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Neogene restoration of geometry of the Neotethyan suture zone in Central Anatolia (Turkey)

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ABSTRACT

We have restored the geometries of suture zones that involved various continental blocks in central Anatolia during the Neogene, using palaeomagnetic data. Previously, the Kırşehir Block was proposed to be an NNE-SSW striking tectonic block broken into three fragments that they underwent clockwise rotations in the north and counter-clockwise rotations in the south during the Palaeogene, due to collision and N-S shortening of the Kırşehir Block between Tauride-Menderes Block in the south and the Pontides in the north. Our new results point out five distinct Neogene tectonic domains with distinct rotation patterns that indicate the rotational deformation of Central Anatolia is far more complex than generally presumed. Among these, 1) Kırıkkale-Bala Domain is rotated ~18° clockwise, 2) the Tuz Gölü Domain underwent ~14° counter-clockwise rotation, 3) the Alcı-Orhaniye Domain rotated ~35° counter-clockwise sense, 4) the Northern Haymana Domain underwent ~12° counter-clockwise rotation while 5) the Southern Haymana Domain underwent very small (~5° clockwise) net rotation since the early Miocene. The results also indicated that pre-Neogene configuration of the Izmir-Ankara Suture Zone was striking almost E-W while Inner-Tauride and Ankara-Erzincan suture zones were almost N-S in the study area. In addition, the fault zones that define the these domains extend from the Kırşehir Block into the over-riding blocks (Pontides) continuously without any deflection indicating that they were active during the Neogene and fragmented and dislocated the suture zones in the region.

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1. Introduction

Ongoing convergence between African-Eurasian and Arabian plates since at least Triassic gave way to the subduction, collision, and amalgamation of various continental blocks within the Tethyan realm (Dewey and Sengör 1979; Şengör and Yılmaz 1981; Okay 1986; Robertson 2004; Barrier and Vrielynck 2008; Moix *et al.* 2008; Robertson *et al.* 2009). In Anatolia, three continental blocks are involved in collision and amalgamation (Görür *et al.* 1984; Kaymakcı *et al.* 2003a, 2009; Lefebvre *et al.* 2013). These include the Pontides in the north with Eurasian affinity, the Menderes-Tauride Block (MTB) with Gondwana affinity in the south. However, the Kırşehir Block with Gondwana affinity was located between the Pontides and the MTB block during much of Mesozoic and early Tertiary as an independent microcontinent (Şengör 1984; Kaymakcı *et al.* 2001, 2009) (Figure 1). Collision and further convergence of these blocks gave way to the development of İzmir-Ankara (İASZ) between the Pontides and the Menderes-Tauride Block, Ankara-Erzincan Suture Zone (AESZ) between the Pontides and the Kırşehir Block and Inner-Tauride Suture Zone (ITSZ) between Kırşehir Block and the Menderes-Tauride Block (Görür *et al.* 1984; Whitney and Dilek 1997; Pourteau *et al.* 2010).

The active convergence between Africa and Anatolia is accommodated by northward subducting African slabs along Mediterranean trenches (e.g. Pliny-Strabo, Hellenic, and Cyprian trenches) (e.g. Le Pichon and Angelier 1979; van Hinsbergen *et al.* 2010; Biryol *et al.* 2011; Özbakir *et al.* 2013; Schildgen *et al.* 2014). The slab-edge processes along this subduction system gave way to the development of backarc extension in the Aegean-west Anatolian region, since at least early Miocene (Seyitoğlu and Scott 1994; Gautier *et al.* 1999). In contrast, collision and ongoing convergence between Eurasian and Arabian plates resulted in the development of compressional deformation and N-S shortening in the eastern Anatolia-Iranian Plateau region, which ultimately gave way to the westward escape of Anatolian Plate

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Supplemental data for this article can be accessed here.

along the dextral North Anatolian and sinistral East Anatolian fault zones towards the free face of the Hellenic trench by the late Miocene (Şengör *et al*. 1985; Burke and Şengör 1986; Flerit *et al*. 2004; Hüsing *et al*. 2009; Gülyüz *et al*. 2020).

