

# Lithospheric structural control on inversion of the southern margin of the Black Sea Basin, Central Pontides, Turkey

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## ABSTRACT

To illustrate the structural evolution of the Black Sea Basin in the context of Neotethyan subduction and subsequent continental collisions, we present the first lithosphere-scale, ~250-km-long, balanced and restored cross section across its southern continental margin, the Central Pontides. Cross-section construction and restoration are based on field, seismic-reflection, geophysical, and apatite fission-track data. The structure of the onshore Pontides belt is predominantly controlled by inverted normal faults, whereas the offshore areas are devoid of large structural inversion. The restored section indicates that Cretaceous crustal thinning occurred synchronously with (probably buoyancy-driven) exhumation of a forearc high-pressure blueschist wedge likely during Neotethyan slab retreat. Apatite fission-track data show that structural inversion of the forearc zone, which formed the Central Pontides fold-and-thrust belt, started at ca. 55 Ma. This Eocene structural inversion followed upon collision of the Kırşehir continental block and the arrest of Neotethyan oceanic subduction below the Central Pontides. Compared to the Central Pontides belt, which underwent significant shortening (~28 km, i.e., ~33%), the relatively colder and stronger Black Sea lithosphere prevented the northern offshore areas from undergoing inversion. We propose that the location of Cenozoic contractional deformation is related to the absence of lithospheric mantle below the southern Pontides (forearc) zone as a consequence of the Cretaceous high-pressure wedge exhumation.

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## INTRODUCTION

Lithospheric heterogeneities may temporally and spatially influence deformation (e.g., Ziegler et al., 1998). The Black Sea—the largest European back-arc basin (Fig. 1A; Okay et al., 1994)—is an isolated extensional basin formed from Cretaceous to Paleocene times behind a north-dipping Neotethyan subduction zone (Letouzey et al., 1977; Zonenshain and Le Pichon, 1986; Görür, 1988; Hippolyte et al., 2010; Okay et al., 2013). Seismic-reflection and deep geophysical data from the Black Sea show, from continental margins toward the basin center, thinned continental crust, exhumed upper mantle, and inferred oceanic crust beneath thick Cenozoic sedimentary sequences (e.g., Robinson et al., 1996; Yegorova and Gobarenko, 2010). In contrast, the continental margins of the Black Sea are characterized by compressional mountain belts: the Balkans in Bulgaria, Crimea in Ukraine, the Greater Caucasus in Georgia and Russia, and the Pontides in Turkey (Fig. 1A). Inversion of the Black Sea margins mainly started in the Eocene period and is locally still

active (Belousov et al., 1988; Robinson et al., 1996; Reilinger et al., 2006; Khriachtchevskaia et al., 2010; Munteanu et al., 2011; Yildirim et al., 2011).

This paper aims to constrain the structural architecture and evolution of the Pontides belt–Black Sea Basin system, and the way in which this system was included into the Alpine-Himalayan belts with only peripheral structural inversions. On the basis of structural, seismic-reflection, geophysical, and apatite fission-track data, we present the first lithospheric-scale balanced and restored cross section across the Central Pontides and southern Black Sea margin. This new balanced and restored cross section allows us to geometrically and quantitatively reconstruct the southern Black Sea margin during the Neotethyan subduction and subsequent continental collisions. We then discuss the role played by inherited lithospheric heterogeneities in the large-scale kinematic evolution of the Pontides belt–Black Sea Basin system.

## GEOLOGICAL SETTING AND PRESENT-DAY STRUCTURAL ARCHITECTURE

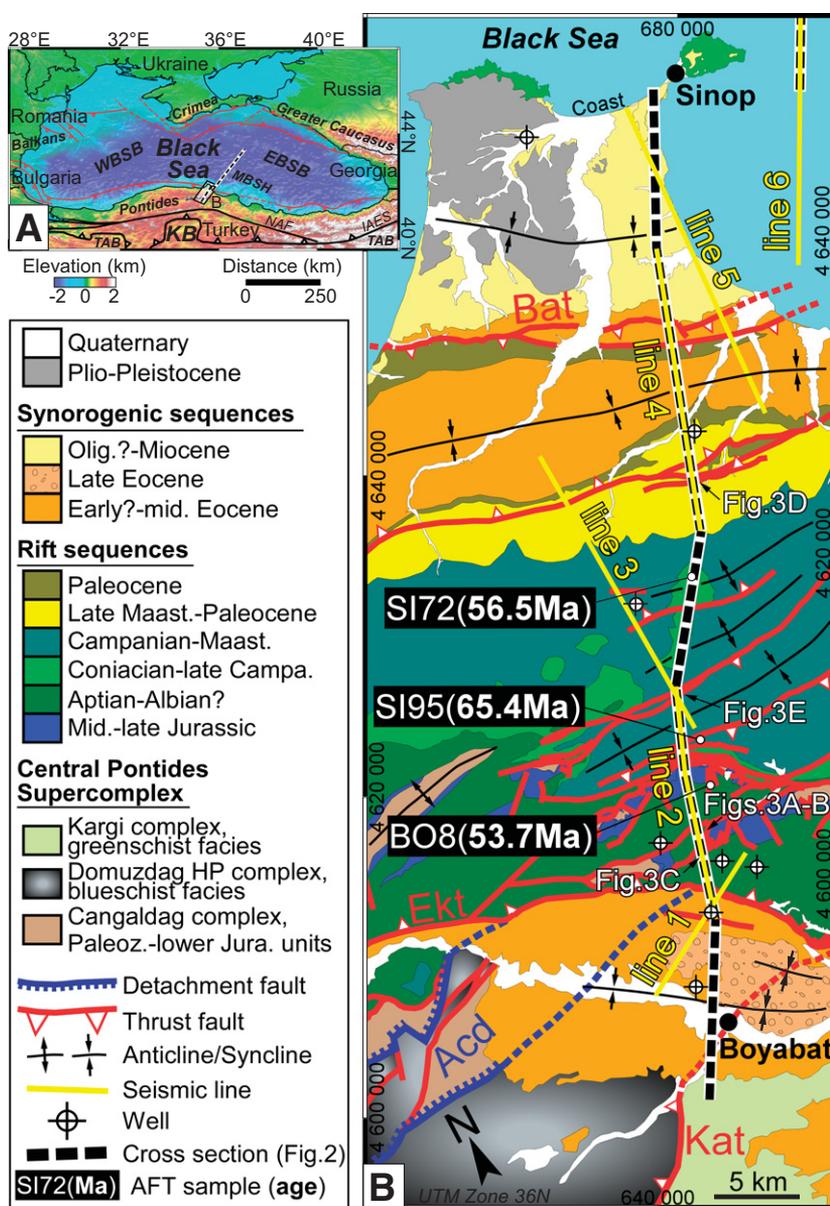
The Pontides mountain belt extends over ~1000 km along the southern coast of the

