lei & Zhao, 2007](#); [Zor, 2008](#); [Biryol et al., 2011](#); [Salaun et al., 2012](#); [Govers & Fichtner, 2016](#); [Portner et al., 2018](#)) and by some seismic RF studies ([Abgarmi et al., 2017](#)). Based on S-RF, the lithosphere thickness increases eastwards from ca. 80 km in western

Turkey to ca. 100 km beneath the East Anatolian Plateau (Kind et al., 2015), in an overall agreement with our results that also show a general trend in lithosphere thickening eastwards. However, seismic tomography models show a very different and inconsistent pattern (Fig. 12), so that the lithosphere thickness in Anatolia still remains unconstrained by seismic methods.

Global tomography models, especially based on surface waves, have a low lateral resolution and can hardly map systematic differences between different parts of Anatolia (Fig. 12cde). All regional models show an extremely complex pattern of seismic velocity anomalies at different depth slices (Fig. 12ab) in the upper mantle and at vertical profiles at any location in the region. This complexity does not allow to identify the “seismic lid” which can be interpreted as the lithosphere and therefore does not allow to determine the seismic LAB (the lithosphere-asthenosphere boundary). Indeed, vertical cross-sections indicate a complex pattern of anomalies that can better be interpreted as images of slabs and slab windows (Lei & Zhao, 2007; Zor, 2008; Biryol et al., 2011; Salaun et al., 2012; Govers & Fichtner, 2016). Such interpretations are justified by the known tectonic evolution of the region, where paleoslabs are expected to be associated with the Paleo- and Neo-Tethys subduction systems, and young slabs may be associated with the orogenies in the Caucasus and Zagros and with the Hellenic and Cyprus subduction systems (Fig. 1c).

In western Anatolia, high velocity anomalies associated with the Hellenic and Cyprus subduction systems have a continuous pattern (Bakırc et al., 2012; Salaun et al., 2012) which allows for an easy geodynamic interpretation as subducting slabs. Our results also show the presence of low-temperature anomalies with a thick lithosphere surrounded by an overall very thin and very hot lithosphere of western Anatolia, which we interpret as being related to the Hellenic subduction (Fig. 11).

Slab fragmentation was proposed for central Anatolia based on full-waveform tomography (Govers & Fichtner, 2016). This model imaged a highly heterogeneous S-velocity pattern at 50 km and 100 km depths, which was interpreted as a fragmented Neo-Tethys slab. Our model also shows heterogeneous lithosphere structure beneath the Central Anatolian Plateau with lithosphere thickness variations from more than 150-175 km to ca. 50 km depth. The largest thickness corresponds to the Tethyan ophiolites in the NE part of the Kırşehir Massif, and we interpret this block of a very thick lithosphere as a remnant of the Tethyan slab. Region with a very thin lithosphere in the southern part of the Kırşehir Massif corresponds to a linear belt of the Neogene volcanoes, which we interpret as also being related to a speculative paleosubduction system, resolved in our model as an elongated belt of a cold and thick (ca. 150 km) lithosphere (Fig. 11bcd). The anomaly, especially its SW part, is also resolved in Bouguer residual and Bouguer deviation (Fig. 3cd), which indicate the presence of a dense subcrustal material. Similar to our results, in the same region in western Taurides north of Cyprus, S-wave tomography imaged a high velocity anomaly at a 100 km depth (Govers & Fichtner, 2016), interpreted as a “west Cyprus slab”.

Beneath the East Anatolian Plateau, a P-wave tomographic model (Zor, 2008) imaged a negative velocity anomaly at a 100-200 km depth; it was attributed to a partially molten asthenosphere, although the model has resolution problems in the upper ca. 200 km. Some vertical profiles across eastern Anatolia show a strong regional 3D velocity heterogeneity, with a mixture of high- and low- velocity anomalies, and without a continuous high velocity anomaly expected for a slab. RF studies of the mantle transition zone also show a strong regional heterogeneity beneath the East Anatolian Plateau which was explained by a detached slab and delaminated lithosphere fragments (Ozacar et al., 2008). In contrast, a regional teleseismic P-wave tomography model shows a relatively homogeneous velocity structure of the mantle

transitions zone, interpreted as an image of a trapped flat-lying Tethyan lithosphere (Biryol et al., 2011). Our results show that the lithosphere structure of eastern Anatolia is, overall, more uniform than in western and central Anatolia, with a typical lithosphere thickness of 80-140 km. However, in the East Anatolian Plateau we also observe strong short wavelength variations, with the smallest values of lithosphere thickness determined for the region of the Neogene volcanism (Fig. 11). These values are similar to the LAB depth estimates by receiver functions (Angus et al., 2006; Ozacar et al., 2008)), while the largest values (ca. 125 km in case of DT=0.5 km and ca. 140 km for DT=1.0 km, Fig. 11bc) are similar to the LAB depth estimate of 110-130 km based on gravity modeling, seismic tomography and RF (Mahatsente et al., 2018).