Relatively recent seismotectonic (e.g. Armijo *et al*. 1999; Hubert-Ferrari *et al*. 2002; Şengör *et al*. 2005), Global Navigation Satellite Sytems (GNSS) (e.g. Reilinger *et al*. 2006) and palaeomagnetic studies (Kissel *et al*. 1987, 1993; Tatar *et al*. 1995; Piper *et al*. 1996, 1997, 2010; Gürsoy *et al*. 1998, 1999, 2003, 2011; Çinku *et al*. 2016; Hisarlı *et al*. 2016; Çinku 2017) studies support the escape tectonics model, and almost all of these studies claimed that the Anatolian Plate had been rotated counterclockwise (CCW) since Miocene. These studies generally assume that (i) the Anatolian Plate is a single homogeneous body fleeing westwards along crustal-scale faults (NAFZ and EAFZ) and stretched by slab-pull related extension along the Hellenic Trench and (ii) Miocene and younger vertical block rotations are related only to the still active transcurrent tectonics, 'the Neotectonic Period,' while pre-late Miocene tectonics – covering the complete closure of Neotethys ocean in the region- is considered as 'Paleotectonic Period' (Şengör *et al*. 1985). These studies, however, cannot explain the continuous deformation since Oligocene and onwards and related vertical block rotations (Kaymakcı *et al*. 2003a, 2007, 2018; van Hinsbergen *et al*. 2005, 2010; Meijers *et al*. 2010; Lefebvre *et al*. 2013; Uzel *et al*. 2015; Koç *et al*. 2016, 2017). Similarly, recent palaeomagnetic studies from western and southwestern Anatolia demonstrated that the rotational deformation of Anatolian Plate is not uniform, and it is far more complex than presumed previously. Some of these studies include Thrace Fault (Kaymakcı *et al*. 2007), İzmir- Balıkesir Transfer Zone (Uzel *et al*. 2015, 2017) Central Tauride Orocline (Koç *et al*. 2016), SW Anatolian rotation (Özkaptan *et al*. 2014; Kaymakcı *et al*. 2018). Each of these studies documents heterogeneous vertical block rotation patterns continuous from early Miocene to recent. The similarly heterogeneous deformation pattern that took place since early Miocene is also valid for Central Anatolia. In this regard, the main purpose of this paper is to demonstrate how continuous rotational deformation in Central Anatolia, since at least early Miocene, shaped the present complex geometries of İzmir-Ankara and Inner-Tauride suture zones that are related to the closure of the Neotethys Ocean and the collision of intervening continental blocks. The Central Anatolian region has been exposed to progressive compressional deformation since at least Late Palaeocene by the beginning of collision between Pontides and the Kırşehir Block (Kaymakcı *et al*. 2009; Gülyüz *et al*. 2013; Advokaat *et al*. 2014; van Hinsbergen *et al*. 2016; Gülyüz 2020a) which have led to complex deformation in the region. Our study is based on vertical block rotation restorations of post-Oligocene units based on palaeomagnetic results collected from 39 new sites and reliable literature data (Supp. Table 1, Figure 1).

2 Geological background

2.1. Stratigraphy

In the literature, sedimentary sequences in Central Anatolia are classified as pre-early Miocene paleotectonic units that represent the sequences related to the closure of the Neotethys ocean and collision of intervening continental units. They are categorized as Late Cretaceous to Oligocene fore-arc to foreland basin deposits (Görür *et al*. 1984; 1998; Gülyüz *et al*. 2013, 2019; Kaymakcı *et al*. 2009; Koçyiğit 1991). The second group comprises post- late Miocene continental fluvio-lacustrine sequences that are classified as Neotectonic units (Şengör *et al*. 1985; Koçyiğit 1991; Kaymakcı *et al*. 2001) deposited by the beginning of transcurrent tectonics related to the westward escape of Anatolian Plate and they are the main concern of this study.

The Neotectonic units seem to unconformably overlay the paleotectonic units almost everywhere in Turkey, although the ages of most of these units are in places poorly constrained. In most cases, the first unit unconformably overlying the so-called Paleotectonic units are regarded as late Miocene, and the age of the sequence is ascribed recursively without providing any biostratigraphic or radiometric evidence (e.g. Koçyiğit 1991; Koçyiğit *et al*. 1995). In order to overcome such a limitation, the ages of the studied sections in this study are based on available biostratigraphic and radiometric data wherever available otherwise, we followed Saraç (2003) and the ages suggested by the 1/250.000 scale geological maps series of the Geological Survey of Turkey (Işıker 2002). The sampled horizons, in this study, range mainly from Early Miocene to Early Quaternary and they can be traced over more than 100 km distance, especially in the Haymana and Tuzgölü basins. They are horizontal to gently undulating and deformed around local and regional faults, making lateral correlations straightforward and reliable (Figure 1, Supp. Table 1). In the Alcı-Orhaniye and Çankırı basins, biostratigraphic data is adequately abundant (Saraç 2003), which provided better constraints on the ages of the sampled units (Figure 1).

2.2. Geological setting

The tectonic elements in the study area include various basins and major folds and faults that controlled the rotation deformation of the region. Among these,

