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Evidence for a minimum 52 ± 1 km of total offset along the northern branch of the North Anatolian Fault in northwest Turkey

Kenan Akbayram [a,*], Christopher C. Sorlien [b,1], Aral I. Okay [c]

[a] General Directorate of Mineral Research and Exploration (MTA), Department of Marine and Environmental Research, 06800 Çankaya, Ankara, Turkey
[b] Earth Research Institute, University of California, Santa Barbara, CA, USA
[c] Eurasia Institute of Earth Sciences Department of Geology, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey

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ABSTRACT

The North Anatolian Fault (NAF) splits into two major branches in northwestern Turkey with most of the present strain accumulation and Holocene displacement being along the northern branch (NAF-N). Estimates of total offset along the NAF-N range between 4 km and 70 km in the Marmara Sea region. These different estimates lead to different interpretations on the formation of Marmara Sea basins. In this study, we use Cretaceous faults sub-perpendicular to the NAF-N as precise offset markers. Based on these faults, as well as the offset of the Middle Eocene volcanic belt, we report a minimum 52 ± 1 km cumulative dextral displacement along the NAF-N east of Marmara Sea near 31°E longitude. The displacement of the Middle Eocene volcanic belt shows that the offset is post-Middle Eocene. If we assume an additional 15 km dextral displacement on the second strand of the NAF-N (Düzce fault), the total offset along the NAF-N can be estimated as ~67 km in the Eastern Marmara region. Adding the published offsets that range from 16 to 26 km on the Southern Branch of the NAF give a total offset estimate of whole NAF zone as 88 ± 5 km in the eastern Marmara region. The GPS velocity estimate indicates ~23 mm yr^{-1} of total plate motion across and near eastern Marmara Sea that would take 3.9 million years to accumulate 88 km of displacement on the NAF. Additionally, the Anatolian Plate would not have instantaneously accelerated to its modern rate of motion. Thus, initiation of transform displacement must somewhat pre-date 3.9 Ma.

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1. Introduction

The North Anatolian Fault (NAF) is one of the largest active strike-slip fault zones in the world, extending for ~1400 km from eastern Turkey to the North Aegean Trough (Fig. 1A) (Barka, 1992; Şengör et al., 2005). The NAF between the Anatolian and Eurasian plates currently accommodates 23–24 mm yr^{-1} of dextral motion near the Marmara Sea (Ergintav et al., 2014; Reilinger et al., 2006). In northwestern Turkey, the NAF splits into two major branches: the northern branch and the southern branch (Fig. 1B) (Şengör et al., 2005, 2014). However, most of the present strain accumulation and Holocene displacement is along the northern branch (NAF-N) (Ergintav et al., 2014). This fault is continuous with the İzmit fault to the east and the Ganos fault to the west (Fig. 1B). Bathymetric basins as deep as 1.3 km and sedimentary basins as deep as 6 km are arrayed along the NAF-N within Marmara Sea (Fig. 1B) (Carton et al., 2007; Laigle et al., 2008; Okay et al., 2000).

Estimates of total offset along the North Anatolian Fault in the eastern and central Anatolia range between 30 and 75 km (Barka and Gülen, 1989; Herece and Akay, 2003; Hubert-Ferrari et al., 2002; Şengör et al., 2005). A similar range of total displacement across the NAF has been published for northwest Turkey. West of Marmara Sea, Armijo et al. (1999) has reported 70 ± 2 km offset on the NAF-N, based on the correlation of folds on both sides of the NAF-N. This correlation was disputed by Yaltırak et al. (2000) since it relies on correlation of fold axial surfaces in the Upper Miocene sediments, making a low angle (20°–25°) with the strike of the North Anatolian Fault. However, large displacements along the NAF-N were also suggested by Yaltırak (2002) based on proposed offsets east of Marmara Sea. He interpreted a fluvial river valley to be an abandoned Sakarya River pathway offset by 58 km on the NAF-N. Other estimates for displacement include a minimum of 40 km "since the latest Miocene" on the Ganos fault (Okay et al., 2000) and ~28 km to form Tekirdağ basin after an early Quaternary reorganization (Seeber et al., 2004).

A 50 km displacement on the NAF-N documented by Herece and Akay (2003) was mostly accommodated by distributed, immature faulting within Marmara Sea in the Şengör et al (2005) model. More recently, Şengör et al. (2014) conclude that the present-day fault families younger than about the medial Miocene in the Marmara Sea are all parts of the North Anatolian Shear Zone and have shared among themselves

* Corresponding author. Tel.: +90 532 330 8189.
E-mail addresses: kakbayram@gmail.com, akbayram@itu.edu.tr (K. Akbayram), christopher.sorlien@ucsb.edu (C.C. Sorlien), okay@itu.edu.tr (A.I. Okay).
[1] Tel.: +1 401 560 0368.