Black Sea (Fig. 1A). The crust of the Central Pontides was formed by accretion of Gondwana-derived microcontinents to the southern margin of Eurasia during the closure of the Paleotethys Ocean, in Jurassic times (e.g., Şengör and Yılmaz, 1981; Okay et al., 2006). To the south, the Izmir-Ankara-Erzincan “Neotethys” suture separates the Central Pontides from the Kırşehir continental block (Fig. 1A). The Kırşehir block accreted to the southern margin of Eurasia (i.e., the southern Black Sea margin) in the Late Cretaceous to Paleocene period (Kaymakci et al., 2003; Meijers et al., 2010; Lefebvre et al., 2013; Okay et al., 2013). The Central Pontides zone (Okay et al., 2006) has the largest onshore portion (Sinop Peninsula) with extremely good cross-sectional exposure of geological structures, and good coverage of seismic-reflection data and exploration wells (Fig. 1B). To illustrate the two-dimensional structural architecture of the southern Black Sea margin, we combined six seismic-reflection profiles (labeled from 1 to 6 and provided by Turkish Petroleum Affairs database) from this zone and built a synthetic ~250-km-long section (Figs. 1 and 2). A time-depth conversion of each seismic profile was performed using the  $V_0k$  method (see Table

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DR1 in the GSA Data Repository<sup>1</sup>). Structural and stratigraphic interpretations of the 70-km-long onshore Pontides section were achieved by using lines 1–5, eight exploration wells, and new geological mapping (Figs. 1B and 2A; see also Fig. DR1 [see footnote 1]). For the 180-km-long offshore Black Sea section (Fig. 2B; see also Fig. DR2 [see footnote 1]), we used line 6 and followed the structural and stratigraphic interpretation provided by Robinson et al. (1996).

From south to north, the Central Pontides belt consists of the Central Pontide Supercomplex (Okay et al., 2013), the Boyabat basin, the Sinop range, and the Sinop basin (Figs. 1B and 2A). From south to north, the Central Pontide Supercomplex includes the Kargi, Domuzdağ, and Çangaldağ metamorphic complexes. The Kargi complex is composed of greenschist-facies mineral assemblages (Okay et al., 2013). It is tectonically overlain by the Domuzdağ complex (along the Kadilar thrust), a highly deformed mid-Cretaceous (ca. 105 Ma; mica Ar-Ar geochronology) high-pressure complex, including blueschist, eclogite, and gneiss (Okay et al., 2006). To the north, the Domuzdağ complex is separated from greenschist-facies rocks of the Çangaldağ complex by the north-dipping Acisu normal detachment fault system. This ENE-trending detachment system is an important structural feature, 30 km long in the section, but it is poorly exposed because it is unconformably covered by Cenozoic deposits of the Boyabat syncline (Figs. 1B and 2A). The asymmetric Boyabat syncline is characterized by a steep and sheared northern limb overthrust by the Sinop range (Fig. 2A). The Sinop range is a 40-km-wide bivergent thrust system bounded to the south by the Ekinveren thrust and to the north by the Balifaki thrust system (Fig. 2A; Sonel et al., 1989; Aydın et al., 1995). The southern flank of the range is deformed by steep thick-skinned thrusts involving Permian–Lower Jurassic (and probably older) metamorphic sequences, and Middle Jurassic to Lower Cretaceous sedimentary cover with some volcanic components (Aydın et al., 1995; Şen, 2013). Field and subsurface data show strong thickness variations (from ~4 km to less than 300 m) in the Lower Cretaceous turbiditic sequences across the faults. Major thrust faults, like the Ekinveren thrust, correspond to reactivated normal faults