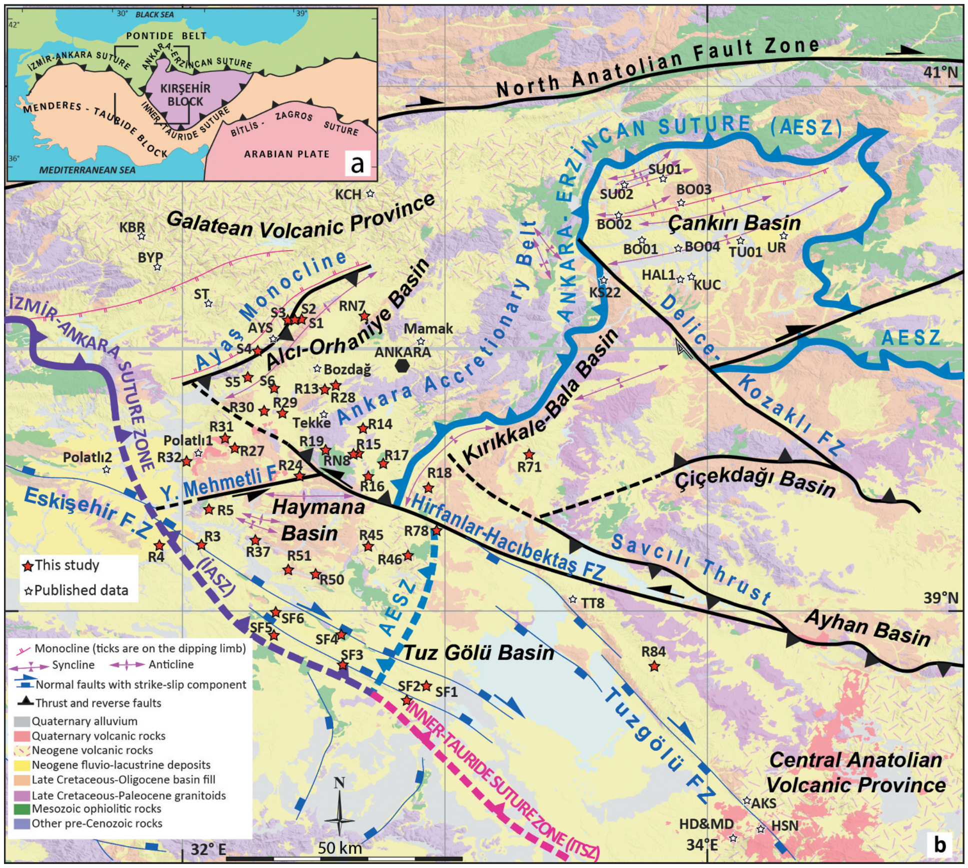

Figure 1. A) Major tectonic divisions of Anatolia (Kaymakcı *et al.* 2009). b) Simplified geological map (Işıker 2002) of the study area and sampled locations.

Haymana Basin, Tuzgölü Basin, Alcı-Orhaniye Basin, and Çankırı Basin and its SW extension in Kırıkkale-Bala region, are very important in terms of hosting Neogene deposits from which sampling was carried out.

The Haymana Basin is located at the southernmost tip of the Central Pontides and straddles the İzmir-Ankara Suture Zone in the north NW part of the Inner-Tauride Suture Zone (Kaymakcı *et al.* 2009) (Figure 1). The Neogene structures affecting the basin are the Eskişehir Fault Zone (EFZ) in the south and the Dereköy Fault (DF) in the north. The Dereköy Fault is a reverse fault zone that is reactivated as a sinistral strike-slip fault zone with a reverse component during the Neogene. It is the north-western continuation of the Hirfanlar-Hacıbektaş Fault Zone (Lefebvre 2011; Lefebvre *et al.* 2013; Özkaptan and Gülyüz 2019). Gülyüz *et al.* (2019) have documented kinematic data on two newly recognized NE-SW striking Neogene strike-slip faults that segmented and controlled the deformation in the Haymana Basin.

The Çankırı and Kırıkkale-Bala basins are fore-arc to fore-land basins that straddle the Ankara-Erzincan Suture Zone (Figure 1) and their Tertiary (foreland basin) configuration sandwiched between the Pontides and Kırşehir Block (Kaymakcı *et al.* 2009; Özkaptan 2019). The main structures that controlled the Neogene tectonics of the Kırıkkale-Bala Basin are the Tuz Gölü Fault, Delice-Kozaklı and Hacılar-Hirfanlı Fault zones (Gülyüz *et al.* 2013; Lefebvre *et al.* 2013).

The Tuz Gölü Basin straddles the Inner-Tauride Suture Zone and is located both on the Kırşehir and the Tauride blocks. Its Neogene evolution is dominated by the Tuz Gölü Fault Zone along its eastern margin and Eskişehir Fault Zone along the western margin (Çemen *et al.* 1999; Gülyüz 2020b).

The Alcı-Orhaniye Basin is located within the Pontides and bounded in the east by the basement rocks of the Pontides exposed within the Ankara Accretionary Belt (Rojay 2013). In the west, the Ayaş Monocline – an inverted normal fault reactivated as a west verging reverse fault, delimits the basin (Kaymakcı *et al.* 2009).

Two major magmatic complexes emplaced mainly during the Neogene dominate the tectono-magmatic evolution of the region. The Galatian Volcanic Province (GVC, (Tankut *et al.* 1999) (Tankut *et al.* 1999) is developed within the Pontide Block at the NW part of the study area, and the Central Anatolian Volcanic Provence Central Anatolian Volcanic Provence (CAVP, Toprak and

Göncüoglu 1993) is developed within the Kırşehir Block in the SE part of the basin. The origin of the GVC is attributed to post-collisional magmatic processes along the İzmir-Ankara Suture Zone (Wilson *et al*. 1997; Aydar *et al*. 2012) whereas the origin of CAVC is attributed to the Mediterranean subduction systems (Toprak 1994, 1998; Di Giuseppe *et al*. 2018).