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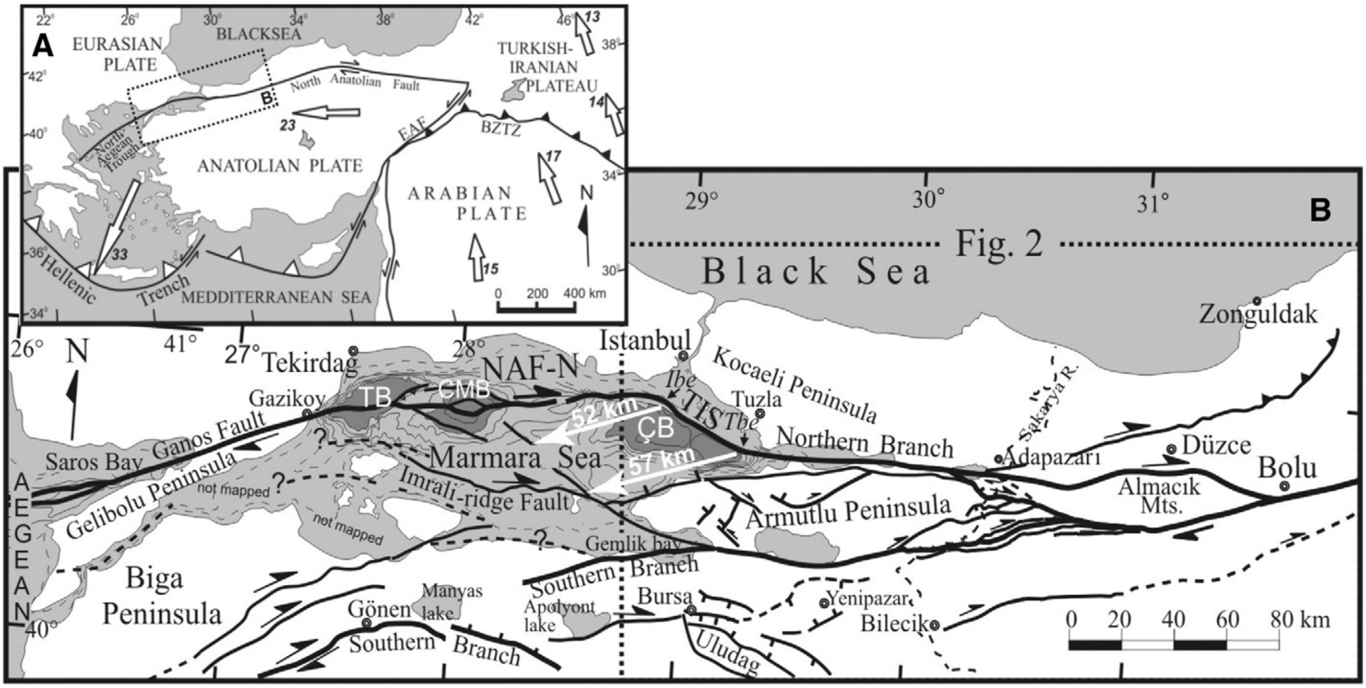

Fig. 1. (A) Tectonic map of eastern Mediterranean and Middle East. Arrows and numbers indicate global positioning system (GPS)–derived velocities with respect to Eurasia. EAF: East Anatolian fault; BZTZ: Bitlis Zagros thrust zone. (B) Active tectonic map of the Marmara region. White arrows indicating the distance (52–57 km) between the Tuzla–İstanbul segment (TIS) in the northeast and the İmralı fault in the southwest. The bathymetric contours in the Marmara Sea, drawn at 50, 100, then at every 200 m, are slightly modified from Okay et al. (2000). The map is compiled from Smith et al. (1995), Okay et al. (1999, 2000), Herece and Akay (2003), Kuşçu et al. (2009), Gasperini et al. (2011), Sorlien et al. (2012), Akbayram et al. (2013), Emre et al. (2013). CMB: Central Marmara Basin; ÇB: Çınarcık Basin; Ibe: Istanbul bend; TB: Tekirdağ Basin, Tbe: Tuzla bend.

a total offset of some 55 km along this zone since the later medial Miocene. However, faults of such a broad shear zone have never been delineated on a geological map.

Several publications interpret NAF displacements to have been taken up by pull-part basins connected by short right-lateral faults until 200 ± 100 ka, when a through-going strike-slip fault first formed, accumulating ~4 km of displacement (Rangin et al., 2004; Şengör et al., 2005). The pull-apart displacements are "about 30 km" in Rangin et al. (2004).