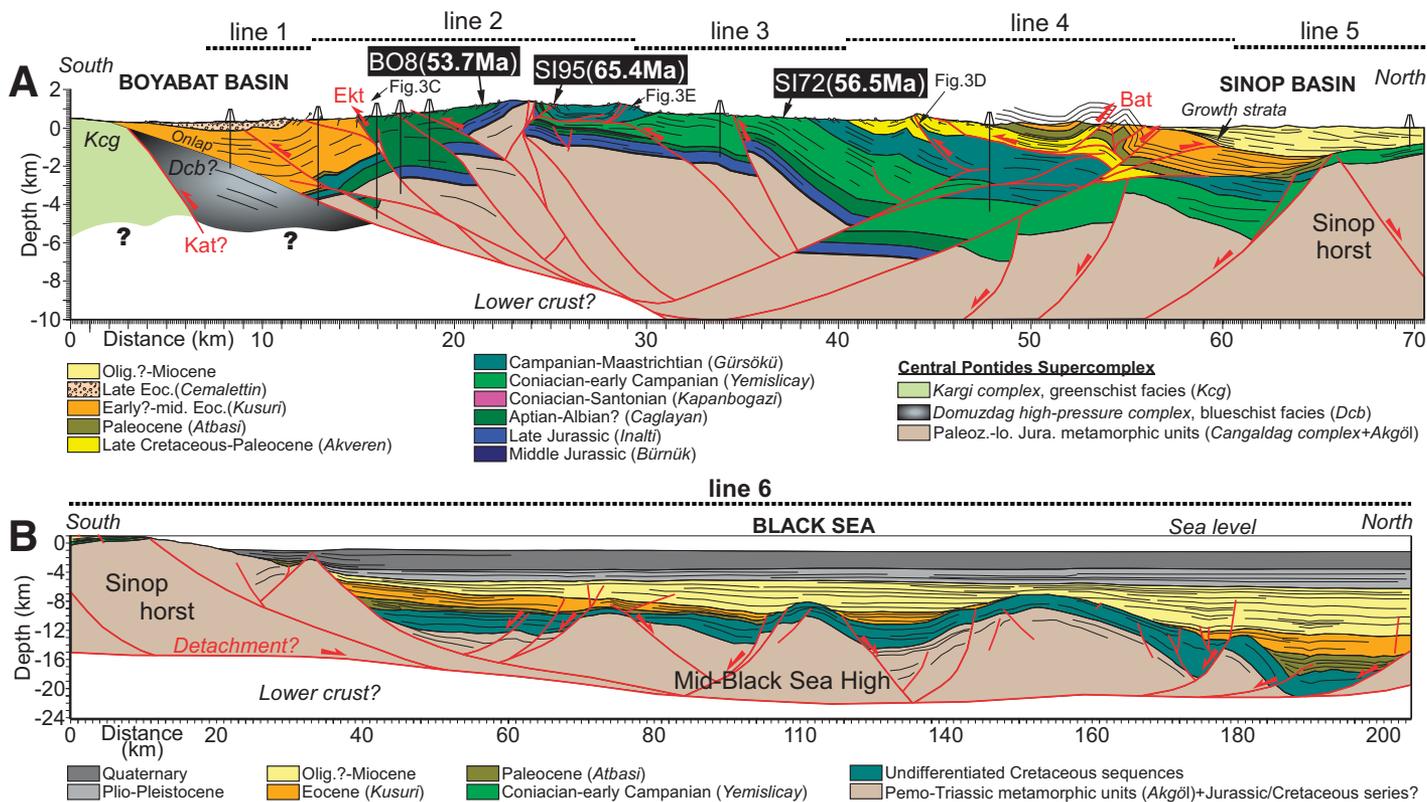


**Figure 1.** (A) Geodynamical setting of the Black Sea and surrounding mountain belts. The white rectangle locates the Central Pontides geological map shown in B. The black and white dashed lines locate the synthetic cross sections of Figure 2. Red lines show peripheral and small structural inversions in the offshore areas. The Black Sea is composed of two subbasins—the western Black Sea Basin (WBSB) and the eastern Black Sea Basin (EBSB)—separated by the Mid-Black Sea High (MBSH). NAF—North Anatolia fault; IAES—Izmir-Ankara-Erzincan suture zone; KB—Kırşehir block; TAB—Taurus-Anatolide block; (B) Geological map of the onshore Pontides belt showing locations of seismic-reflection profiles (yellow lines 1–6), wells, and apatite fission-track samples (central/young ages). Locations of Figures 3A–3E are also shown. Ekt—Ekinveren thrust; Bat—Balifaki thrust; Kat—Kadilar thrust; Acd—Acisu detachment. HP—high pressure; AFT—apatite fission track.

<sup>1</sup>GSA Data Repository item 2014093, Figure DR1 (interpreted onshore seismic profiles), Figure DR2 (interpreted offshore seismic profile), Table DR1 (velocities for time-depth conversion), and Table DR2 (nannoplankton determinations) are available online at [www.geosociety.org/pubs/ft2014.htm](http://www.geosociety.org/pubs/ft2014.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

(Figs. 3A and 3B), mainly inherited from the Early Cretaceous extensional period (Aydın et al., 1995). Small-scale tilted normal faults are common within Aptian turbiditic series (Fig. 3C). The northern flank of the range is deformed at depth by south-dipping reactivated normal faults, which are responsible for the northward

thickening of the Upper Cretaceous turbiditic sequences. These faults branch upward into thin-skinned thrust systems associated with major disharmonic folding (Figs. 3D and 3E). The Balifaki thrust front is a complex imbricate fan deforming Eocene–Miocene sequences of the southern edge of the Sinop basin (Fig. 2A).



**Figure 2.** Interpretation of the synthetic seismic-reflection transects, including lines 1–6, across the onshore Central Pontides belt (A) and offshore southern Black Sea Basin (B). Locations of Figures 3C–3E are shown. Note the difference in scale between the two transects. See synthetic seismic profile interpretations in Figures DR1 and DR2 (see text footnote 1). Apatite fission-track samples with central/young ages (black rectangles) are projected onto the cross section. Kat—Kadilar thrust. Ekt—Ekinveren thrust; Bat—Balifaki thrust.

The Balifaki thrust extends WNW-ESE along the strike of the Pontides into the offshore areas (Figs. 1A and 1B).

The offshore section extends from the eastern shelf of the Sinop Peninsula to the center of the Black Sea Basin across the Mid-Black Sea High (Figs. 1 and 2B). The Sinop shelf is a 40-km-large horst-like structure, mainly composed of Upper Cretaceous volcanic rocks with a magmatic arc signature, and Eocene turbidites, unconformably overlain by Miocene strata (Fig. 2A; Yılmaz et al., 1997). To the north, seismic-reflection data show a zone of stretched upper crust overlain by a thick (10–15 km) sedimentary package: inner horsts and grabens bounded by high-angle normal faults (forming the Mid-Black Sea High), and outer roll-over structures (Fig. 2B). As suggested by Robinson et al. (1996), we infer that the normal faults connect down onto a low-angle, north-dipping, mid-crustal detachment fault at ~16 km depth (Fig. 2B), which is consistent with geophysical data (Çakır and Erduran, 2004). Normal faults were mainly active during the Cretaceous–Paleocene extensional period (Robinson et al., 1996) and locally during the Eocene–Miocene as a conse-

quence of sedimentary loading and the effect of residual thermal subsidence (Cloetingh et al., 2003; Fig. 2B; Fig. DR2 [see footnote 1]). These extensional structures are overlain by an ~4-km-thick flat-lying Pliocene–Quaternary sediment package (Shillington et al., 2008). Although offshore structural inversions occur lateral to the Sinop Peninsula (Munteanu et al., 2011), no evidence of major structural inversion is found further north along the studied offshore section (Rangin et al., 2002; Şen, 2013).

