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**Reconstructing deformation of the North Anatolian
Fault Zone through restoring the Oligo-Miocene
exhumation pattern of the Almacık Block (NW Turkey)
based on the apatite (U-Th)/He ages**

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21 *Abstract*

22 The Almacık Block is a ~73 km long and ~21 km wide tectonic sliver formed by the North
23 Anatolian Fault Zone (NAFZ) in north western Turkey. Morphologically, it is one of the most
24 pronounced structures along the North Anatolian Fault Zone (NAFZ). All of the segments
25 bounding the Almacık Block are ruptured during the second half of the 20th century.

26 Fifty-four apatite (U-Th)/He ages we obtained show that the region including the Almacık
27 Block has exhumed during the Oligo-Miocene interval and then original exhumation pattern
28 was distorted by the NAFZ during the Miocene to recent. To interpret this distortion and to
29 reconstruct it to the original state, we modelled an “Λ” shaped mountain fronts in most
30 probable deformation scenarios.

31 The block has been tilted southward about an approximately E-W trending, horizontal
32 (slightly dipping to the east) axis. As a result of this rotation northern part of the block has
33 been uplifted ~2800 m whereas southern part has subsided ~430 m probably during last 2.5
34 Ma. The exhumation in the region studied started at around 34 Ma ago and lasted until 16 Ma
35 with a mean exhumation rate of ~60 m/Myr.

36

37 **Keywords:** NW Turkey, Almacık Block, NAFZ, apatite (U-Th)/He, rotation

38

Introduction

Apatite (U-Th)/He (AHe) and fission track (AFT) dating are the frequently used methods in low-T thermochronological studies (e.g., Zattin et al., 2010; Stübner et al. 2018; Cavazza et al. 2018; Ballato et al., 2018). The low closure temperature of AHe thermochronometer (c. 60°C, Farley 2002; Ehlers and Farley 2003) and the presence of apatite as accessory minerals in many rock types have led usage of this method in many tectonic studies. Considering a typical geothermal gradient (about 25 °C/km), this closure temperature corresponds to a depth of approximately 2-2.5 km (Farley 2002; Green and Duddy 2006). Therefore, it provides valuable age constraints for exhumation events and for the determination of exhumation rates. In this study, we aim at introducing the usage of AHe ages to restore post-exhumation deformations such as post-collisional strike-slip faults.

The North Anatolian Shear Zone (NASZ) extends between the Karlıova Triple Junction in the east and the Northern Aegean in the west of about 1600 km, roughly parallel to the Black Sea coast (Barka, 1992; Ketin, 1948 and 1969; Şengör, 1979; Şengör et al. 2005; Şengör and Zabcı, 2019, Fig. 1). This dextral shear zone is confined to the Tethyside Accretionary Complexes that in general widens from east to west in northern Turkey, reaching its maximum width of about 100 km in the Marmara Region (Şengör et al. 2005; Şengör and Zabcı, 2019). The widening of the deformation zone is also well defined by the multi-strand structure of the North Anatolian Fault (NAF) (Barka and Kadinsky-Cade, 1988; Şengör et al. 2005). The Almacık Block is a well-documented fault-bounded block in the NAF system (Barka, 1992; Şengör et al 2005, Fig. 1). For the purposes outlined above, we focus the Almacık Block bounded by the active northern and the middle strands of the North Anatolian Fault Zone (NAFZ) that was ruptured with five large earthquakes ($M_s > 7.0$) during the last century (1944 Gerede, 1957 Abant, 1967 Mudurnu Valley, 1999 İzmit, and Düzce earthquakes; see Ambraseys et al. 1969; Barka 1992, 1996; Kondo et al. 2005 and 2010;

Duman et al. 2005; Pucci et al. 2007; Akyüz et al. 2002; Çakır et al. 2003a). Another important feature of the Almacık Block is that it represents an elevated mountain peak (~1650 m) in an E-W trending mountain range namely the Bolu-Ilgaz Mountains that is ~ 300 km long and up to ~2000 m high. This mountain range preserve the pre-NAFZ history of the whole northern part of Anatolia. This range formed in the Oligocene (see Sunal and Erturaç 2012 for a review) after the closure of the northern branch of the Neotethys ocean and due to subsequent compression (Şengör and Yılmaz 1981 and see also Keskin et al. 2008 for a review). In the Eocene, almost the entire Izmir-Ankara-Erzincan Suture Zone (IAESZ) was covered by marine turbidites, with a volcanic and volcanoclastic. This succession is generally thicker than 2 km in most places, such as in the Ganos Mountain, where apatite-fission track dating was applied on a more than 4 km thick sequence (Zattin et al., 2005 and 2010). All tectonic units exposed in and around the Almacık Block are covered by Eocene sequences (Fig. 1). The post-Eocene burial reset the AHe system in the basement and thus it is possible to determine the age of onset of exhumation in this block. This is one of the main goals of our study. The second aim is to extract NAFZ related deformation using the AHe cooling age pattern as a reference frame. This is an indirect way to understand of the behavior of the NAFZ in this region. In order to elucidate the exhumations history, we performed apatite He thermochronology both from the northern part of the Middle Strand of the NAFZ (from the Almacık Block) and southern part of the Middle Strand of the NAFZ (from the Sakarya Zone). Although, there are attempts to restore later deformations using former exhumation data especially in extensional regions (e.g., Fitzgerald and Gleadow 1990; Stockli, 2005 and references there; Fitzgerald et al. 2006), studies dealing with large continental strike-slip faults post-dating collisional orogenies are rare. Therefore, this study will bring a new perspective for the evaluation of deformations phases that follow exhumation.