The pull-apart models have implications for formation of the deep NAF-N transform basins. The Armijo et al. (2002) model has steady oblique-normal right-lateral motion for the last 5 million years to accumulate 70 km of displacement on the NAF-N and an additional 15 ± 10 km on faults farther south. Alternatively, the formation of a nearly pure strike-slip fault in the last ~200 ka, resulting in deactivation of the extensional basins was suggested by Le Pichon et al. (2001, 2003), İmren et al. (2001) and Rangin et al. (2004). However, such a major young reorganization has been questioned (Okay et al., 2004; Seeber et al., 2004, 2006; Sorlien et al., 2012). Evidence for steady displacement on the NAF-N over at least the last half million years at rates of 15–20 mm yr^{-1}, similar to today's GPS rates (Ergintav et al., 2014; Reilinger et al., 2006), was recently published (Grall et al., 2013; Kurt et al., 2013). These authors propose that the Tekirdağ and Çınarcık basins formed as a result of a steady oblique right-lateral-normal on releasing segments of the NAF-N (Fig. 1B) (Kurt et al., 2013; Okay et al., 2004; Seeber et al., 2004, 2006). The central basin is also proposed to continuously grow by transtensional slip on multiple fault strands (Grall et al., 2012; Laigle et al., 2008).

Having a robust estimate on the total NAF displacement in the Marmara Sea region is necessary to discuss the kinematic models for the opening of the Marmara Sea. Some of the published displacement estimates are based on models and not on distinctive, dated offset lines or steeply dipping planes (e.g., Okay et al., 2000; Rangin et al., 2004). Here we provide a robust estimate of 52 ± 1 km displacement along the NAF-N located east of Marmara Sea near 31°E longitude; this estimate is based on the offset of Early Cretaceous palaeotectonic markers (Figs. 2 and 3A) (Akbayram et al., 2013). Outcrop of Neo-Proterozoic basement flanked by Campanian sedimentary rocks are permissive of an additional ~15 km displacement on the Düzce fault (with large errors) (Fig. 3). The combined displacement, if accumulated at the post-~0.5 Ma rate of Kurt et al. (2013) or Grall et al. (2013), supports a Pliocene inception of the Marmara Basins.

2. Total offset of the NAF-N in the Marmara region

An ideal marker to estimate the cumulative offset along a fault should be independent of that faulting, pre-date that faulting, strike at high angles to it, and should be steeply dipping. All of these features are met by three steeply east-dipping palaeotectonic units (Figs. 2 and 3), which crop out south of the NAF-N in the Armutlu Peninsula, and which are recently studied and mapped by Akbayram et al. (2013). These are (a) a Triassic phyllite–metasandstone–marble sequence, over 2800 m thick (Maşukiye Group); (b) Lower Cretaceous metabasites and phyllites with serpentinite lenses (Sapanca Complex); and (c) a high-grade metamorphic unit of metadunite, metapyroxenite, amphibolite, gneiss, marble, metaquartzite, and calcschist, intruded by Neo-Proterozoic to Ordovician metagranitoids (Pamukova Complex). The Rb-Sr mineral ages from the three units are Early Cretaceous (Akbayram et al., 2013). The faults separating these three units dip at 60° to 75° and strike north-northeast (30° azimuth), which makes an angle of 70° with the NAF-N (yellow thrust faults in Figs. 2 and 3). Corresponding units crop out north of the NAF-N in the Almacık Mountains (Fig. 3) with a tectonic geometry very similar to that seen in the Armutlu Peninsula (Bozkurt et al., 2013; Gedik and Aksay, 2002; Pehlivan et al., 2002). Matching of the corresponding faults on both sides of the NAF-N gives a cumulative offset of 52 ± 1 km. This new estimate is based on a new detailed geological mapping of the eastern Armutlu Peninsula on a 1:50,000 scale (Akbayram, 2011).

Our estimate is also supported by some of the offset markers reported in Herece and Akay (2003) between Almacık Mountains and