The geometry of the deeper crustal and lithospheric levels is constrained by previously published geophysical data (Jiménez-Munt et al., 2003; Starostenko et al., 2004; Figs. 4A and 4B). Two different structural domains that approximately coincide with the onshore and offshore areas can be distinguished (Fig. 2). The Pontides belt is characterized by an ~45-km-thick crust and an ~105-km-thick lithosphere. In contrast, the Black Sea has a significantly thinner crust, ranging between ~5 and ~15 km (below a 10–15-km-thick sedimentary package; Figs. 2B and 4A), and an ~115-km-thick lithosphere. The northern edge of the section is characterized by extreme crustal thinning and

probably lithospheric mantle rocks exhumed to shallow depth beneath sedimentary series. This lateral variation is also revealed by thermal data (Fig. 4C), which show low values of surface heat flow in the Black Sea (~30 mW m<sup>-2</sup>), and higher surface heat-flow values (~60 mW m<sup>-2</sup>) for the Pontides (Kutas et al., 1998; Jiménez-Munt et al., 2003). Present-day low heat-flow values in the Black Sea Basin areas would result from the blanketing effect of the very thick Cenozoic sedimentary succession (Fig. 2B) over a Mesozoic cold lithospheric mantle (Cloetingh et al., 2003; Stephenson and Schellart, 2010).

**TIMING OF INVERSION**

To unravel the exhumation age of the Pontides belt in response to structural inversion of the southern Black Sea margin, we collected three sandstone samples across the Sinop range at different stratigraphic levels for apatite fission-track analysis (Figs. 1B and 2A; Gallagher et al., 1998). Samples were analyzed using the laser ablation–inductively coupled plasma–mass spectrometry method at Apatite to Zircon, Inc., laboratory (see details of the method in

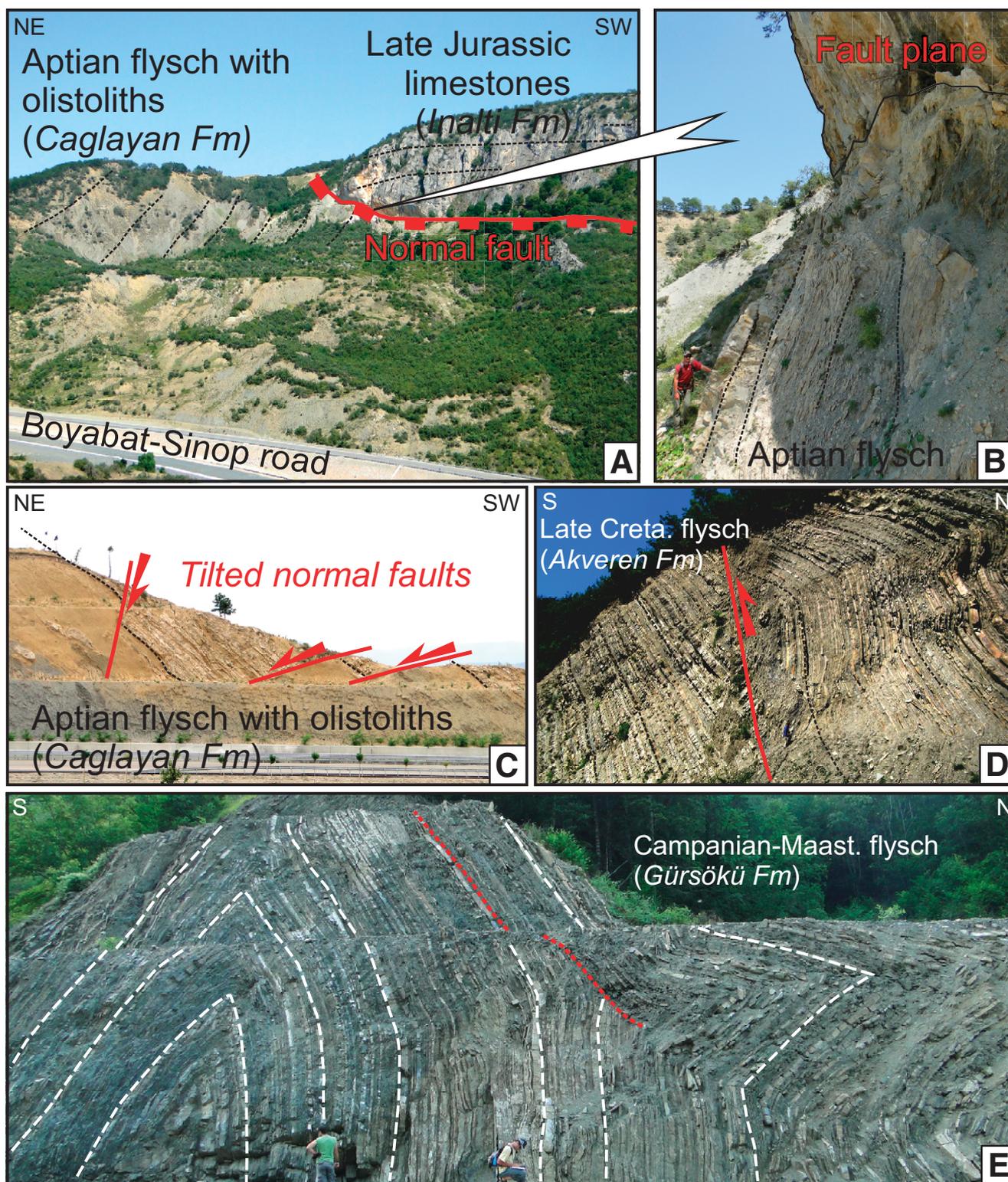
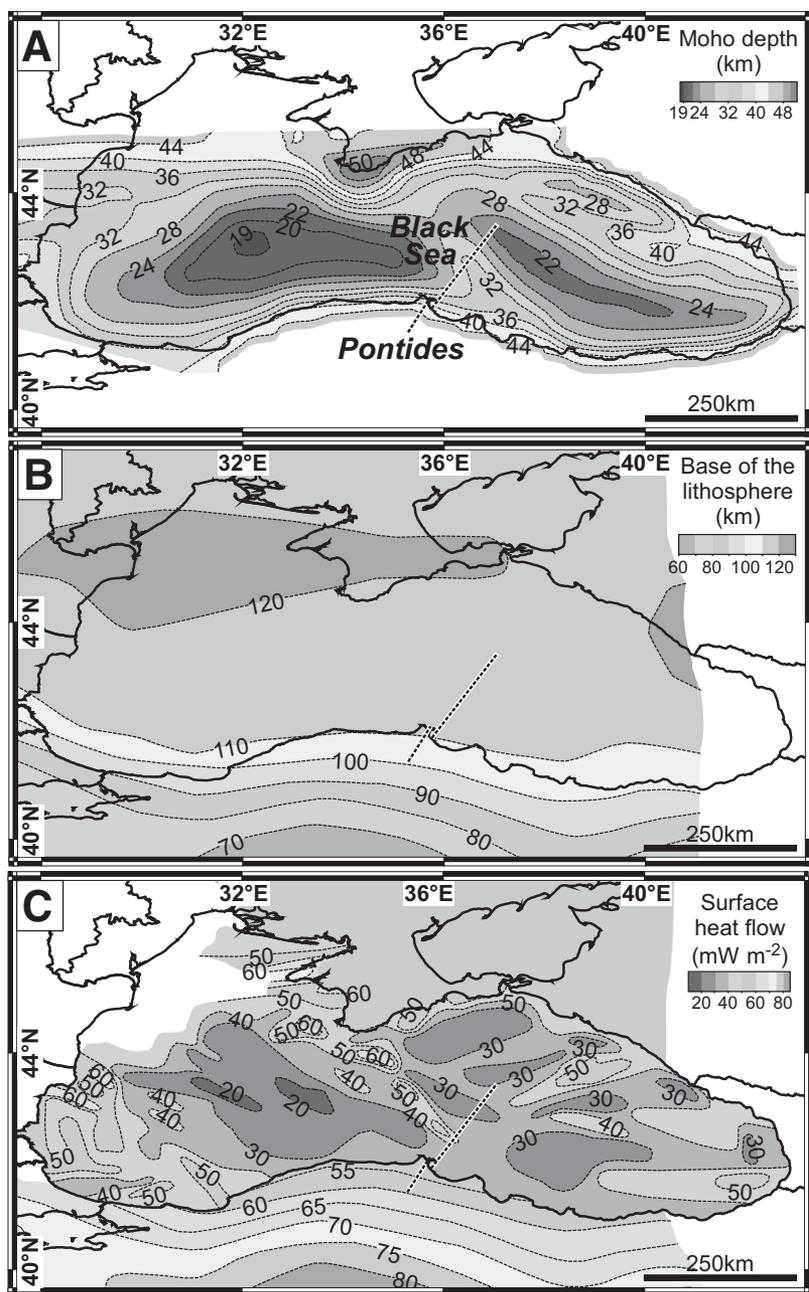