89 ***Geology of the region***

90 The Almacık Mountain is a fault-bounded lensoidal block, where the block and the
91 immediately adjacent region are characterized by different tectonic zones of NW Anatolia. To
92 the north of the block (north of the northern branch of the NAFZ, Fig. 1) is the Istanbul Zone
93 exposed with a Precambrian metamorphic basement (Chen et al. 2002) and unconformably
94 overlying Ordovician arkoses and quartz arenites and Carboniferous chert and flysch (Lom et
95 al., 2016). On the contrary, the southern side of the block (south of the Middle Strand of the
96 NAFZ, Fig. 1) is composed of the rocks of the Sakarya Zone (Okay and Göncüoğlu 2004).
97 The Sakarya Zone includes Jurassic volcanic and volcanoclastic rocks of the Mudurnu
98 Formation (Altınır et al. 1991; Genç and Tüysüz 2010), Upper Jurassic- Lower Cretaceous
99 limestones (Abdüsselamoğlu 1959) and Upper Cretaceous-Lower Eocene wild flysch deposits
100 with giant blocks of limestones and granitoids (for detailed geological map of the region see
101 supplementary Fig.1).

102 In the Almacık Block, both the Istanbul and the Sakarya zones are exposed and separated by a
103 suture zone called the Intra-Pontide Suture Zone (IPSZ). The age of the suture is given as
104 early Eocene (Cuisian (Late Ypresin), Akbayram et al. 2016). In contrary to the southern part
105 of the Almacık Block, there is a metamorphic succession in the western part of the block (Fig.
106 1) that is also assigned to the Sakarya Zone (Bozkurt et al. 2013). These schists, calc-schists,
107 and marbles are Late Jurassic to Early Cretaceous in ages (Çelik et al. 2009; Akbayram et al.
108 2012). The IPSZ is located in the center of the block with roughly N-S alignment. The IPSZ
109 contains metamorphosed ophiolitic rocks such as amphibolites, serpentinites, and meta-
110 trondhjemite dykes (Bozkurt et al. 2013). Ordovician quartz arenites of the Istanbul Zone are
111 exposed in the eastern part of the block, a large portion of which is covered by the Upper
112 Cretaceous-Lower Eocene wild flysch deposits (MTA map, Gedik and Aksay 2002) that
113 contains marbles, chert, and Precambrian granitoid blocks.

All of the units constituting both the Almacık Block and southern part of the Middle Strand of the NAFZ are transgressively overlain by a common cover of Eocene volcanic and volcano-clastic formations.

There are a number of published reports on the deformation of the Almacık Block (Şengör et al. 1985; Sarıbudak et al. 1990; İşseven et al. 2009 and Yıldırım and Tüysüz 2017) during the development of the NAFZ in the region. According to Şengör et al. (1985), taking into account the position of the (IPSZ) (Cuisian (Late Ypresin), Akbayram et al. 2016), the Almacık Block underwent a 110° clockwise rotation around a vertical axis. Sarıbudak et al. (1990) proposed a much more clockwise rotation of about 212° (the paleomagnetic measurements from the Eocene volcanics). However, recent studies claim that the amount of the rotation is between $\sim 20^\circ$ (Yıldırım and Tüysüz 2017) and $\sim 28^\circ$ (İşseven et al. 2009) in the clockwise sense. İşseven et al (2009) reported the rotation based on paleomagnetic measurements from Eocene volcanic rocks whereas Yıldırım and Tüysüz (2017) used much younger morphological features (Pliocene-Pleistocene river incisions) to calculate the rotation. Hisarlı et al. (2011) proposed a counterclockwise tectonic rotation of $22.3^\circ \pm 7.8^\circ$ (paleomagnetic data from the Middle Eocene volcanics) in the Almacık Block relative to the Istanbul Zone.

Sampling and analytical techniques

In the Almacık Block, the samples were collected from the metamorphic formations of the Sakarya Zone and from Upper Cretaceous flysch and Eocene volcanic and volcano-clastic formations developed on the İstanbul Zone (supplementary data Table S1). Altitudes of the samples range from 554 to 1568 m. All the samples collected from the southern part of the Middle Strand of the NAFZ are from rocks of the Sakarya Zone (Fig. 1). In the western part of the area, mainly Upper Cretaceous flysch and its blocks were sampled. Some additional

139 samples were collected from Middle Jurassic volcanics and volcanogenic sandstones of the
140 Mudurnu Formation with altitudes ranging between 116 and 1471 m.
141
142 The quality of the dated samples was checked for possible secondary fluid affect. Samples
143 were fresh and lacking apparent fluid-alteration. The AHe analyses were carried out at the
144 GÖochron Laboratory at the University of Göttingen. Single-grain apatite aliquots were dated,
145 usually three aliquots per sample. The crystals were selected carefully; only fissure-free grains
146 were used, with well-defined completely convex external morphology. Shape parameters
147 (such as length of prism, total length and width of the crystals) of preferred Euhedral crystals
148 were determined and archived by multiple digital microphotographs. The crystals were
149 wrapped in platinum capsules of ca. 1x1 mm size and the capsules were heated up by an infra-
150 red laser. The extracted gas was purified using a SAES Ti-Zr getter at 450°C. The chemically
151 inert noble gases and a minor amount of other rest gases were then expanded into a Hiden
152 triple-filter quadrupol mass spectrometer equipped with a positive ion-counting detector.
153 Beyond the detection of helium, the partial pressures of some rest gases were continuously
154 monitored (H_2 , CH_4 , H_2O , N_2 , Ar, CO_2). Crystals were checked for degassing of He by
155 sequential reheating and He measurement. Following degassing, samples were retrieved from
156 the gas extraction line, spiked with calibrated ^{230}Th and ^{233}U solutions and dissolved in 2%
157 HNO_3 . Each sample batch was prepared with a series of procedural blanks and spiked normals
158 to check the purity and calibration of the reagents and spikes. Spiked solutions were analyzed
159 by a Perkin Elmer Elan DRC II ICP-MS with an APEX micro-flow nebulizer. Sm, Pt and Ca
160 were determined by external calibration. The ejection correction factors (F_t) were determined
161 for the single crystals by a modified algorithm of Farley et al. (1996) using an in-house
162 spreadsheet.