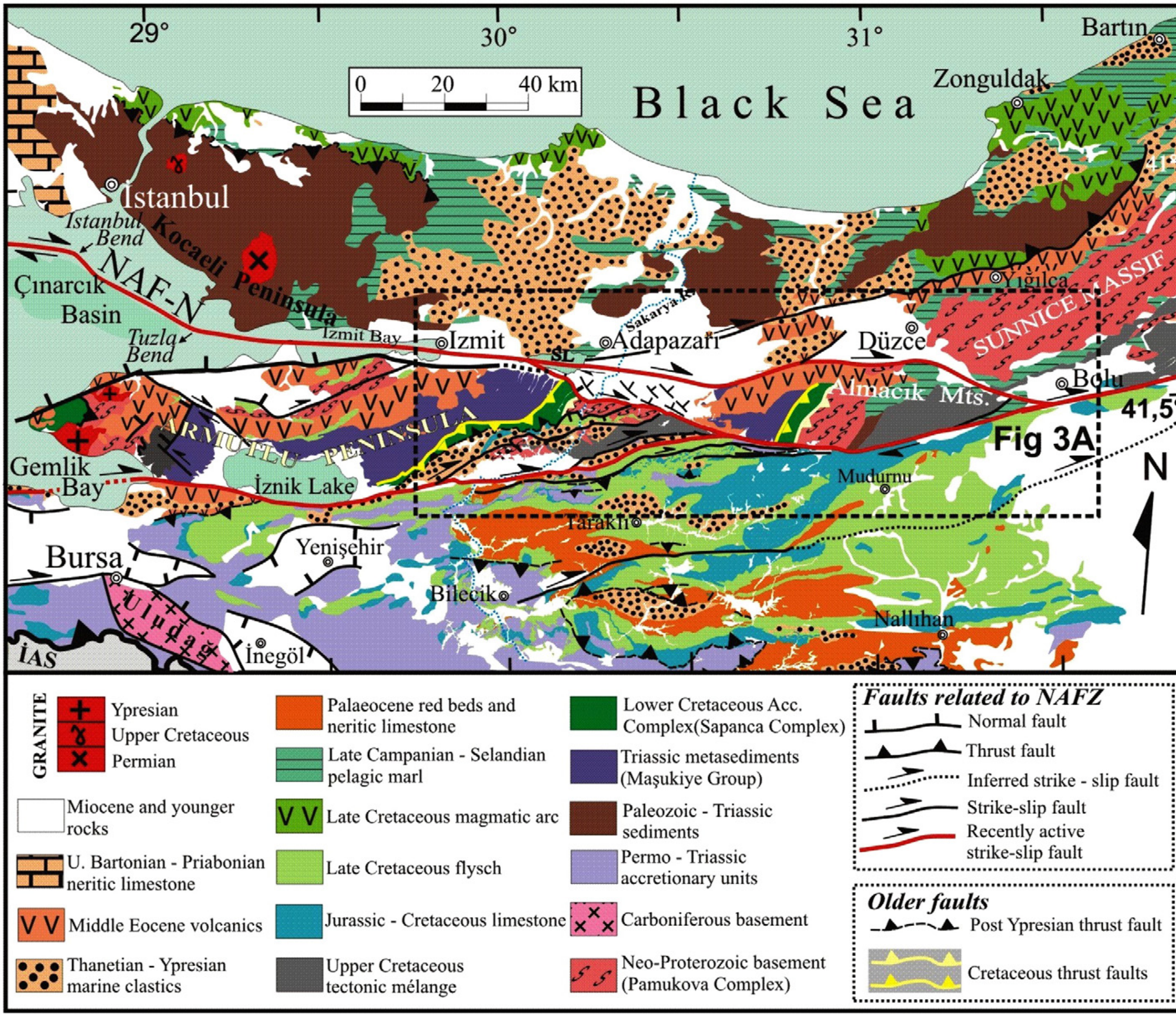

Fig. 2. Simplified geological map of a part of northwestern Turkey. Yellow lines with triangles are Cretaceous thrust faults showing the apparent 52 ± 1 km offset along the NAF-N. For location, see Fig. 1B. The map is compiled from Gedik and Aksay (2002), Pehlivan et al. (2002)), Türkecan and Yurtsever (2002), Herece and Akay (2003), and Akbayram et al. (2013). SL: Sapanca Lake.

Armutlu Peninsula together named as Almacık-Armutlu offsets. Herece and Akay (2003) reported five different offset markers, giving different offset values ranging from 33 to 61.5 km for the same region along the NAF-N. Two of these markers give 48 and 49 km offsets, which can be correlated with our 52 ± 1 km offset, are (1) a boundary between Paleozoic to Middle Jurassic schist–marble–metabasite unit and ultramafic tectonites, and (2) a Devonian tectonic slice sitting in ultramafics. The other two offset markers reported by Herece and Akay (2003), which give 33 and 36 km offsets in the same region, are (1) a marble body bounded between Lower Senonian breccia and Maastrichtian–Paleocene limestones, and (2) a Devonian tectonic slice thrusted over ultramafic cumulates and metavolcanites. The marker that gives the biggest offset value in the Almacık–Armutlu area, reported as 61.5 km, is the eastern stratigraphic boundary of the Eocene volcanics with the underlying Paleozoic to Middle Jurassic schist–marble–metabasite unit. Since it relies on correlation of a stratigraphic boundary making a low angle (15°–20°) with the strike of the North Anatolian Fault (see also similar reconstructions of Armijo et al., 1999), this largest offset value has large errors. The same 61.5 km offset can be obtained by matching the Middle Eocene volcanic rocks of similar geochemistry (Gülmez et al., 2013) on both sides of the NAF-N (Fig. 3A–C). This also shows that the offset is post-Middle Eocene.

3. Implications of the 52 ± 1 km offset along the NAF-N

Our results indicate a minimum of 52 ± 1 km of right-lateral displacement entering the Marmara Sea near İzmit; this robust value and an additional 15 km right displacement on the Düzce fault gives a total displacement along NAF-N of ~67 km (Fig. 3). A range of published estimates for the Sakarya River offset suggests 16 to 26 km of displacement on the Southern Branch entering Marmara Sea at Gemlik Bay (Fig. 1) (Koçyiğit, 1988; Özalp et al., 2013; Şengör et al., 2005). Adding these values give a total offset estimate of whole NAF zone as 88 ± 5 km in the Eastern Marmara region. It is not possible to use global plate circuits (e.g., Atwater and Stock, 1998) to determine past velocities between the Eurasian and Anatolian plates because there has been no Neogene sea floor spreading on either side of the Anatolian Plate. Thus, extrapolating the GPS-based current plate motion back into Pliocene time arguably provides the best estimate of plate velocities for the last few million years. The most recent GPS velocity estimate based on motion of the