3. Palaeomagnetism and rock magnetisms

3.1. Palaeomagnetic sampling

We have carried out an extensive palaeomagnetic sampling campaign and collected 914 standard palaeomagnetic core samples (25 mm Ø) from 40 sites comprising Miocene to Pliocene sedimentary sequences (Figure 1 and Supp. Table 1). The sampling was performed using a gasoline-powered drill or using a portable generator and an electric drill. Between 6 and 46 (22 on average) oriented core samples were collected at each site, over 5 to 15 metres stratigraphic thickness to average out palaeosecular variation (PSV). In addition to sedimentary sites, three igneous sites (R13, R45, R46) were sampled, each consisting of at least 7 different lava flows. The sedimentary sites are composed of Miocene shale/ silty clay, marl and limestone, and Pliocene mudstone/marl and limestone. The igneous sites are composed of andesitic and basaltic lava flows. Core orientations and bedding planes were measured with a magnetic compass which was corrected for the present-day declination (+4.5°E). Sampling was carried out between 2011–13 and measurements were made in 2013–14. The preparation of the samples, as well as demagnetization and rock magnetic experiments, were carried out at the Fort Hoofddijk Palaeomagnetic Laboratory at Utrecht University (the Netherlands).

3.2. Demagnetization procedures

The palaeomagnetic samples were cut into standard specimens (2.2 cm in length), per core sample usually resulting in several specimens (referred to as A, B) providing the opportunity to compare single core results. Natural remanent magnetizations (NRM) were analysed by applying both thermal (TH) and alternating field (AF) stepwise demagnetization. A total of 976 specimens were demagnetized. At least 5 specimens per site were thermally demagnetized. The demagnetization started from room temperature (20°C) and went up to a maximum of 680°C (using 20–50°C steps for a total of 16–20 steps). The TH demagnetization was carried out in a magnetically shielded oven (ASC, model TD48-SC) with a residual magnetic field < 10 nT. Specimens were measured on a 2 G Enterprises horizontal 2 G DC SQUID cryogenic magnetometer (noise level 3×10^{-12} Am^2).

In addition, on average 6 specimens per site were heated to 150°C before AF demagnetization to remove possible stress in magnetite due to low-temperature oxidation (weathering) (Van Velzen and Zijderveld 1995). The rest of the specimens were only AF demagnetized, carried out with increments of 3–10 mT up to a maximum of 100 mT for a total of 14–18 steps. AF demagnetization was done using an in-house developed robotized 2 G Enterprises DC SQUID cryogenic magnetometer (noise level 1–2 $\times 10^{-12}$ Am^2) in a magnetically shielded room (Mullender *et al*. 2016).

3.3. Thermomagnetic experiments

In order to determine the nature of the dominant magnetic carrier(s) in the studied rocks and their alterations under different temperatures, thermomagnetic experiments were carried out on at least one specimen per site. Representative results of 15 specimens of different rock types and ages are illustrated in Figure 2. Curie balance runs were carried out in the air, using a modified horizontal translation type Curie balance with a sensitivity of ~5x10-9 Am^2 (Mullender *et al*. 1993). Approximately 0.3–0.9 g of powdered rock sample was put into a quartz-glass sample holder and measured in a number of heating-cooling cycles (with rates of 10°C /min), up to a maximum temperature of 700°C. We used the following heating-cooling cycles (in °C): 20–150, 50–250, 150–350, 250–400, 300–450, 350–525, 420–580, and 500–700.

3.4. Palaeomagnetic analysis

The directional and statistical results were analysed using the online portal Palaeomagnetism.org (Koymans *et al*. 2016). The demagnetization results from AF, TH and combined measurements were analysed by orthogonal projection diagrams (Zijderveld 1967) (Figure 3). Characteristic Remanent Magnetization (ChRM) directions were determined using principal component analysis following an eigenvector approach (Kirschvink 1980) by taking approximately five to seven vector points. Interpreted directions are plotted in equal-area projections (Figure 4). In the case of two or more overlapping coercivity or temperature components, ChRM directions were determined by following the great circle approach of McFadden and McElhinny (1988) (Figure 3). The means of both ChRM directions and their corresponding virtual geomagnetic poles (VGP) were computed using Fisher (1953) statistics. We used the Deenen *et al*. (2011) criteria to test for sufficiently