Figure 3. Key geological field observations illustrating the structural style of the Pontides belt. (A) Large-scale Aptian normal fault located in the southern flank of the Sinop range. (B) Details of the fault zone shown in A. (C) Other small-scale tilted Aptian normal faults near Boyabat city. (D–E) Thin-skinned thrusts and major disharmonic folding within turbiditic series in the northern flank of the Sinop range. Bedding traces are enhanced by thin dashed black or white lines. See location on Figures 1B and 2A.



**Figure 4.** Geophysical and thermal data of the Black Sea Basin and surrounding margins. (A) Moho depth (modified from Starostenko et al., 2004). (B) Base of the lithosphere (modified from Jiménez-Munt et al., 2003). (C) Surface heat flow (modified from Kutas et al. [1998] for offshore area and Jiménez-Munt et al. [2003] for onshore area). The black and white dashed lines show location of the synthetic cross sections of Figure 2.

Hasebe et al., 2004; Chew and Donelick, 2012). Because samples are sedimentary rocks with multicompositional apatites (mean maximum diameters of fission-track etch figures parallel to the c axis (Dpar) range from 1.8 to 3.5 μm), we used central ages (Galbraith and Laslett, 1993). In addition, we statistically decomposed sample grain-age distributions into peak ages

using RadialPlotter (Fig. 5; Vermeesch, 2009). The youngest peak ages were used to determine the last cooling event. Complete results are provided in Table 1.

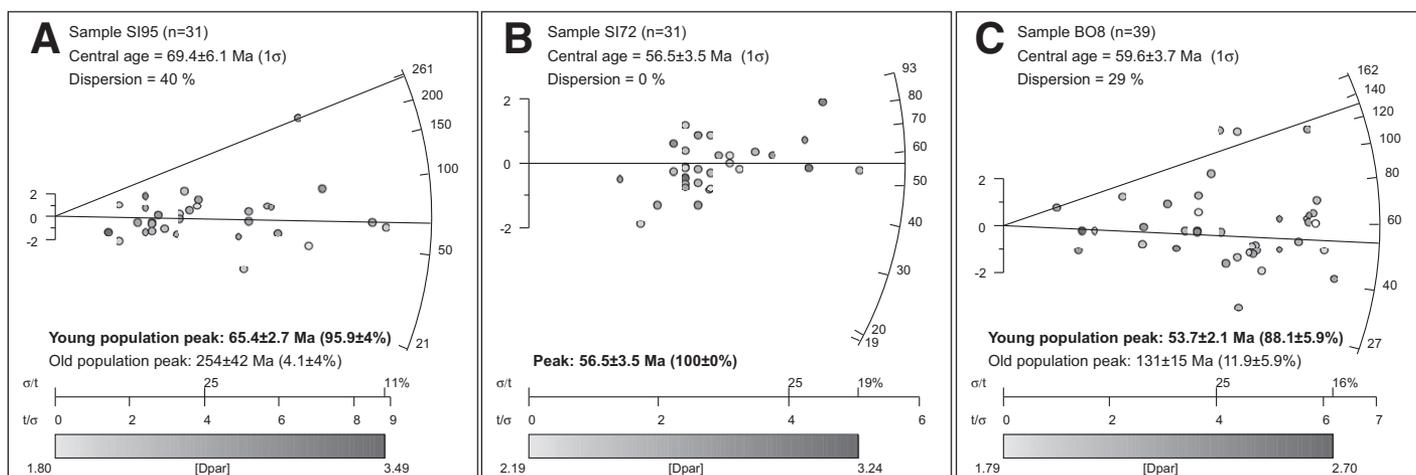
Assuming that samples were affected by a similar burial history related to the rifting of the southern Black Sea margin, we approximately reconstructed the position of the exhumed apa-