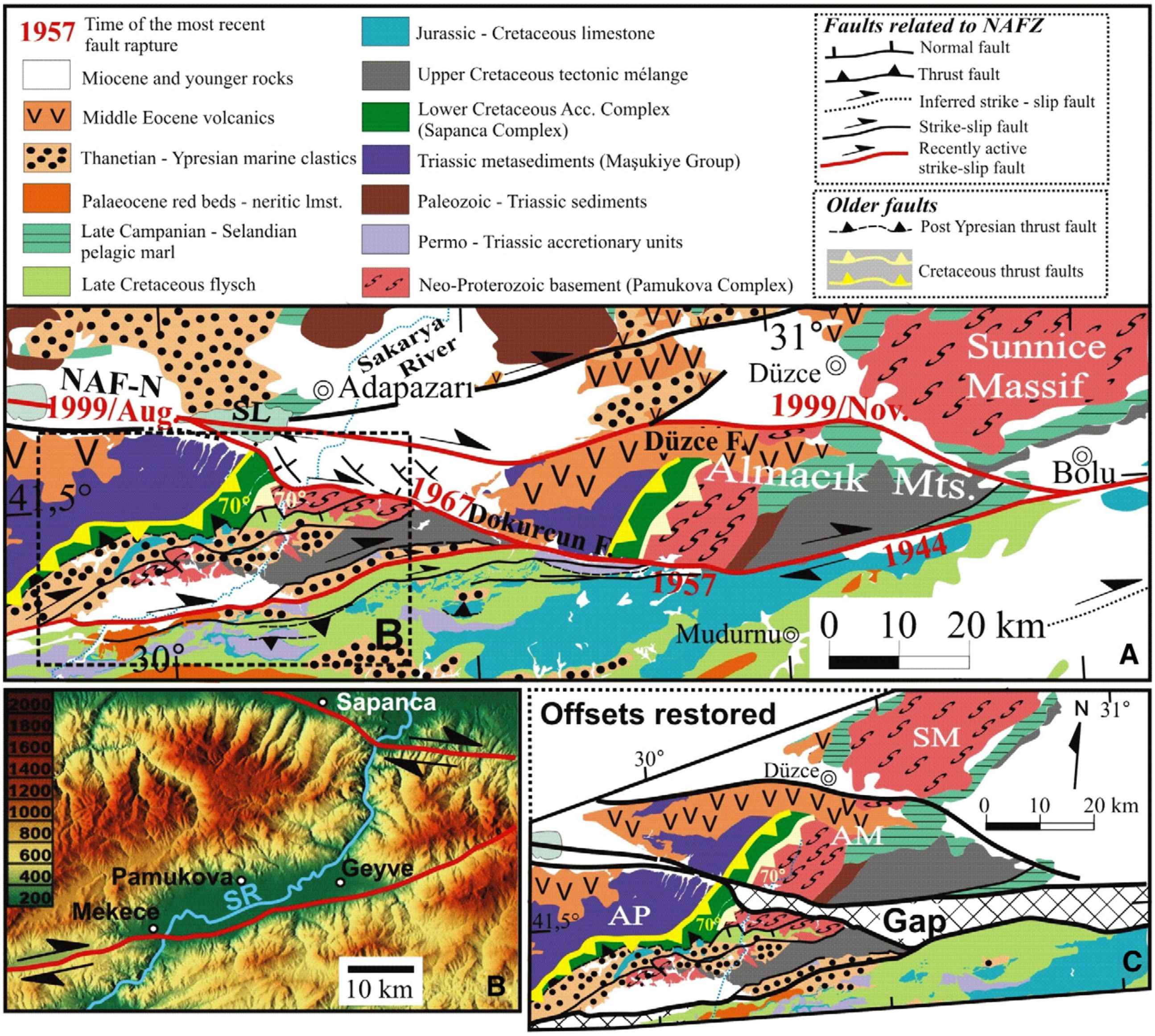

Fig. 3. (A) Simplified geological map of the area between the Marmara Sea and Almacık Mountains. Yellow lines with triangles are Cretaceous thrust faults showing the apparent 52 ± 1 km offset along the NAF-N. For location, see Fig. 2. Red lines are faults ruptured by recent earthquakes (Ms > 6.8) (Emre et al., 2013). (B) Shaded relief topography of the area between Sapanca Lake and Pamukova basin (from http://www.maps-for-free.com/) showing the dextral offset observed in Sakarya River (SR) along the Southern Branch of NAF. For location, see Fig. 3A. (C) Restoration of the dextral offsets along the Northern Branch, Düzce Fault and the Southern Branch of NAF-N.

interiors of the Eurasian and Anatolian plates, and a calculated pole and rate of rotation, is ~23 mm yr^{-1} of total plate motion in the eastern Marmara Sea region (calculated by M.H. Cormier using an online calculator: http://www.geo.uu.nl/~wwwtekto/PlateMotion/ and Table 2Sb from Reilinger and McClusky, 2011). Similar rates have been measured directly across this area using GPS (Ergintav et al., 2014). At this rate, it would take 3.9 million years to accumulate 88 km of displacement on the northern and southern branches of the NAF. Additionally, the Anatolian Plate would not have instantaneously accelerated to its modern rate of motion (Şengör et al., 2005). Thus, initiation of transform displacement must pre-date 3.9 Ma.