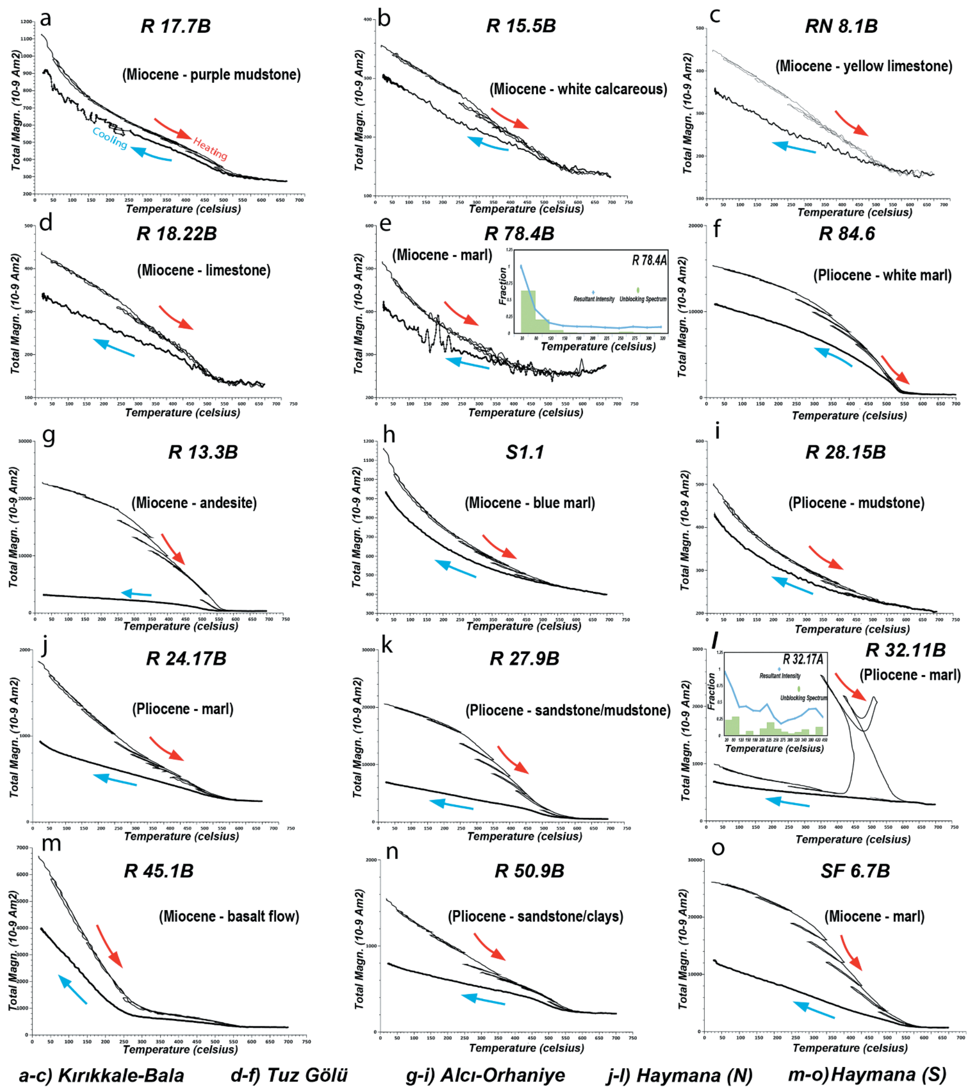

Figure 2. Thermomagnetic (curie-balance) curve generated with the stepwise heating protocol (Mullender *et al.* 1993) for 15 representative samples in five different domains in Central Anatolia. The thin black line (red arrow) shows heating phases. The final cooling segment is indicated with a thicker black line (blue arrow). A noisy appearance is indicative of a weak magnetic signal. Thermal decay curves indicate weak and non-magnetic behaviour. Detailed explanations are given in the text.

averaging out palaeosecular variation (PSV), by calculating the A95 of the VGP distribution. If A95 is within the N-dependent range (between A_{95min} and A_{95max}), it may be assumed that the rocks have recorded PSV. We applied a fixed cut-off (45°) to remove outliers, following Johnson *et al.* (2008) and Deenen *et al.* (2011). The errors in declination (ΔD_x) and inclination (ΔI_x) were determined from A95 of the VGP distribution (according to Butler 1992; see also Deenen *et al.* 2011).

In determining the means per domain each consisting of multiple sites, we averaged all individual directions of the sites of that domain. We, therefore, break with palaeomagnetic tradition to average the site means per domain, although these are given in Supp. Table 1. Site means are unit vectors irrespective of the number of samples per site, and therefore site mean cones of confidence (A95) and dispersion (K) are not propagated (VGP plots in Appendix). By taking all site directions together, sites with more samples have, naturally, more weight. Since we use the Deenen *et al.* (2011) criteria, this approach is warranted because the range of acceptable A95 is N-dependent, contrary to the traditional criteria (e.g. Van der Voo 1990; see the discussion and Figure 3 in; Deenen *et al.* 2011). Since A95 should fall within the $A95_{min}$-$A95_{max}$ envelope, the test becomes more strict ('narrower') with increasing N. The estimate of dispersion (k or K) of the distribution, however, is largely independent of N (for N sufficiently large, say N > 10) and for increasing N becomes an increasingly better estimate for the true dispersion (κ) of the distribution. The Deenen *et al.* (2011) approach is now widely recognized as key to determine if the distribution of ChRM directions can be