tite partial annealing zone (Fitzgerald, 1992) by comparing the central/young apatite fission-track ages with the respective stratigraphic ages (Table DR2 [see footnote 1]) and relative stratigraphic thicknesses (i.e., paleodepth) of the analyzed samples inferred from the cross section (Figs. 2A and 6). The shallowest sample SI95, collected in the late Campanian–early Maastrichtian series (ca. 72 Ma), has a young fission-track peak age of ca. 65 Ma and a mean track length of 13.41 μm. We interpret sample SI95 as partially reset with respect to its stratigraphic age (Fig. 6). The intermediate SI72 and deepest BO8 samples were collected in the early Campanian (ca. 81 Ma) and Aptian series (ca. 119 Ma), respectively. Both samples have similar central/young fission-track ages ( $56.5 \pm 3.5$  Ma and  $53.7 \pm 2.1$  Ma, respectively, i.e., ca.  $55 \pm 5$  Ma), much younger than their depositional ages, and longer mean track lengths than for sample SI95 (14.31 μm and 14.21 μm, respectively; Fig. 6). According to high vitrinite reflectance (Ro) values measured in wells on similar Aptian–early Campanian series (1.0%–2.9%; Turkish Petroleum Affairs database; Sweeney and Burnham, 1990), we conclude that samples SI72 and BO8 were subjected to major reheating below the partial annealing zone (80–110 °C) during Cretaceous–Paleocene burial. These results are compatible with strong rift sedimentary accumulation, reaching locally ~4 km in thickness. Apatite-bearing sandstones are rare in the study area, so the age results from three samples presented here provide only limited constraints on regional exhumation. However, the fission-track age versus paleodepth analysis places a minimum age of cooling related to the structural inversion of the southern Black Sea margin and growth of the Sinop range at ca.  $55 \pm 5$  Ma. This Eocene cooling age is consistent with those from other thermochronological studies in the Western and Eastern Pontides regions (Boztuğ et al., 2004; Cavazza et al., 2012). This age is also consistent with the deposition of Eocene siliciclastic turbidite sequences in both the Boyabat and Sinop synclines (Aydin et al., 1995). In addition, the Cenozoic growth of the range was recorded by Oligocene(?)–Miocene growth strata at the southern edge of the Sinop basin as revealed by seismic-reflection data (Fig. 2A; Fig. DR1 [see footnote 1]).

**DISCUSSION AND CONCLUSIONS**

**Balancing and Restoration**

Cross-section balancing (Dahlstrom, 1969) was used to build a viable lithospheric-scale structural model of the Central Pontides–south-



**Figure 5.** Apatite fission-track peak ages and mean maximum diameter of fission-track etch figures parallel to the c axis (Dpar) representations for each sample using RadialPlotter (Vermeesch, 2009). Apatite fission-track data from sedimentary rocks often exhibit significant variance because individual apatite crystals are likely to have different chemical compositions (represented by Dpar), influencing the annealing behavior (Carlson et al., 1999). We interpret the youngest peaks as apatite populations partially or totally annealed by the Cenozoic reburial heating, while the oldest peaks correspond to more thermally resistant apatite populations.

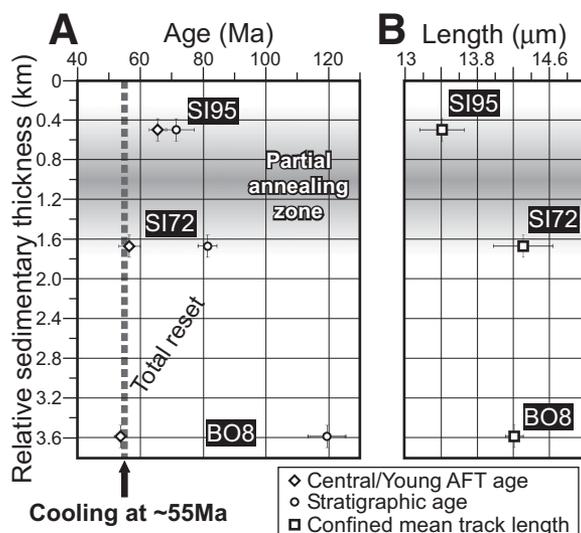
TABLE 1. APATITE FISSION-TRACK DATA USING LASER ABLATION–INDUCTIVELY COUPLED PLASMA–MASS SPECTROMETRY (ICP-MS) METHOD

Sample name	Longitude (m)	Latitude (m)	Elevation (masl)	Strat. age (Ma)	Gr	Ns	Rho (cm <sup>2</sup> )	P	σP	Zeta	σ Zeta
SI95	658 366	4 612 820	1092	71 ± 5	31	877	0.16E10–5	0.7410	7.59E10–2	12.35698	0.2251356
SI72	663 036	4 623 537	513	81 ± 2	31	289	6.5E10–5	0.7417	7.53E10–2	12.35698	0.2251356
BO8	657 146	4 609 426	1114	119 ± 5	39	859	0.13E10–5	1.3588	5.99E10–2	8.272661	0.1407127

Sample name	Q(χ <sup>2</sup> )	Pooled age (Ma)	Central age (Ma)	YPA (Ma)	% grains in YP	OPA (Ma)	% grains in OP	MTL (μm)	Standard deviation (μm)	Dpar
SI95	0	65.5(–5.5,6.0)	69.4 ± 6.1	65.4 ± 2.7	96	254 ± 42	4	13.41 ± 0.25(63)	1.95	2.50
SI72	0.9	54.7(–6.5,7.4)	56.5 ± 3.5	–	–	–	–	14.31 ± 0.33(200)	4.69	2.61
BO8	0	55.6(–4.7,4.6)	59.6 ± 3.7	53.7 ± 2.1	88	131 ± 15	12	14.21 ± 0.1(200)	1.35	2.16

Note: Coordinates are in UTM Zone 36N. Gr—number of counted grains; Ns—sum of spontaneous tracks; rho—area of spontaneous track counting with its error; P—corrected <sup>238</sup>U/<sup>43</sup>Ca isotopic ratio (10<sup>–3</sup>) with its error (σP); Zeta—ICP-MS zeta factor with its error (σ Zeta) for each sample; YPA and OPA—young and old peak ages from RadialPlotter (Vermeesch, 2009); MTL—mean track length (number of tracks); Dpar—mean maximum diameter of fission-track etch figures parallel to the c axis. Pooled ages are ±95% confidence interval. Central and peak ages are ±1σ.