Results

Apatite (U-Th)/He dating

Twenty-four samples were dated from the Almacık Block and 30 samples from the southern part of the Middle Strand of the NAFZ (supplementary data Tables S1 and S2, respectively). Granitoids and metabasic rocks yielded the most and best apatite crystals, but apatites from the Upper Cretaceous flysch and the Middle Jurassic Mudurnu Formation (Altıner et al. 1991) contain also euhedral crystals suitable for dating, as they were fed by adjacent arc-derived rocks with short transport.

The unweighted sample mean ages reveal three groups: > 36 Ma, 33 - 16 Ma, and 12 - 2.5 Ma (Fig. 3, supplementary data Table S2). The oldest AHe age of the Almacık Block (~65 Ma, sample MK38 not shown in Fig. 3 a) is obtained from the base of the Eocene sedimentary cover (see Figs. 1 and 2). The remaining older ages are from the southern part of the Middle Strand of the NAFZ (Fig. 2 and 3, supplementary data Table S2), which is oriented roughly NE to SW. The second age group is the largest one and obtained from different altitudes (between 600-1600 m). There are only two ages in the Almacık Block that belongs to the youngest group: samples MK57 and MK61 that gave 10.7 ± 0.2 and 7.0 ± 1.3 Ma, respectively. The remaining younger ages are located in the southeastern part of the Middle Strand of the NAFZ (Fig. 2). They cluster in a region where NE-SW trending faults are present and range in altitude between 1100 and 1500 m (supplementary data Table S1).

Discussion

Data interpretation and reduction

The age-elevation relations (Fig. 3) do not show well-developed simple and single correlation trend. The most critical constraint for the evaluation of the AHe data is the ca. 36 Ma thermal

overprint event. Ages older than this threshold are interpreted as partially reset data. As described earlier, the Eocene deposits are the key units not only for the study region, but also for all of the northern parts of Anatolia. After the closure of the IAESZ during the Paleocene interval, all the region was covered by thick Eocene turbidites deposited in intramontane basins (49.3±2 to 38.1±1.9 Ma, Gülmez et al. 2013). Therefore, the ages older than 36 Ma (the lower radiometric age of the Eocene unit) represent unreset of partially reset pre-burial ages. For this study, the same assumption was made, that is, that Eocene deposition caused reburial of the whole region and reset of older He ages.

The studied region is controlled by the NAF that is thought to have initiated in Late Miocene (~12 Ma; Şengör et al. 2005), but the age of displacements along its strike is not well known. Furthermore, Şengör et al. (2005) claim that before the NAF became a single narrow fault zone that had already existed as an early, broader shear zone running roughly parallel to the IAESZ. This dextral shear zone (North Anatolian Shear Zone, NASZ) then evolved to the NAFZ that is initiated in the east and then migrated to the west (Şengör et al., 2005). Therefore, the onset of the zone was almost synchronous all along the NAFZ (~12 Ma) but its activity as a single fault was diachronous. Consequently, the ages younger than 12 Ma are probably related to the NAFZ activity in the region. The possible meaning of the youngest age group is discussed in the section of “Evolution of the Almacık Block in the NAFS”.

We observe two positively correlated age versus altitude trends in the Almacık Block and a rough one in the southern part of the Middle Strand of the NAFZ are observed (Figs. 3 a and b). In the Almacık Block, the one with low exhumation rate is much more pronounced than the higher one.

The distribution of the AHe ages in age-elevation graph belonging to the southern part of the Middle Strand of the NAFZ is much more complicated (Fig. 3b). The age data in the southern part of the Middle Strand of the NAFZ have wide scatter and the area is dissected by several

branches of the NAFZ (Fig. 2). The separation lines that represent the faults observed in the field are roughly drawn in the graph in Fig. 3b. Note that they have no geographical information just separation lines distinguishing the ages same as the faults observed in the field.

The range of ages is considerably wider than can be expected from the uncertainties of the analyses. There are two exhumation trends in the Almacık Block that cannot be explained spatially because they are next to each other. Furthermore, distribution of the data in the southern part of the Middle Strand of the NAFZ has a zonal distribution similar to higher exhumation rate in the Almacık Block. We hypothesize that the region studied here was exhumed with a steady state rate until the onset of displacement along the NAFZ. To test this idea, we created a synthetic dataset with a certain exhumation rate and distorted it using common geological deformational structures.

Post-deformational styles of the exhumation data

For the sake of simplicity, we applied constant exhumation rate, as in case of curvilinear trends solutions can be much too complicated. Because the ages are constant and the only variable is the altitude, dip of the deformed block (the surface that includes isochrones) is a direct indication of the change in the exhumation rate. There is a linear relationship between the dip of the surface of the mountain front and exhumation rate.

We first illustrate the terminology used in the following figures and explanatory texts. Fig. 4 shows elements of a synthetic exhumation dataset and relevant terms. On the right side of Fig. 4 we designed a mountain range profile (the N-S topographic section is real and taken from in the middle section of the Almacık Block) and for more simplicity, it is also schematized as a “Λ” shape. Every ascending sample from parts of the earth depths deeper than the PRZ, has a travel time indicating an age that marks its pass from the apatite closure temperature (~60 °C

isotherm). The intersection between altitude (morphology) and different 60°C isotherms creates isochrones of different ages (left side of the Fig. 4). Those isotherms or isochrones do not represent a flat surface, rather they have upward concave shapes under the mountains (Farley 2002; Ehlers and Farley 2003; Reiners et al. 2003; Reiners et al. 2017). Note that the amplitude of the isotherms is not the same as the amplitude of the mountain profile (“Λ”) because the recent morphology of the Almacık Block formed after the NAFZ dissection but the shape of the isotherms formed when the Almacık Block was a part of a larger mountain range. Therefore, today’s morphology of the Almacık Block has a high amplitude and low wavelength (~1.5 km and ~20 km, respectively) but when its position was deeper, below a large mountain range during the Oligo-Miocene, isotherms formed relatively lower amplitudes and longer wavelength (>1.5 km and >80 km, respectively, see Akbayram et al 2016, fig.3c for post-Eocene restoration of the region). However, we do not know the real shape (amplitude and wavelength) of the isotherms.