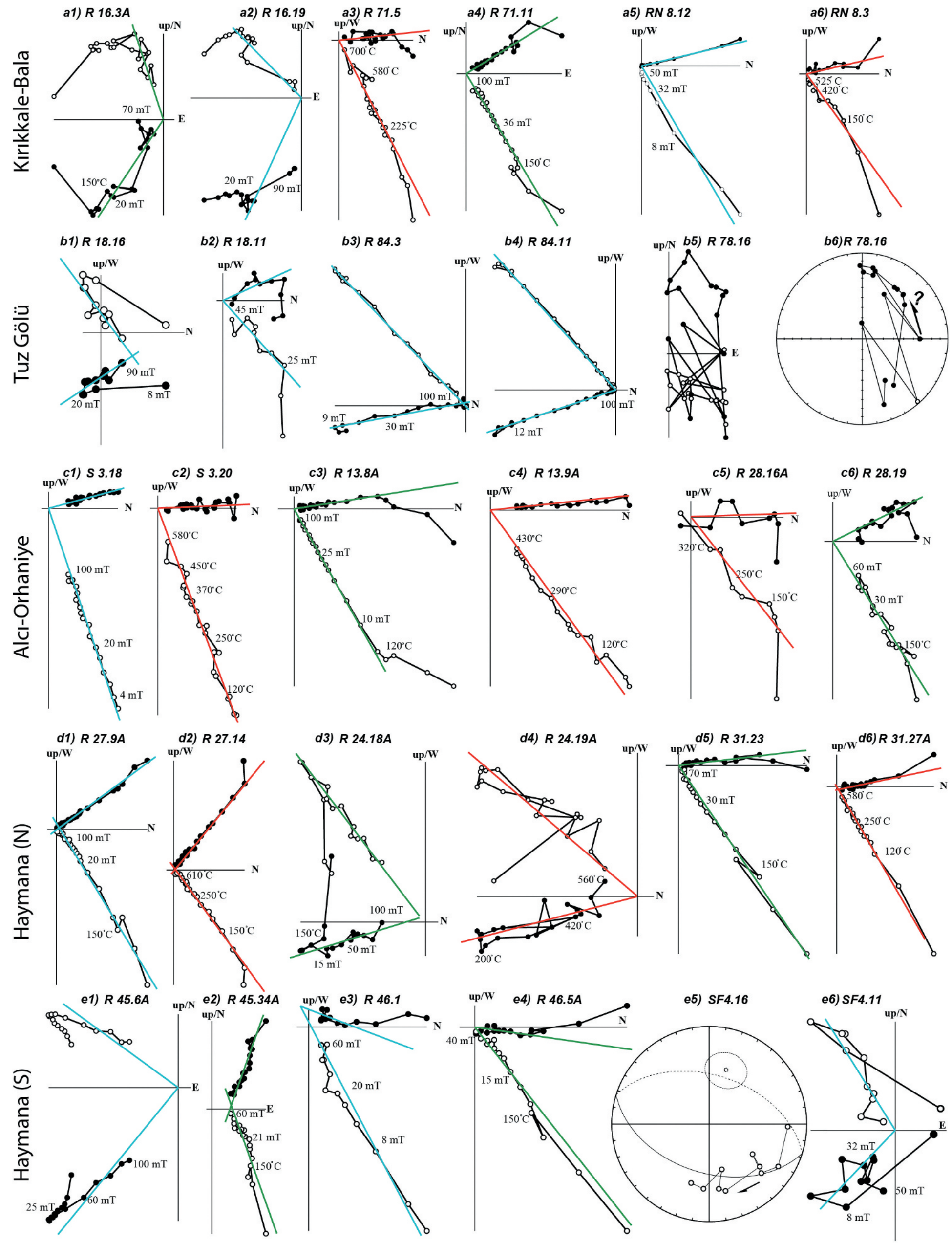

Figure 3. Zijderveld diagrams (Zijderveld 1967) of representative samples at five domains demagnetized using thermal (red lines, TH), alternating field (blue lines, AF), and preheated alternating field (green lines, TH-AF) demagnetization shown in tectonic coordinates. The solid and open dots represent projections on the horizontal and vertical planes, respectively. Great circle plots (b6, e5) use the technique of McFadden and McElhinny (1988). Demagnetization step values are in °C, in mT, or both.

explained be secular variation (e.g. Meert *et al.* 2020). To determine whether two distributions share a common true mean direction (CTMD), we used the coordinate bootstrap test (Tauxe 2010, Figure 5). When there are ChRM distributions of opposite polarity, this amount to a reversal test. We have conducted fold tests – where possible – by means of a bootstrapped eigenvector approach (Tauxe and Watson 1994) on the Alcı-Orhaniye and Kırıkkale-Bala domains in order to test the pre-folding origin of the ChRM.

4. Rock magnetism, NRM properties and palaeomagnetic results

4.1. Rock magnetism

Thermomagnetic experiments were implemented for every site of which we selected 2 volcanic and 13 sedimentary rocks. In general, the Curie balance curves point to a dominant presence of magnetite as the main magnetic mineral, considering the Curie temperatures of 580°C found in the majority of the curves, hovewer for