The measured 52 ± 1 km offset along the northern strand of the NAF-N plus a possible 15 km on the Düzce fault has direct implications for the age of arrival or inception of the NAF in the Marmara region and on the origin of the Marmara basins. We propose a total of ~67 km displacement on faults entering İzmit Bay in easternmost Marmara Sea. Here, we explore how that displacement might be accommodated in Marmara Sea. The simplest accounting would be for the entire displacement to continue along the NAF-N to the Ganos fault onshore (Fig. 1). This would be similar to the Armijo et al. (1999) model except with less extension. A minimum of 30 km of displacement on the NAF-N along the north edge of Çınarcık basin is supported by the following argument. The distance between the eastern edges of the oldest and youngest depocenters interpreted by Carton et al. (2007) is 30 km. A model for subsidence at the eastern (Tuzla) bend of the Tuzla–Istanbul releasing segment interprets the eastern edge of active deposition to be near the broad Tuzla bend (Seeber et al., 2006; Kurt et al., 2013). With time, depocenters are buried and transported to the west-northwest by fault slip. The 30 km of depocenter migration is a minimum because the average age of the oldest stratigraphic interval interpreted by Carton et al. (2007) is younger than the oldest sedimentary rocks at the base of the modern basin.

Part of the 67 km of NAF-N displacement documented in the Düzce area may not be accommodated on the NAF-N along the north edge of Çınarcık basin but is instead is distributed farther south on faults and by continuous deformation. This may be especially true for the Pliocene part of deformation because the Pliocene sequence and any associated faults are deeply buried in places and thus not as well-imaged by seismic reflection data.

The 16 to 26 km of displacement across the Southern Branch is inferred from the deflection of the Sakarya River (Fig. 3B) (Koçyiğit, 1988; Özalp et al., 2013; Şengör et al., 2005); the southern branch of NAF enters Marmara Sea at the Gemlik Bay and splits westward into several strands (Fig. 1, e.g., Okay et al., 2014). It is not well-understood how these strands extend farther west.

4. Discussion: origin of the Marmara basins with a minimum 52 ± 1 km dextral offset on NAF-N

The main contribution of this paper is in documenting a minimum of 52 ± 1 km, preferred ~67 km of dextral offset, for the NAF-N as it enters the İzmit Gulf and northern Marmara Sea. Some publications also use ~50 km of displacement for NAF-N in the İzmit Gulf and northern Marmara Sea (e.g., Armijo et al., 1999). Other papers propose high slip rates for the last ~200 ka on a newly formed NAF-N but are not specific on how much transform displacement was accommodated earlier (Le Pichon et al., 2001, 2003). İmren et al. (2001) and Rangin et al. (2004) propose a pull-apart extensional geometry to have accommodated transform plate motion between ~5 Ma and 200 ka, before the NAF-N formed or propagated through, deactivating basin-bounding normal faults. However, the majority of studies explain the formation of the modern sedimentary basins in the Marmara Sea as the result of the current oblique-normal slip on releasing segments of the NAF-N (Kurt et al., 2013; Okay et al., 2000, 2004; Seeber et al., 2004, 2006). These publications do not incorporate precise estimate displacements of NAF-N in the northern Marmara Sea. Here, we propose that oblique displacement including a minimum of 52 ± 1 km of right-lateral motion is sufficient to explain the 6 km depths and the along-strike lengths of the modern basins (see also Muller and Aydın, 2005).

We do not exclude the possibility of much of the earlier part of the displacement having been by distributed shear (Şengör et al, 2005, 2014) or part of it being accommodated by normal slip on NW-SE faults in a pull-apart model (e.g., Rangin et al., 2004). We explore the implications to crustal thickness and heat flow for tens of km of pull-apart extension accommodating the transform motion. The 200 ka reorganization models are based on interpretations of bathymetric features offset by 4 km (e.g., Le Pichon et al., 2003) and interpretations of normal faults being abandoned (e.g., Rangin et al., 2004). These interpretations have been questioned (e.g., Sorlien et al., 2012). In this paper, we consider the 4 km bathymetric offsets and normal fault abandonment as interpretations, and not facts. These interpretations are not disproved here, but we focus on steady-state large-displacement models.