Assuming rotation

The first deformation style we consider here for the distortion of original exhumation data is rotation. There are three possible geometries: rotation about the vertical axis, rotation about the horizontal axis, and a combination of the two (oblique axis). The rotation about the vertical axis does not alter the relative position of samples unless it combines with other deformation styles. In contrast, the rotation about the horizontal or oblique axes including tilting and some sort of folding significantly changes the exhumation pattern. In Fig. 5, we applied rotation to a “Λ” shaped theoretical mountain profile (we call it as a pyramid) about the horizontal axis. All the scenarios in this figure represent different sort of rotation about the horizontal axes. In the cases given in Figs 5a and b, the rotation axes are set parallel to t₂ isochrone on the right side, but with a different sense of movements, one being clockwise the other counterclockwise. Because

the rotation axis is on one side (right flank (F1)) of the pyramid, the apparent exhumation rates increases rotating around the t2 isochrone (rotation axis) in clockwise sense when compared to the original exhumation rate of the flanks. However, the apparent exhumation rate of both flanks decreases in counterclockwise rotation state. When we put rotation axes again parallel to the t1 isochrone instead of t2 (parallel to the lower corner), we have similar results with the previous situations, except for rotation of the data in the graphs that occurs along different rotation axes (Figs. 5c and d). If there is no information about the initial stage of the data, there is no way to distinguish them. Similar results are also obtained when rotation axes are placed parallel to the crest, along with the t1 isochrone (Figs. 5e and f). Note that here the original state of the trend line in the graph stays inside of the distorted ones whereas in the previous states they either crosscut one of the later trends or align outside of them. The common features of those distorted trends' patterns are wedge-shaped appearances, pinching out t3 isochrone.

In the final step of the rotation, rotation axes are designed as perpendicular to the isochrones (Figs. 5e and f). Both in clockwise and counterclockwise situations they reveal zonal distribution (ages are dispersed in a zone) rather than a wedge-like shaped.

In the evolution of the Almacık Block, rotation about a vertical axis is proposed by several paleomagnetic studies (Şengör et al. 1985; Sarıbudak et al. 1990; İşseven et al. 2009 and Yıldırım and Tüysüz 2017). Thus, we applied vertical and horizontal stepwise rotations on a north-dipping side of the pyramid (Fig. 6). For the sake of simplicity, we show only one side of the pyramid, as the other side will be the opposite. In each step, there is a 5° counterclockwise rotation about the vertical axis and 1° southward tilting (rotation around the horizontal axis) with the vertical axis being located in the center of the block. Furthermore, the horizontal axis is designed in the middle of the block, parallel to the longer sides of the block (Fig. 6). In this situation, increasing rotation and tilting lead to widening of the data (zonal distribution), lowering of the apparent exhumation rate, and finally the reversal of the

age versus altitude correlation (negative correlation). The sense of rotation about the vertical axis does not affect evolving distortion, but if we change tilting direction from south to north, the rate of the exhumation increases and finally becomes vertical (not shown here). The reversal pattern of the exhumation rate depends on the style of deformation. For example, tilting via any kind of faulting does not create any reversal in the exhumation trend, but the formation of an overturned limb of a mega-scale fold can.

Assuming faulting

Compared to the rotational scenarios, the simulation of faulting results simpler patterns (Fig 7 a-d), except for some combination of both rotation and faulting (Figs. 7 e and f). A clear offset is observed in the case of dip-slip faults (normal or reverse) when their strikes are placed parallel to the long side one of the flanks (along with the isochrones) (Figs. 7 a and b). Instead of an offset, a repetition occurs when faults' strikes are positioned perpendicular to the long side of one of the flank (perpendicular to the isochrones) (Figs. 7 c and d). However, it should be noted that because the fault crosscuts only one of the flank, the offset occurs only along one flank that is not altered. In isochrone parallel situations, a rotation occurs synchronously in the footwalls of the faults if we have listric (e.g. detachment faults, Fig. 7e) or imbricated (thrust faults, Fig. 7f) faults. Additionally, it should be kept in mind that in domino-type normal faults and in duplicated thrust faults, accompanying rotation with an offset should be expected.

Zonal data distribution (repetition of the data to create a zone) are observed in all isochrone perpendicular situations (Figs. 5 e and f; Figs. 6 b to g; Fig 7), but distortion in the fault situations has only twinning (or duplication) rather than zonal dispersion (Figs. 7 e and f). In pure strike-slip faults (Figs. 7 g and h), any changes can occur because there is no vertical

movement during the fault activity. However, oblique faults can generate very complicated patterns.

The Almacık Block case

In the previous sections, some possible (common) deformation styles affecting the former exhumation trends are outlined. Here we would like to interpret our thermochronological data from the Almacık Block in the light of the deformational scenarios discussed above.

In this study, we planned to collect data not only from the Almacık Block but also south of it (south of the Middle Strand of the NAFZ). The main reason is that rotational deformations on the Almacık Block is known from the literature but the area south of the Middle Strand of the NAFZ, where there is no information about a rotation or vertical movement, has only strike-slip faults (Fig. 2). Our expectation was to get less distorted and simple exhumation trend in this area, but it turned out that it was complicated as well (Figs. 3 and 8), expressing a post exhumation deformation history. Therefore during the data reduction, ages related to the NAFZ, PRZ and those isolated in different fault-bounded domains are discarded. Distribution of remaining ages shows a zonal pattern in the southern domain. As previously illustrated, the zonal distribution generally occurs in the isochrones perpendicular situations of rotation (Figs. 5 e and f and Figs. 6 c to g) and isochrones perpendicular offset of dip-slip faults (Figs. 7 c and d). However, along the southern part of the Middle Strand, there are splays of the NAFZ (Fig. 1). Such faults are mainly strike-slip faults, but they are parallel to the long axis of the deformation ellipsoid and perpendicular to the σ_1 , which indicates that they are oblique strike-slip faults with a reverse component. Some of the faults we infer in the region are not reported in the published fault maps (Emre et al., (2011), but the repetition in the age trends suggests the presence of these faults (see Figs. 1b and 2). Taking this into account, we calculated individually almost parallel three different exhumation rate groups; ~15 m/Myr

337 (only one trend line #1 in Fig. 8), between 59 and 66 m/Myr (three trend lines #4, 5 and 6 in
338 Fig. 8), and between 117 and 119 m/Myr (two trend lines #2 and 3 in Fig. 8).