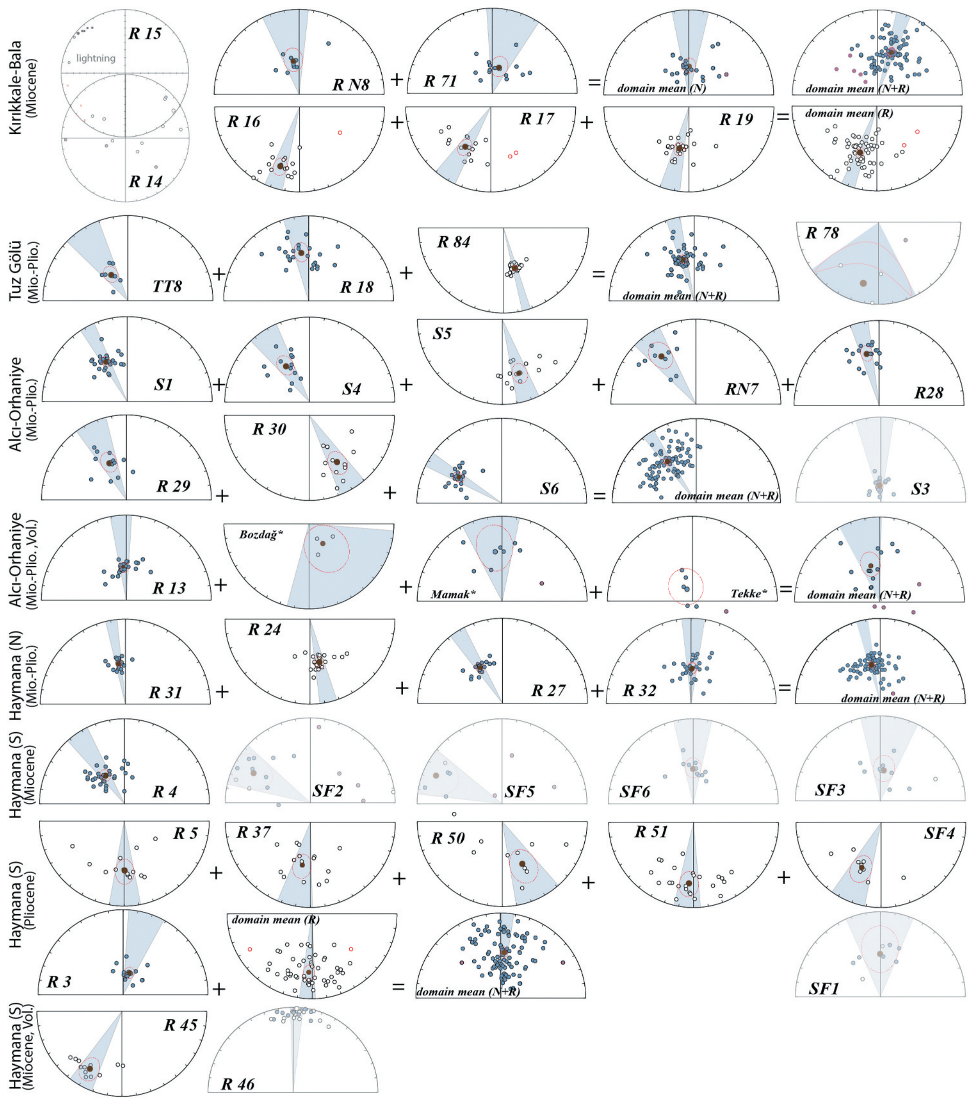

Figure 4. Equal area projections of ChRM directions for each domain and their means with associated error ellipses (ΔDx, ΔIx) according to Deenen *et al*. (2011), after tectonic correction (TC). Rejected directions (after 45° cut-off) are displayed in red, and normal (reverse) directions are shown as solid (open) circles.

the volcanic rocks, the Curie temperature is slightly lower (~560°C), pointing to Ti-poor magnetite. Occasionally we find evidence for Fe-sulphides like greigite – see also the thermal demagnetizations in Figure 3 – or pyrite, especially in marls, n some cases, we find an inflection around 350°C, pointing to either greigite (rarely) or the presence of some maghemite (Dankers 1978), possibly because of some low-temperature oxidation (like weathering).

Representative diagrams from five different localities are given in Figure 2. Two types of thermomagnetic curves can be observed in the volcanic sites. Site R13 (andesite) dominated by magnetite since the major decay occurs at ~575°C (Figure 2(g)), while some magnetization is lost above 350°C, pointing to some maghemite possibly due to low-temperature oxidation (weathering). Site R45 shows a sharp decrease in magnetization with a Curie temperature around 300°C which suggests the presence of Ti-rich titanomagnetite as the dominant magnetic carrier (Figure 2(m)). A second Curie temperature of ~550-580°C supports the presence of Ti-poor magnetite as well. Most sedimentary sites show Curie temperatures of ~550-580°C pointing to magnetite as the main carrier of the NRM. In many cases, the curves show that some magnetization is lost at temperatures above ~350°C, but usually, cooling curves become reversible again above 450–500°C which suggests the presence of some maghemite in the samples that at ~350°C may invert to haematite and thus the sample becomes less magnetic (Dankers 1978).

A few specimens represent a sharp irreversible increase in total magnetization with increasing temperature above 390–420°C, which is characteristic for the occurrence of pyrite (Figure 2(l)). Above ˜400°C, pyrite starts to transform to magnetite (Passier *et al*. 2001) which often causes spurious magnetization so further thermal demagnetization is not meaningful. Generally, lake sediments present relatively low magnetizations and the curves suggest the dominant presence of paramagnetic minerals (e.g. Figure 2(h,i)). Nevertheless, in most cases, in both volcanics and sediments, the main magnetic carrier of the ChRM is magnetite, as determined by the Curie temperatures of ˜580°C.