Across the Greater and Lesser Caucasus, a P-wave tomographic model indicates a strongly heterogeneous structure of the upper mantle (Zor, 2008). A southwards dipping high-velocity (ca. +2%) anomaly imaged at ca. 160-600 km depth at a N-S profile at 41°E was interpreted as a detached Neo-Tethys slab beneath eastern Turkey. However, the same anomaly was not resolved at profiles 0.5° to the east and west, nor at other adjacent profiles (Zor, 2008). Furthermore, a strong but low-velocity (-1-2%) upper mantle anomaly, also dipping southwards and crossing the mantle transition zone was imaged at ca. 45 °E. For the region beneath the Lesser Caucasus where a deep slab is tomographically imaged, our model indicates the presence of a 150-200 km thick lithosphere. For the Greater Caucasus our model is not well constrained due to the lack of seismic data on the Moho depth (Fig. 2b).

4. Geodynamic implications

Geological evidence, in particular the presence of wide-spread ophiolites (Fig. 1c), indicates that subduction dynamics, including e.g. possible roll-back, slab fragmentation, delamination, creation of slab windows, should have played a critical role in topography evolution and magmatism in Anatolia. Seismic tomography models, although controversial (Fig.

12), form basis for a number of regional geodynamic models (e.g. [Hafkenscheid et al., 2006](#);
[Bartol & Govers, 2014](#); [Komut, 2014](#); [Göğüş et al., 2017](#); [Portner et al., 2018](#)). Here we address
some of them in view of our thermal model. Note that our model cannot resolve the vertical
structure of (paleo)subduction zones, as proposed for different parts of Anatolia based on seismic
models. In our model, such zones would appear to have a thick lithosphere when slabs are
attached to the upper plate, while in places where slabs may be fragmented or delaminated, our
model would show a thin lithosphere ([Fig. 11](#)).

4.1. East Anatolian Plateau

The presence of a fragmented and delaminated lithosphere beneath the East Anatolian
Plateau as proposed based on seismic models (e.g. [Zor, 2008](#)) is supported by our model which
shows a highly heterogeneous thermal upper mantle structure in the region ([Fig. 11](#)). However,
the hypothesis that the high topography of the plateau is solely due to a hot mantle after
lithosphere delamination ([Sengör et al., 2003](#); [Bartol & Govers, 2014](#)) is only partially supported
by our results, which indicate that a significant part of the high topography can be explained by
the crustal root ([Fig. 4, 10a](#)), while lithosphere thickness of 80-140 km beneath the East
Anatolian Plateau indicates that a significant portion of the lithosphere mantle is still present.
However, about 60-70 km of its lower lithosphere may have been delaminated, assuming that a
thick (150-200 km) lithosphere of the Eastern Pontides may be representative of the Tethyan
collision and subduction. The presence of a thick lithosphere beneath the East Anatolian Plateau
may also indicate that the plateau may have a significant component of continental lithosphere
fragments, in agreement with recent geochemical data ([Topuz et al., 2017](#)).

The presence of several blocks with a very thin (ca. 75 km) lithosphere beneath the plateau
clearly indicates the on-going lithosphere destruction, such as associated with various scenarios
of slab fragmentation. In particular, a low-Vp anomaly resolved by [Zor \(2008\)](#) beneath the

Lesser Caucasus at ca. 44 °E is also present in our results, as well as a high-Vp anomaly at the south-eastern end of the Black Sea (Fig. 11). Our results favor a model with a slab detachment or a slab window at the south-eastern part of the Caucasus with a further slab fragmentation beneath the Neogene volcanic area of the East Anatolian Plateau and south of it.

4.2. Central Anatolian Plateau

Based on regional seismic tomography models, the recent uplift of the Central Anatolian Plateau has been explained by a slab retreat and the associated lithosphere delamination (Bartol & Govers, 2014; Schildgen et al., 2014; Göğüş et al., 2017). Our results do not disprove the presence of a localized lithosphere delamination and indicate that the Central Anatolian Plateau has a less than 100 km thick lithosphere, which is in general 30-50 km thinner than beneath the East Anatolian Plateau (Fig. 11).

We favor a model where lithosphere thinning is possibly related to a proposed SE dipping paleo-subduction beneath the southern Kirsehir Massif and the Taurides (Fig. 11). The presence of the associated cold slab in the upper mantle seems to be imaged by regional tomography models (Bijwaard & Spakman, 2000; Piromallo & Morelli, 2003) (Fig. 12ab), and its possible presence is neither supported nor rejected by a recent RF study (Abgarni et al., 2017). The proposed paleo-subduction may (at the SW part) interact with the, still speculative, Cyprus subduction, therefore complicating geodynamic evolution of southern Turkey and possibly channeling mantle melting associated with the Cyprus subduction towards the Antalya block and along the East Anatolian fault (Fig. 11d).