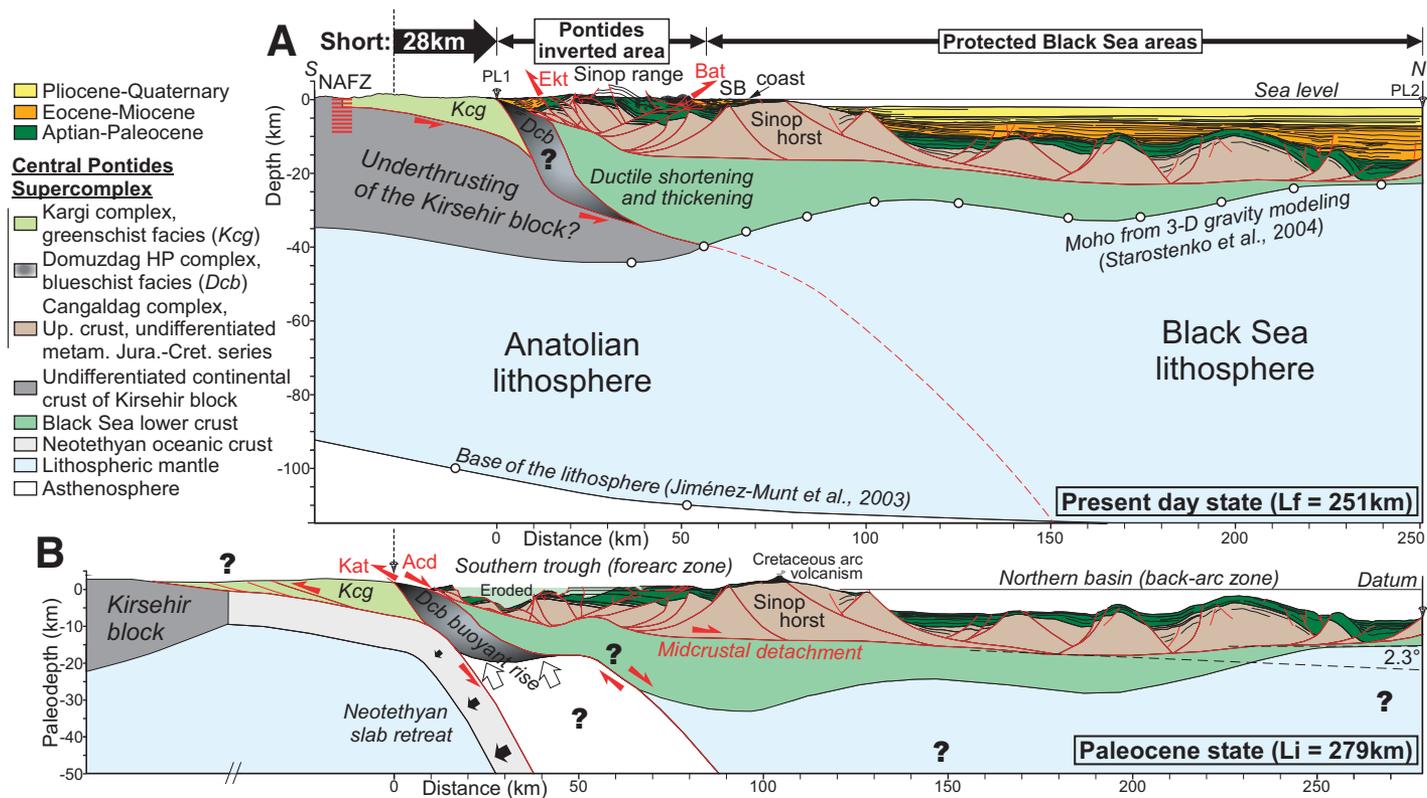
**Figure 6.** (A) Plot of the central/young apatite fission-track (AFT) and stratigraphic ages of the analyzed samples vs. stratigraphic thickness. (B) Plot of the mean confined track length vs. stratigraphic thickness.

ern Black Sea margin (Fig. 7A), integrating the aforementioned data. The ~250-km-long balanced cross section was constructed using classical thrust tectonic concepts (e.g., Boyer and Elliott, 1982; Suppe, 1983; Suppe and Medwedeff, 1990; Shaw et al., 2005) and the “Move2013” structural modeling software. The restoration was performed using a flexural-slip algorithm (Ramsay and Huber, 1987) for both sedimentary cover and upper crust, and the area-balance approach (Mittra and Namson, 1989) for the lower crust. Interpretation of the seismic profiles (Fig. 2) shows major lateral and vertical variations in lithology and thickness of the sedimentary series, which made the estimation of decompaction difficult. Nevertheless, cross-section restoration without sediment decompaction yields correct structural results in such a configuration (Nunns, 1991; Zhou et al., 2006). According to apatite fission-track results and stratigraphic constraints, we restored the cross section for the Paleocene configuration (ca. 66–56 Ma; Fig. 7B), i.e., before Eocene contraction and inversion.

Cross-section restoration shows that crustal extension of the margin might have taken place via a low-angle detachment to which other normal faults connected (Fig. 7B). This north-dipping detachment led to the formation of two main Cretaceous–Paleocene extensional basins separated by the Sinop horst (volcanic arc): a narrow trough to the south (forearc zone), which subsequently was inverted and incorporated into the Sinop range, and a wider and deeper extensional basin (back-arc zone) to the north, corresponding to the present Black Sea Basin (Fig. 7B). In this deep basin, the detachment is associated with Cretaceous to Paleocene extreme crustal thinning. According to the gentle warping and tilting (~2.3°) of the Black Sea Basin during Cenozoic, we assume that crustal thicknesses beneath the Black Sea Basin at the end of rifting (Paleocene) were similar to the present thicknesses. Our restoration supports the structural model of Okay et al. (2006) for the exhumation of the Domuzdağ complex as a high-pressure wedge below the Acisu detachment. East-trending inverted normal faults of

the Pontides belt may be linked to the eastern continuation of this major detachment system (Fig. 1B). Thus, the extensional Central Pontides forearc zone might have had no, or a thinned, lithosphere in the Cretaceous (Fig. 7B), because the high-pressure complex of the subducting Neotethyan crust moved all the way into the crust to the surface.