339 The ages assigned to the PRZ and the NAFZ in the Almacık Block are less than those in the
340 southern part of the Middle Strand (Fig. 3a). After data reduction, three exhumation trends
341 can be distinguished; the first one has a more pronounced low exhumation rate (~ 15 m/Myr,
342 Fig. 8); the second one is represented by two more or less parallel high exhumation rates, and
343 the third one has a moderate rate (Fig. 8). It is possible to interpret high exhumation rate as a
344 zonally distributed pattern. The constructed semi-parallel high exhumation rates give ~ 117
345 and 119 m/Myr exhumation rates, respectively. Furthermore, the moderate rate reveals ~ 66
346 m/Myr (Fig. 8) that is very close to the exhumation rate obtained from the southern part of the
347 Middle Strand (Fig. 8). The lowest and the highest exhumation rates converge to a point
348 making a wedge, which is very typical for rotations where the axis is parallel to the isochrones
349 (Figs. 5 a to f).

350 In each simulated case shown in Figs. 5 a to f, a wedge-shaped pattern of converging rates is
351 observed. However, in order to confidently determine which simulation coincides roughly to
352 the real case, an independent observation is needed from a region where deformation is
353 relatively low or negligible. Without the knowledge about the initial exhumation rate, it is not
354 possible to determine if any of the arms of the wedge is original or distorted. To determine
355 the original arm in the wedge obtained in the Almacık Block (Figs. 8 and 9), we have to
356 analyze the southern part of the Middle Strand. In doing so, it may be possible to obtain the
357 exhumation rate (Figs. 3 and 8) that can be used as the initial exhumation rate for the whole
358 region (at least the closest one).

359 Fig. 8 shows recognized trend lines that belong to the whole region (a), the general outline of
360 them (b), and subsequent data reconstructions. Before proceeding further, we would like to
361 explain our premise. The trend lines obtained from the southern part of the Middle Strand

362 have similar slopes even though they are apart from each other (trends #5 and 6 in Fig 8b). A
363 similar case is also observed from the Almacik Block (trend #4 in Fig 8b). Because the
364 southern part of the Middle Strand is less deformed compared to the Almacik Block, we
365 assume that ~ 60 m/Myr represents the initial (at least very close to initial) exhumation rate of
366 the region. We further propose that the exhumation rates higher or lower than ~ 60 m/Myr is
367 due to distortion of original trends after rotation of the Almacik Block.

368 The trend lines obtained from the southern part of the Middle Strand are the same, but one is
369 in the higher elevations (# 5 in Fig. 8 b) and the another one is in the lower elevations (# 6 in
370 Fig. 8 b). Similar trend line is also obtained from the Almacik Block (# 4 in Fig. 8 b). We
371 think that ~ 60 m/Myr is most probably the real exhumation rate of the region and other rates
372 represent distorted ones because the southern part of the Middle Strand is less deformed
373 compared to the Almacik Block. At least there are predictions about the deformation of the
374 Almacik Block and one can expect more deformation in a thin and long block rather than a
375 uniform southern part. Therefore, we assign ~ 60 m/Myr rate as the original and less disturbed
376 trend line for the region. If not, the way of reconstruction should be reconsidered.

377 The wedge shape of the trends from the Almacik Block (# 1, 2, and 3 in Fig. 8 b) surrounds
378 higher exhumation trend of the southern part of the Middle Strand (# 5 in Fig. 8 b). We
379 interpreted these trends (1, 2, 3, 4 and 6 in Fig 8 b) as being derived from the trend #5 by
380 various amount of rotation and faulting, similar to the scenarios shown in Fig 5 and 7. If that
381 is the case, the trend line marked as # 5 is the closest state of the original exhumation trend. If
382 this inference is valid, all other trends should also be corrected according to ~ 60 m/Myr rate
383 (to # 5 in Fig. 8 b). During the correction processes it should be taken into account that the
384 age data are solid and the only variables are the altitudes of the samples dated. The trend # 6
385 is parallel to the trend #5 but there is a ~ 453 m altitude difference between them (Fig. 8b).
386 Thus, we must add this height to the samples constructing the trend #6. Then # 6 will be

387 corrected with respect to #5 (Fig. 8 c). The only way to determine where to put a tectonic
388 boundary or rotation axes to correct one apparent trend trajectory (#6) to the original one (#6)
389 is to draw trend trajectories on the map (Fig. 9). We draw all trend trajectories (Fig. 8) on the
390 topographic map of the region (Fig. 9). Every trajectory is constructed using relevant samples
391 from the lowest and the youngest to the highest and the oldest (zig zag trajectories in Fig. 9).
392 Considering trajectories #5 and 6, they are almost parallel to each other but there are some
393 inconsistencies in some regions. However, it should be noted that the straight lines drawn
394 between individual samples to construct trajectories, they could be curvy lines. In the case of
395 overlap, when samples fall within another trend are excluded from further calculations.
396 The only problem in the trend #6 is that one of the sample that represents the upper
397 endmember of the trend trajectory falls within the eastern part of the PRZ (in a different
398 domain, see Fig. 9). Either western or eastern part of the PRZ must be a tectonic boundary
399 because there are ages representing higher altitudes on both sides of this belt. Thus, the trend
400 #6 can be an artificial one. However, even in this case, it still indicates that there has to be a
401 tectonic boundary between trends belonging to different altitudes (trends #5 and #6). The
402 difference can be a reason for a possible fault boundary in the western part of the PRZ (a
403 thrust in Fig. 9). If it is a fault, it should be a reverse one because its alignment is
404 perpendicular to the σ_1 direction in a dextral strike-slip shear zone (Fig. 9).
405 Similar but much higher correction is also needed for the trend #4 in the Almacık Block (Fig.
406 8 d). The calculated altitude difference of the samples between the trends #4 and #5 is ~845
407 m. The trajectory #4 is almost parallel to the trajectories #5 and 6 and slightly oblique to the
408 isochrones (Fig. 10). However, trend #4 is located in the Almacık Block unlike trends #5 and
409 6. Therefore, the boundary for correction should be in the north of the trajectory #4 instead of
410 its south where middle part of the NAFZ is situated (Fig. 9). Similarly, because of its

orientation in a given dextral-strike-slip shear zone deformation ellipse, the possible tectonic boundary is assumed to be a reverse fault with a strike-slip component (Fig. 9).