4.3. Western Anatolia

Our results support the geodynamic models that the Hellenic subduction and a possible slab roll-back have a strong control on the tectonics of the western Anatolia (e.g. Jolivet et al.,

2012). Most of the region has an anomalously thin (50-75 km) and hot lithosphere (possibly locally thinned to the crust) (Fig. 11), and local lithosphere thickening to ca. 90 km in the southern part of the Menderes Massif seems to be spatially related to the known Precambrian basement rocks (Fig 1c).

There is a sharp stepwise increase in lithosphere thickness by ca. 60-80 km from the Menderes Massif to the Sakarya Zone in the north, where the lithosphere thickens to 140-160 km. The region includes the Paleo-Tethys accretionary complex (Fig. 1c), and therefore our results may indicate the presence of a Paleo-Tethys lithosphere root south-east and south-west of the Marmara Sea.

5. Conclusions

We review geophysical models for the crustal and upper mantle structure in Anatolia, including seismic models, gravity anomalies, the Curie depth variations, and surface heat flux data. These models are poorly correlated, and do not show clear correlations with geology and distribution of young volcanic centers. Therefore, geodynamic interpretations of geophysical models remain controversial, and we argue for a heterogeneous hydration of the upper mantle by paleoslabs.

1. Significant correlations between the Moho depth, the Bouguer anomalies and topography for the Anatolia region indicate that crustal isostasy plays an important role in regional topography variations. These correlations imply that average crustal density in Anatolia is higher than normal continental (2.90 g/cm^3), suggesting an overall mafic composition of the Anatolian crust. From these correlations we estimate an average in situ lithosphere mantle density of 3.24 g/cm^3 , which implies hot lithosphere geotherms.

2. Thermal structure of the Anatolian lithosphere is highly heterogeneous with mosaics of short-wavelength anomalies. This pattern is characteristic and reflects a complicated geodynamic evolution of Anatolia with lithosphere formed by a mosaic of amalgamated continental and oceanic terranes, fragmented and teared in many places by subduction systems of different ages.

3. The average temperature at the Moho depth in Anatolia is 800-900 °C (with strong short wavelength variations) in case all topography is explained by the lithosphere-scale isostasy and it is 600-700 °C if mantle contribution to topography is 1 km. We favor the model with a regionally average value of 650-850 °C for the Moho temperature. In most of western/central Anatolia the lithosphere is hot and thin, and lithosphere temperatures approximately follow a 100-120 mW/m² continental geotherm (Pollack & Chapman, 1977). In eastern Anatolia lithosphere temperatures are significantly colder and approximately follow a 80 mW/m² continental geotherm in case of no dynamic topography and a 60 mW/m² continental geotherm if dynamic topography is 1 km. These estimates are in agreement with regional heat flow measurements from deep boreholes.

4. We calculate lithosphere thermal thickness in Anatolia for 3 models of dynamic topography contribution (0 km, 0.5 km, and 1 km). The results differ in amplitude but have the same patterns. Lithosphere thickness ranges from 50-75 km in the Menderes Massif and part of the Kirsehir massif to 80-140 km beneath the East Anatolian Plateau and the Central Pontides, 140-160 km beneath the Sakarya Zone, and 150-200 km beneath the Eastern Pontides and the Lesser Caucasus.

5. Our results are consistent with lithosphere destruction in western Anatolia, possibly associated with the Hellenic subduction. We argue that the patchy pattern of lithosphere thermal heterogeneity in eastern Anatolia is caused by teared Tethyan slabs, and the thick lithosphere of the Eastern Pontides and the Lesser Caucasus corresponds to the Neo-Tethys slab.

6. We interpret a characteristic pattern of lithosphere thickness variations, marked by a linear belt of young volcanoes at the southern part of the Kırşehir Massif, by a SW-dipping paleosubduction beneath the western Taurides, where the lithosphere is ca. 150 km thick. We propose that the interplay of this proposed paleoslab with the young subducting slab at Cyprus may cause deviation of melts from the mantle wedge towards the Antalya block and along the East Anatolian fault.

7. The presence of a thick (80-140 km) lithosphere beneath the East Anatolian Plateau indicates that the region may include significant fragments of continental lithosphere, in contrast to a wide-spread opinion that its basement consists entirely of oceanic accretionary complexes.