The comparison between the geometries at the end of rifting and after inversion provides direct estimation of the amount of horizontal shortening. We calculated the shortening using pin lines in the southern edge of the Domuzdağ complex (PL1) and in the northern edge of the cross section (PL2; Fig. 7A). The length of the Paleocene reconstructed margin is ~279 km, and the modern length is ~251 km, leading to an estimate of ~28 km of crustal shortening after the Eocene. This crustal shortening was mainly focused in the onshore Pontides belt domain, that is, ~33% shortening only applies between the Domuzdağ complex and Sinop basin (Fig. 7A). Paleomagnetic data indicate that this ~28 km Eocene–Miocene NNE-oriented shorten-



**Figure 7. (A)** Lithospheric-scale balanced cross section of the Central Pontides–southern Black Sea margin (see location on Fig. 1). The cross section is ~N18°E, perpendicular to the trend of the structures, and no major strike-slip faults have been crossed. Moho shape is from three-dimensional gravity modeling of Starostenko et al. (2004), and lithospheric thickness data are from Jiménez-Munt et al. (2003) (see Figs. 4A and 4B). **(B)** Restored Paleocene state. The restoration of the margin was obtained by flattening of Paleocene deposits and using the base of the Sinop basin as datum. For the Black Sea Basin, we removed the Cenozoic tilting (~2.3° northwards) and sedimentary cover, and we considered variable water paleodepth. Decompaction is not taken into account. NAFZ—North Anatolian fault zone; Kat—Kadilar thrust; Acd—Acisu detachment; Ekt—Ekinveren thrust; Bat—Balifaki thrust; SB—Sinop basin; PL1 and PL2—pin lines 1 and 2; Short—shortening; HP—high pressure; Lf—final length; Li—initial length.

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ing occurred without significant block rotations within the Central Pontides (Meijers et al., 2010), whereas latest Cretaceous–earliest Paleocene to Oligocene block rotations and shortening occurred in the south around the indenting Kırşehir continental block (Kaymakci et al., 2003).

## Structural Evolution

The evolution of the Pontides forearc and Black Sea back-arc basins was probably governed by the north-directed Neotethyan subduction, and structures inherited from Paleotethys closure may have localized the deformation (Letouzey et al., 1977). The Domuzdağ complex was exhumed during the Late Cretaceous (ca. 93–84 Ma; Okay et al., 2006) contemporaneously with the extensional period in the Pontides forearc and Black Sea back-arc zones. We propose that Neotethyan slab retreat might have provided the necessary space and extensional strain in the forearc domain to allow buoyant rise of the high-pressure wedge to shallow crustal depths, as widely observed in the Mediterranean realm (Fig. 7B; e.g., Jolivet et al., 2008; Husson et al., 2009; van Hinsbergen et al., 2010; Biryol et al., 2011). Our apatite fission-track results show that the structural inversion in the Central Pontides zone started at ca. 55 Ma, which is consistent with previously published thermochronological data in the Western and Eastern Pontides regions (Boztuğ et al., 2004; Cavazza et al., 2012). We propose that the Eocene age of inversion resulted from the collision of the Kırşehir continental block, which may have started to the south in the Late Cretaceous to Paleocene period (Kaymakci et al., 2003; Meijers et al., 2010; Lefebvre et al., 2013), i.e., before inversion of Central Pontides started. The collision of the Kırşehir block is a local phenomenon along the Izmir-Ankara-Erzincan suture zone that is only present south of the Central Pontides (Fig. 1A). The Kırşehir block only played a role in the inversion of the Central Pontides, but not in the Western or Eastern Pontides. Exhumation of the Western and Eastern Pontides occurred synchronously and was mainly related to the collision of the Tauride-Anatolide block (Fig. 1A).

During the inversion stage, the Black Sea lithosphere was not shortened or only slightly shortened. This implies that it acted as a rigid domain compared to the Pontides lithosphere (Fig. 7A), since equilibrated oceanic lithosphere is likely to be stronger than its continental equivalent because of its homogeneity; it lacks the heterogeneities that render the continental lithosphere weak (Ziegler, 1988). Therefore, most of the contractional deformation was taken up by

the Pontides belt. In the upper crust, the shortening was mainly accommodated by the inversion of normal faults. We propose that the cause of the crustal thickening below the Central Pontides belt (from ~15 km to ~45 km; Figs. 7A and 7B) mostly resulted from ductile shortening in lower crust coupled with underthrusting of the Kırşehir continental block (and overlying ophiolites).

## Implications for the Inversion of the Black Sea Basin

Our lithosphere-scale balanced cross section illustrates for the first time the structural architecture and evolution of the Central Pontides–southern Black Sea margin system. This system is characterized by large-scale crustal extension related to the back-arc rifting of the Black sea basin, approximately coeval (at least for the Cretaceous) with the forearc exhumation of the Domuzdağ high-pressure wedge (Okay et al., 2006). Although crustal-scale rift-related anisotropies may have influenced the location of outer contractional structures into orogenic zones in response to the far-field transmission of compressional stresses (e.g., Coward, 1996; Parra et al., 2012; Espurt et al., 2012), the relatively colder and stronger Black Sea lithosphere protected zones of structural weakness from the tectonic inversion (Cloetingh et al., 2003; Stephenson and Schellart, 2010; Yamasaki and Stephenson, 2011) so that extensional structures in the offshore areas are still poorly inverted (Robinson et al., 1996; Munteanu et al., 2011). Because the southern Pontides zone had no, or a thinned, lithosphere during the Cretaceous, it played a major structural role in localizing contractional deformation since the early Eocene. This model may explain why the whole southern Black Sea margin was inverted, creating the more than 1000-km-long Pontides belt, whereas discontinuous inversions characterize its northern margin (Romanian offshore, Crimea, and Greater Caucasus; Fig. 1A; Munteanu et al., 2011). Thus, the large-scale temporal and spatial deformation of the Black Sea Basin is mainly controlled by inherited lithospheric-scale heterogeneities.

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