The next correction is between the trajectory lines #2 and #3 (Fig. 8), which are very close to each other and only a slight correction is needed. There is about 228 m altitude difference between them. For this correction, again trend trajectories should be drawn on the map to put a boundary or rotation axis (#2 and 3 in Fig. 9). However, the trajectory #3 is located inside of the trajectory #2. This situation cannot be resolved defining only one tectonic boundary between them, on the contrary at least two boundaries are necessary (Fig. 9). We defined two boundaries to restrain trend trajectory #3 on both sides (west and east sides). These boundaries are perpendicular to the isochrones (Fig. 10) hence they match perfectly with the faults defined in Fig. 7 (c and d). Furthermore, their orientation corresponds to normal fault geometries in a given dextral strike-slip shear zone and also a dextral strike-slip component should be expected (Fig. 9).

The last correction is to adjust the trends #1 and #2 (Figs. 8 e and f) to the trend #5. Because the trend #5 is the closest state of the original exhumation trend, the last correction would be similar with the situation shown in Fig. e and f. Around the rotation point R (Fig. 8 e), arms of the wedge have to be closed by rotation. There are almost identical angles between trend #5 and other two trends (#1 and 2), which are 18° and 21° , respectively (Figs. 8 e and f). The final state of the exhumation rate (fixed to trend #5, ~ 60 m/Myr) is now achieved for all trends (Fig. 8f).

Evolution of the Almacık Block in the NAFS

In Fig. 10, isochrones have been drawn separately for the Almacık Block and the southern part of the Middle Strand. The isochrones in the Almacık Block are almost parallel to the long axis of the block (E-W) and also to the strike of the Middle Strand. The altitude difference between the actual and corrected heights of the AHe ages in the Almacık Block is

shown in Fig. 11 where the "0" contour represents the rotation axis along with there is no change in the altitudes. Fig. 12 shows the summary tectonic map for the region with tectonic features obtained from AHe ages. While samples were uplifted in the northern side of the rotation axis, they subsided in the southern side (see also Fig. 13). For example, according to the last correction, sample MK 64 (the northernmost sample) has been uplifted ~684 m during the NAFZ activity. When we extend our analyses of deformation to the whole northern part of the Almacık Block, the northernmost rim of the block should be uplifted to 2800 m height. Similarly, the calculated uplift amount from the higher rate correction (trends #2 and 3 in Fig. 8) is about 365 m for the sample MK 68 (the southernmost sample). Note that the trend # 3 is corrected twice. When we extend this bending to the southernmost part of the block until the middle strand of the NAFZ, amount of the uplift is about 431 m.

Unfortunately, there are only few studies were done about the vertical exhumation of the Almacık block. One of the recent studies on the tectonics of the Almacık Block is published by Yıldırım and Tüysüz (2017). Using morphological indicators, they claim that the Almacık Block has $20^{\circ} \pm 2^{\circ}$ clockwise rotation about the vertical axis and calculated surface uplift is 1130 ± 130 m. This value includes both exhumation and the accompanied erosion. Our estimated value represents only the amount of exhumation without erosion.

The northern boundary of the Almacık Block is a north dipping dextral strike-slip fault with normal component, which was ruptured during the 1999 earthquakes (Barka et al. 2002; Akyüz et al. 2002; Çakır et al. 2003 a and b; Bulut et al. 2007). During the Izmit earthquake, western part of the northern edge of the Almacık Block was ruptured in the Karadere region (Fig. 1). The trend of the rupture is approximately SW-NE directed and defines the NW termination of the Düzce Basin. During the Düzce earthquake, rest of the boundary of the Almacık Block broke again two mounts after the İzmit earthquake (Akyüz et al. 2002). Akyüz et al. (2002) reported offset measurements observed right after the Düzce earthquake. In

addition to the dextral offsets, numerous vertical separations were reported as well, which indicates that the northern part of the Almacık Block has been uplifted. Up to 3.5 meters of vertical displacement along the surface rupture were reported but in general they were ~30 cm (Akyüz et al. 2002). Assuming the observed maximum vertical separation of 3.5 m as a characteristic fault slip, creating an uplift of ~2800 m on the northernmost edge of the block takes ~200,000 years assuming a 250 years earthquake occurrence (Barka 1996; Parsons 2004; Şengör et al. 2005; Bohnhoff et al. 2013; Ergintav et al. 2014), whereas when we account average vertical separation of 0.03 m, such an amount of uplift takes ~2.3 Ma. Even if we assign the ages younger than 12 Ma to the activity of the NAFZ, concentration of the young ages is found to be between 7.8 and 2.5 Ma (supplementary data Table S2). It is possible to interpret older ages as the age of the shear zone of the NAFZ, but younger ones at around ~2.5 Ma are most probably representing the age the NAF. This inference can also be correlated with the formation of the wide pull-apart Adapazari Basin in the west of the Almacık Block where the earliest deposition is dated back to latest Villanyian (latest Pliocene) and the Biharian (Early Pleistocene) (~3 Ma, Ünay et al. 2001). If the region began to uplift at 7.8 Ma, the uplift rate would be calculated as ~359 m/Myr. Such a trend is seven times more than the rate (~60 m/Myr) obtained for regional exhumation in the region. As a result, if we take the age of the NAF is 2.5 Ma in the region, it is still enough to generate such an amount of uplift.