There are three ~1200 m deep bathymetric basins (Tekirdağ, Central and Çınarcık Basins) along the northern Marmara Sea where the subsidence has been faster than in the rest of Marmara Sea (Armijo et al., 2002; Kurt et al., 2013; Muller and Aydin, 2005; Okay et al., 1999, 2000; Seeber et al., 2006). Subsidence is expected in areas where crust is thinning due to extension (e.g.; Muller and Aydin, 2005). A component of extension across Çınarcık basin northeastern Marmara Sea is indeed suggested by crustal thickness (Fig. 4) (Bécel et al., 2009). Deep crustal reflection data combined with refraction along the deepest part of Çınarcık basin indicate 19 km thick crust between the Moho and the base of the ~6 km of sedimentary basin fill (Armijo et al., 1999; Bécel et al., 2010; Carton et al., 2007; Laigle et al., 2008) and the non-extended crustal thickness near Marmara Sea is 35 km (Fig. 4) (Bécel et al., 2009). GPS data indicate ~23 mm yr^{-1} right-lateral plate motion across and near eastern Marmara Sea (Ergintav et al., 2014; Reilinger et al., 2006).

There are two main sets of models proposed for the opening of the Marmara Sea basins. The first idea suggests that the Marmara basins are essentially extensional basins, later cut and deactivated by the NAF-N (İmren et al., 2001; Le Pichon et al., 2003; Rangin et al., 2004; Şengör et al., 2005). In the second set of models, the Marmara basins formed through an extensional component between bends of the North Anatolian Fault; thus, they are strike-slip basins (Armijo et al., 1999, 2002; Kurt et al., 2013; Okay et al., 1999, 2004; Seeber et al., 2004, 2006, 2010). The first set of models proposes a reorganization followed by about 4 km of dextral offset by a narrow NAF-N fault, which is proposed to have formed at ~200 ka based on extrapolation of a 25 mm yr^{-1} plate motion. The second set of models does not include reorganization in the last few million years (Armijo et al, 2002; Grall et al., 2013; Kurt et al., 2013). There is no abandonment of the extensional basins in the latter set of models although local reorganizations within basins have been proposed (e.g., Grall et al., 2012). For example, a minimum subsidence rate of 7 mm yr^{-1} of the deepest part of Çınarcık basin has been continuous for the last half million years (Kurt et al., 2013), continuing into Holocene time (Seeber et al., 2006). The total 6 km depth of the modern Çınarcık (and Central) basin can develop in less than one million years at this rate. However, depocenter migration models allow basin formation to have continued much longer without additional deepening (Seeber et al., 2010 and references therein).

There are two sub-models among the studies suggesting that the Marmara basins formed through transform motion on the North Anatolian Fault, without requiring a major reorganization. The first sub-model proposes that the Marmara Sea basins formed as pull-apart basins (e.g., Armijo et al, 1999, 2002; Flerit et al., 2003). The second sub-model interprets the Marmara basins as asymmetric basins associated

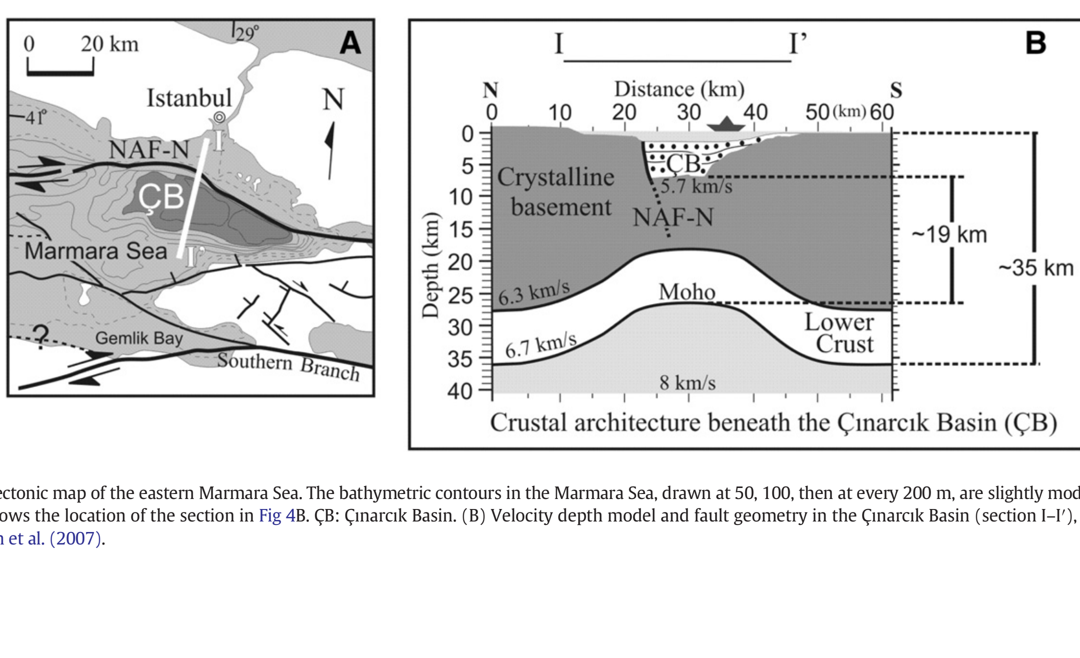

Fig. 4. (A) Active tectonic map of the eastern Marmara Sea. The bathymetric contours in the Marmara Sea, drawn at 50, 100, then at every 200 m, are slightly modified from Okay et al. (2000). I–I′ line shows the location of the section in Fig 4B. ÇB: Çınarcık Basin. (B) Velocity depth model and fault geometry in the Çınarcık Basin (section I–I′), compiled from Bécel et al. (2009) Carton et al. (2007).

with bends in the major through-going strike-slip faults (Okay et al., 2000, 2004; Seeber et al., 2006, 2010).