Acknowledgements

Numerous discussions with A.M.C. Sengör and A. Okay on regional tectonics, geodynamics, and geology are gratefully acknowledged. IMA acknowledges discussions and insights at the Turkish Geological Congress (2019) by the invitation of O. Göğüş. Constructive comments by B. Steinberger who has drawn our attention to regional importance of dynamic topography, by N. White who has suggested to include a comparison with geochemical data, and by an anonymous reviewer are gratefully acknowledged. Data used in the modeling are publicly available as referenced in the paper.

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Figure captions

Fig. 1. (a) Regional topography based on ETOPO1 model (Amante & Eakins, 2008); (b) simplified tectonic map (after Okay & Tuysuz, 1999). Major fault zones are based on the USGS catalogue (www.usgs.gov); young volcanoes are from <http://www.volcano.si.edu/world>, and the Miocene-Quaternary volcanic fields are after Yilmaz et al. (1997); (c) sketch of paleo-tectonics (based on Sengör, 1981; Okay & Tuysuz, 1999); yellow and pink background – Laurasia and Gondwanaland terranes, respectively.

Fig. 2. (a) Thickness of sediments, (b) Moho depth, and (c) crustal Vp/Vs. Data sources for (a): NOAA database for off-shore domain, the EUNaseis seismic model for on-shore domain (Artemieva & Thybo, 2013), updated for Turkey (Gurbuz & Evans, 1991; Frederiksen et al., 2015). Data sources for (b): the EUNaseis seismic model (Artemieva & Thybo, 2013), updated by seismic RF data for Turkey (Karabulut et al., 2013; Vanacore et al., 2013). Color symbols show data used for interpolation. Black dots – seismic stations with RF estimates for the Moho depth, that are excluded from interpolation due to complexity of the local crustal structure and clear inconsistency with other local Moho models.

Fig. 3. Gravity anomalies based on EGM2008 global model (Pavlis et al., 2012); (a) free air anomalies, (b) Bouguer anomalies (BA) for reduction density of 2.67 g/cm^3 , (c) residual BA calculated by subtracting from (b) the Bouguer anomalies predicted from the Moho depth assuming uniform bulk crustal density of 2.8 g/cm^3 , (d) BA deviation calculated by subtracting from (b) the Bouguer anomalies predicted from the BA-versus-Moho depth regional trend (Fig. 4a). The results indicate the presence of a heavy mantle material beneath the Caucasus - Eastern Pontides and of a hot mantle beneath western and central

Anatolia. The absence of an anomaly beneath eastern Anatolia indicates that its high topography is largely supported by the crust.

Fig. 4. Data density for regional correlations between the Moho depth, Bouguer anomalies (a) and hypsometry (b). Strong correlation in (a) suggests that most of topography can be explained by crustal isostasy, while strong correlation in (b) allows for calculating anomalous topography that cannot be explained by crustal isostasy, and therefore for calculating lithosphere temperature anomalies. Line marked DT=0 corresponds to the case without mantle contribution to topography, line marked DT=1 km assumes a 1 km contribution of dynamic topography (DT). Off-shore trend is poorly constrained due to limited data on the Moho depth. Therefore the results for the off-shore regions are also poorly constrained.

Fig. 5. Theoretical correlations for on-shore regions between the slopes of the Moho depth vs Bouguer anomalies (BA) (a, d) (Fig. 4a) and the slopes of the Moho depth vs topography (b, e) (Fig. 4b) and average crustal density, average in situ density of the lithosphere mantle (a, b), and average temperature of the lithosphere mantle (d, e). Two slopes (Moho-BA and Moho-topography) are controlled by two densities (crustal and mantle) and therefore allow for determining regional average crustal (c) and average in situ lithosphere mantle (f) densities for the entire on-shore Anatolia from the two slopes. Black dashed lines – regional average values for Anatolia. Notations in equations: ρ_c and $\rho_m^{SPT}=3.37 \text{ g/cm}^3$ – densities of the crust and the lithospheric mantle (index SPT refers to room P-T conditions); $\alpha=3.5 \cdot 10^{-5} \text{ 1/K}$ – coefficient of thermal expansion; T_m – mantle temperature.

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Fig. 12. Depth slice from seismic tomography models at a 75-100 km depth. (a, b) – regional P-wave models (Piromallo & Morelli, 2003; Bijwaard & Spakman, 2001); (c-e) – global S-wave models (Schaeffer & Lebedev, 2013; Shapiro & Ritzwoller, 2004).

Table 1

Regionally average temperatures in on-shore Anatolia at different depths

Depth	No dynamic topography (DT)	DT=0.5 km	DT=1.0 km
Moho	832±230 °C	680±194 °C	612±179 °C
50 km	1023±343 °C	929±359 °C	841±355 °C
100 km	1227±156 °C	1175±180 °C	1121±195 °C

Figures

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