The southern boundary of the Almacık Block also was ruptured by earthquakes during the last century; 1944 Bolu-Gerede, 1957 Abant, and 1967 Mudurnu Valley earthquakes (Barka 1992; Barka et al. 2002; Akyüz et al. 2002; Kondo et al. 2005, 2010; Duman et al. 2005; Pucci et al. 2007; Seyitoğlu et al. 2015). However, the reported offset measurements from the 1967 Mudurnu Valley earthquake rupture do not have any preferred uplift side along its course (Ambraseys et al. 1969; Barka 1996).

486 The younger ages between 7.8 and 2.5 Ma are obtained from the SE part of the study area
487 (Fig. 2). Such ages have a cluster in the region where the Mudurnu Formation of Jurassic is
488 exposed (supplementary Fig. 1). This region is represented by a dense fault branches related
489 to the Middle Strand of the NAFZ. This reset might be related most probably because of the
490 hot fluid activity occurred during the activity of the NAFZ. Today in the western part of this
491 region, along the Middle Strand of the NAFZ, there are two places famous with their hot-
492 springs, namely Kuzuluk and Taşkesti. The SE part of the studied area can be a former and
493 similar hot-fluid discharge region.

494 Another outcome of this study is the inference of potentially active normal and thrust faults
495 that are not reported previously in the region (see the geological map (Supplementary Fig. S1)
496 by Gedik and Aksay 2002). The reason for the absence of these faults on the published
497 geological maps is probably that they have not been discovered yet, or the PRZ we defined is
498 just a reason of a thin Eocene cover in this narrow zone that was a paleo-ridge formed before
499 Eocene deposition. Thus, deposition would be thin over the ridge and did not lead complete
500 reset in the samples. However, there is no information about the second possibility, but in any
501 case, such a linear ridge most probably bounded by a tectonic line(s).

502 Similarly, the normal faults estimated by AHe ages (Fig. 12) are not present in the geological
503 maps published by Gedik and Aksay 2002). These faults are located mainly in the Upper
504 Cretaceous units and could easily be missed.

505 As stated before, all the ages older than 36 Ma (the youngest age of the Eocene cover, Gülmez
506 et al. 2013) are regarded as the PRZ. In the south, they are aligned along a zone but in the
507 north, they are represented by only one age (~65 Ma, MK 38). Its continuation as a zone to
508 the east and the west is not clear. Furthermore, contouring AHe ages and the altitude
509 differences (Figs. 10 and 12) reveals how isochrones are distributed in the region (Fig. 11).
510 Therefore, it allows us to extend the zone of the PRZ all along the Almacık Block (Figs. 11

and 12). To check this estimation, if the position of the PRZ is in the right place, one can control the distribution of the AHe ages that must be getting older when getting away from the PRZ.

Early studies about the horizontal rotation revealed different results. Şengör et al. (1985) used the position of the IPSZ to determine the amount of rotation in the region and obtained 110° clockwise sense. This inference is sensible because, except for the Almacık Block, the orientation of the IPSZ is approximately E-W (see Fig. 1). However, in the Almacık Block, its orientation is ~NE-SW separating the Istanbul Zone in the SE with the Sakarya Zone in the NW, which is in opposite directions in other parts. 212° and 28° clockwise rotations were proposed according to the paleomagnetic studies implemented on Eocene volcanic rocks (Saribudak et al., 1990; İşseven et al., 2009). The amounts of the rotations outlined so far contradict to each other because all of them count post-Eocene rotation. 212° clockwise rotation looks unlikely because the Istanbul and the Sakarya Zones stay in wrong geographical sides of the suture when the rotation is restored. 28° clockwise rotation also seems unlikely because the IPSZ is aligned roughly N-S when the rotation is restored but in general, its position is approximately E-W. A recent study reported ~20° clockwise rotation calculated from the morphological features (Yıldırım and Tüysüz 2017) that formed during or/and after the development of the Pliocene paleo-topography of the region (see Yıldırım and Tüysüz 2017 for detailed discussion and additional references). Furthermore, 110° and 20° clockwise rotations can be both true because they count rotations for different time intervals. Recent studies have shown that before the initiation of the NAFZ in the region an early fault system was active (Zattin et al., 2010; Akbayram et al., 2016). Zattin et al. (2010) proposed that there was a fault system (mainly dip-slip) formed before the inception of the NAFZ in the region. Furthermore, Akbayram et al. (2016) claimed that during and after the closure of the IPSZ a system of dextral strike-slip fault pre-dating the NAFZ. If so, 110° clockwise rotation

proposed by Şengör et al. (1985) represents the long-term rotation (Ypresian to recent) whereas 20° clockwise rotation reported by Yıldırım and Tüysüz (2017) represents the short-term one (only the NAFZ's effect). The horizontal rotation around the vertical axis could not be confirmed by this study because we have mainly data about the rotation along the horizontal and sub-horizontal axes, in other words, we can detect movements mainly along the vertical sense.

Conclusions

Before the inception of the NAFZ in the region, the NW part of the Anatolian block started to exhume at ~34 Ma (Rupelian) and lasted until ~16 Ma (Langhian). Even if different rates have been achieved, the most probable average exhumation rate was ~60 m/Myr.

Different structural models distorting the AHe age-elevation trends have been tested and illustrated to understand the behavior of the NAFZ on the Almacık Block.

Reconstructions made on the distorted AHe age trends revealed the following results;

- Distorted exhumation trends hint the presence of previously unreported NW-SE trending normal and NE-SW trending reverse faults both in the Almacık Block and southern part the Middle Strand of the NAFZ.
- The Almacık Block is rotated about a roughly E-W trending horizontal axis. While the northern part of the block has been uplifting, the southern part has been subsiding.
- The northernmost edge of the block has been uplifted roughly 2800 m probably during last 2.5 Ma, but southernmost part of the block has subsided around 430 m.
- The activity of the NAFZ in the region most probably started later than 8 Ma, but the most intensive deformation took place around is ~2.5 Ma. Here, we interpret these two dates as follows; the activity of the early shear zone of the NAF in the region and the initiation of the NAF itself.