Armijo et al. (2002) offer a steady-state pull-apart for the entire Marmara Sea since 5 Ma and oppose a single post-200 ka through-going fault system suggested by Le Pichon et al. (2001). According to Armijo et al. (2002)), the greater Marmara Sea-wide basin opens along the 70-km-wide right step-over of the Ganos and İzmit faults. Another alternative pull-part model suggests normal faults striking at high angles to NAF-N, which took up the displacement before being abandoned at 200 ± 100 ka (e.g., Rangin et al, 2004). The Rangin et al. (2004) pull-apart model implies the displacement of the Marmara block toward 252°–253° azimuths, with extension between the Tuzla–Istanbul segment in the northeast and the İmralı fault in the southwest. The distance between those two faults along that azimuth is 52–57 km (Fig. 1B). If 4 km of displacement was accommodated by strike-slip after 200 ka, a minimum of 47 km of dextral displacement, and preferred 63 km, was taken up between these faults. Extension equal to this distance would essentially make a hole in the crust with zero crustal thickness. The Cayman Trough in the Caribbean Sea fills such a hole with sea floor spreading (Holcombe et al., 1973). The young pull-apart southwest of the San Andreas fault across Salton Sea is interpreted to have removed the crust (Elders et al., 1972), but to have formed new 20–25 km thick crust by a combination of very rapid sedimentation and igneous intrusion (Parsons and McCarthy, 1996). As discussed above, the crustal thickness beneath Çınarcık basin beneath 6 km of modern basin sedimentary rocks is 19 km, compared to 35 km for unextended crust nearby (Bécel et al., 2009) (Fig. 4). There is no evidence for Quaternary igneous underplating or volcanism in Çınarcık basin (Bécel et al., 2009; Carton et al., 2007), although sedimentation rates have been about 7 mm yr^{-1} for the last half million years in the depocenter of eastern Çınarcık basin (Kurt et al., 2013). The formation of new crust by sedimentation beneath the 6 km-deep bathymetric and sedimentary basin seems implausible for Quaternary time, and the velocities from refraction seismic below the unconformity imaged by the deep reflection data are faster than expected for Pliocene–Miocene sediments (Dessa et al., 2007). The above discussion of crustal thickness does not preclude significant dextral transform displacement being accommodated by a pull-apart model; instead, it casts some doubt on a pull-apart model explaining the majority of >51 km of displacement.

Our estimate of the minimum 52 ± 1 km, preferred 67 km of displacement on the NAF-N combined with the Okay et al. (1999) estimate of a minimum of 40 km of post-latest Miocene displacement on the Ganos fault, is permissive of the Armijo et al. (1999, 2002) reconstruction for 70 km displacement, despite some questions on the geology of this correlation (e.g., Yaltırak et al., 2000). Adding the published 16 to 26 km offsets on the Southern Branch of the NAF produces a total offset estimate of the whole NAF zone as 88 ± 5 km in the Eastern Marmara region, which is similar to the ~85 km total offset estimate of Armijo et al. (1999). With a ~23 mm yr^{-1} slip rate, the 88 km offset along the NAF-N indicates a minimum inception age for the through-going transform in the Pliocene (~3. 9 Ma) in the Marmara region. This displacement along the NAF is sufficient to open the Marmara basins as transtensional structures.

5. Conclusions

Metamorphic units separated by steeply dipping thrust planes trend sub-perpendicular to the strike of the northern branch (NAF-N) of the North Anatolian Fault in northwest Turkey and are offset by 52 ± 1 km in right-lateral sense. The displacement of the Middle Eocene volcanic belts shows that the offset is post-Middle Eocene. The measured 52 ± 1 km offset along the NAF-N plus a possible 15 km on the Düzce fault (with large errors) indicate a total ~67 km offset along the NAF-N in the eastern Marmara region. Adding the published offsets that range from 16 to 26 km on the Southern Branch of the NAF give a total offset estimate of the whole NAF zone as 88 ± 5 km in the Eastern Marmara region (plus unknown error in the Düzce fault displacement estimate). The most recent GPS velocity estimate suggests ~23 mm yr^{-1} of total plate motion across and near eastern Marmara Sea that would take 3.9 million years to accumulate 88 km of displacement on the NAF. The combined displacement, if accumulated at the post-~0.5 Ma rates, supports a Pliocene inception of the Marmara Basins. The minimum of 51 km of right-lateral displacement along the NAF is sufficient to open the Marmara Basins as transtensional structures.

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