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Figure Captions

- Figure 1a: Simplified tectonic map of the Almacık Block and its surroundings (modified after Bozkurt et al., 2013). The block has a fusiform and bounded entirely by the branches of the NAFZ (the North Anatolian Fault). b: detailed structural and post-Paleocene outcrop map of the Almacık Block (after Gedik and Aksay, 2002). Note that Eocene units cover different tectonic units commonly (İstanbul and Sakarya Zones) and there is no Miocene unit on the Almacık block, during that interval the block exhumed. Active faults are from Emre et al. (2011). AM; Almacık metamorphics, IPSZ; Intra-Pontide Suture Zone.
- Figure 2: Apatite (U-Th)/He ages (Ma) plotted on the digital elevation model of the study area (DEM data from NASA JPL., 2013). Green dots represent samples from the Almacık Block, whereas red dots are from the south of the Middle Strand of the NAFZ. Red numbers indicate less reliable age data (see text for explanation).
- Figure 3: Apatite (U-Th)/He age vs. elevation plots (a) data from the Almacık Block, and (b) south of the Middle Strand of the NAFZ (see text for discussion). Numbers are the sample numbers given in Supplementary Table S2. “f” expresses fault (note that they have no geographical information just separation lines); the “?” next to the sample numbers indicates uncertain ages (see Supplementary Table S2).
- Figure 4: Theoretical background and the terms used in the text. The illustrated N-S topographic profile is from the middle part of the Almacık Block.
- Figure 5: Different rotation scenarios along the horizontal axes, which affect the exhumation pattern significantly. Figures from a to f represent isochrone parallel axes (ISPA) while figures from g and h show isochrone perpendicular (ISPE) axes. Original data have shown as red filled circles whereas distorted data illustrated as black dots. See text for discussion. “F” expresses flanks of the “Λ”. CW: clockwise; CCW: counterclockwise; RP: rotation pole; ZD: zonal distribution; R: repetition; CO: clear offset; NVO: no vertical offset; ZD: zonal distribution.
- Figure 6. Plan view of an inclined relief with artificial points of different altitudes and corresponding AHe ages. For the simplicity, we calculated only one flank of the “Λ” shaped mountain profile. 5o counterclockwise rotation around the vertical axis and 2o clockwise rotation along the horizontal axis are applied in every step. The sense of the rotation along the vertical axis does not change the results but rotation along the

horizontal axis does. If the counterclockwise rotation along the horizontal axis would be applied, the rate of the exhumation has increased. Combination of both rotations creates zonal distribution and increasing change in the rates.

Figure 7. Plausible fault scenarios that dissect former apatite (U-Th)/He age patterns. a- ISPA dip-slip normal fault with planar fault plane, b- ISPA dip-slip reverse fault with planar fault plane, c- ISPE dip-slip normal fault with planar fault plane, d- ISPE dip-slip reverse fault with planar fault plane, e- ISPA dip-slip normal fault with listric fault plane, f- ISPA thrust fault with curvy planar fault plane, g and h- are ISPA and ISPE strike-slip faults, respectively. "F" expresses flanks of the "Λ". Abbreviations used are the same as in Fig. 5.

Figure 8. Sorted and interpreted altitude vs. AHe age graphs. Note that there are four different trends in the Almacık Block; 1 has the low rate exhumation trend, and 2-4 have the similar high rate exhumation trends. There are two trends with almost identical exhumation rates in the southern part of the Middle Strand of the NAFZ. See text for details. R: rotation point.

Figure 9. Trajectories of the exhumation trends given in Fig. 8. Every trend is painted in different colors in both graphs and the map. Boundaries of every traces represent either a structural element or an axis of rotation. Later eliminations are performed due to overlaps of the traces of the trend lines in the map. The samples marked with a red circle in the graphs are excluded from the final analyzes. The pink zones are the distribution of the PRZs. Numbers in black circles are trend numbers given in the graphs (see also Fig. 8).

Figure 10. Contoured AHe ages in the region. In the Almacık Block contour lines are almost parallel to the long axis of the block whereas in the south of the Middle Strand of the NAFZ, they show a much-complicated pattern. Ages in red are uncertain ages (see Supplementary Table S2).

Figure 11. Contour map of the altitude difference between actual and corrected heights of the samples in the Almacık Block. The "0" contour represents rotation axis on which there is no altitude changes. The region with positive numbers shows uplifted areas whereas the region with negative numbers subsided ones.

Figure 12. The summary structural map of the Almacık Block and its southern part. Thick lines are our structural estimations derived from analyses of the AHe ages.

Figure 13. East looking model of the Almacık Block. Note that during the clockwise rotation the northern part of the Block has uplifted whereas the southern part subsided.

Supplementary Figure1 (cjes-2018-0283supplb). Geological map of the region with sample locations (after MTA map, Gedik and Aksay, 2002).

Supplementary Data Table S1 (cjes-2018-0283supplc):
Information about the dated samples.

Supplementary Data Table S2 (cjes-2018-0283suppld):
(U-Th)/He Age Data. Gray shaded analytical errors in the table will not be taken into account for later interpretations. The question marks next to the altitudes column indicate the low resolution of the data because of either insufficient number of aliquot ages (generally one age, e.g. MK 53) or averaging of two or more dissimilar aliquot ages (e.g. MG 300).

Almacik Block ●

1. trend

$$y = 15.271x + 1053.4$$

$$R^2 = 0.7638$$

2. trend

$$y = 117.94x - 2203.8$$

$$R^2 = 0.8051$$

3. trend

$$y = 119.86x - 2489.9$$

$$R^2 = 0.6433$$

4. trend

$$y = 66.343x - 1346.7$$

$$R^2 = 0.6937$$

south of the Middle Strand
of the NAFZ ▲

5. trend

$$y = 61.424x - 353.65$$

$$R^2 = 0.9567$$

6. trend

$$y = 59.366x - 755.1$$

$$R^2 = 0.5559$$