4.2. NRM properties

Small viscous remanent magnetization components with a random direction are usually removed at low temperatures (100–120°C) or low alternating fields (4–15mT) while a recent magnetic field overprint – if at all present – could be removed at ˜180-220°C (or ~4-20mT in AF). In a few sites, we suspect the presence of some greigite, which has relatively high coercivity but low Curie temperatures of usually below 400°C. Greigite can be dominant in many Neogene sediments – in particular in some mudstones and marls – in the southern Eurasian basins but still can provide reliable results (Vasiliev *et al*. 2008; Özkaptan *et al*. 2018). In most cases, however, the maximum temperatures required to remove the ChRM entirely are close to ˜580°C or 80–100 mT and point to magnetite as the main carrier of the NRM. Only very occasionally, higher temperatures or alternating fields above 100 mT are required in which case we may have maghemite or some haematite. Relevant examples are shown in Figure 3.

Representative demagnetization steps and NRM directions for five different domains are shown in Figure 3 following both thermal (TH) and alternating field (AF) demagnetization (or a combination of both). In general, demagnetization at higher TH/AF steps (> 500°C/50 mT) show decay trending towards the origin in both normal and reversed polarity results in Kırıkkale-Bala Domain. Some specimens were pre-heated (four steps up to 150°C) to remove possible stress in magnetite due to low-temperature oxidation (following Van Velzen and Zijderveld 1995) and then AF treatment was applied up to 100 mT (Figure 3(a1)). In all cases, the NRM directions from both TH and AF demagnetization show good consistency and lead to a decay trending towards the origin and was used for ChRM direction interpretation. In the Tuz Gölü Domain, there are both normal and reversed polarity directions Some NRM directions results deviate from the origin (Figure 3(b1, e2)). In a few cases, the ChRM could not be determined due to scattered results (Figure 3(b5,b6)). In the Alcı-Orhaniye Domain, a present-day magnetization component was generally removed at very low steps (TH<150°C, AF<20 mT), while ChRM components were isolated at higher steps of 200–580°C or 10–100 mT (Figure 3(c1-c4)). For a few specimens, the NRM was removed at temperatures below 400°C suggesting greigite (Figure 3(c5)). The three types of demagnetization were also applied to the Northern Haymana (NHD) samples. In most cases, a linear decay towards the origin occurred up to temperatures of ~580°C or fields of 100 mT (Figure 3(d1,d2,d5,d6)), likely carried by magnetite. In some cases, the best fit ChRM component deviates slightly from the origin but still shows good correlation between the TH and the AF results (Figure 3(d3,d4)). In the Southern Haymana (SHD) domain, a recent viscous component was removed at temperatures of ~150°C or 10 mT, but the ChRM was interpreted between ~ 240–580°C and ~20–60 mT. Despite some trends not towards the origin (Figure 3(e2,e3)), the ChRM component could generally be determined straightforwardly. Only in a few cases, due to the presence of a pervasive secondary magnetization component, the ChRM was calculated using the great circle approach following the technique of McFadden and McElhinny (1988) (Figure 3(e5)). In the next section we report rotations in terms of declination with respect to North, but if we compare the results against a reference path, we should add between 3° (at 10 Ma) and 0° (at 0 Ma) which is expected declinations with respect to Eurasia (Torsvik *et al*. 2012). However, this small amount is in all cases within error ΔDx, so it is not very meaningful to correct declinations with respect to North to rotations with repsect to a reference point.

5. Palaeomagnetic results

Based on the accepted sites and using literature data, the region was divided into main domains, based on rotation patterns and geological characteristics. Initially, the statistical results were analysed on a site-by-site basis, and subsequently, if the site results passed the consistency test per domain, all directions of all sites were combined for each domain to give the mean rotation result (Supp. Table 1, Figure 4). We recognized five domains, namely: Kırıkkale-Bala (KBD), Tuz Gölü (TGD), Alcı-Orhaniye (AOD), Haymana (NHD), and Haymana (SHD), which are delimited by through going fault zones and intervening blocks show consistent tectonic rotations.

5.1. Kırıkkale-Bala Domain (KBD)

This domain comprises the Kırıkkale-Bala Basin and associated areas. We have collected 7 upper Miocene-Pliocene sites from the domain. Two out of seven sites were disregarded since they did not produce any meaningful results (Table 1). Site R14 produced random directions, and R 15 most probably was affected by lightening. The remaining 5 sites show both normal (R 71, RN 8) and reversed (R 16, R 17, R 19) polarities. The normal polarity sites belong to upper Miocene – Pliocene sequences and indicate no significant rotations (D = 1.1 ± 12.5°) after tilt correction. However, the three reversed polarity sites belong to upper Miocene sequences and all indicate a mean direction of 19.9 ± 4.7°. The reversed polarity site mean inclination (I = 41.3 ± 5.8°) is lower than the expected inclination (I = ~57.5°, Ankara), likely due to inclination shallowing related to compaction of the sediment, whereas the normal site mean has a steep inclination (I = 62.4 ± 7.4°) after tilt correction. This inclination before tilt correction (I = 52.5 ± 8.6°) is not significantly different from the expected inclination at this latitude and therefore very likely caused by a recent field overprint. The reversal test between the mean normal and reversed results is negative (Figure 5) and we therefore retain only the mean of the reversed sites providing a 19.9 ± 4.7° CW rotation with respect to North for the Upper Miocene rocks of the Kırıkkale-Bala Domain (Supp. Table 1). The fold test applied to Upper Miocene-Pliocene sites (except R19) provides a 95% interval of [8–61%] unfolding for maximum eigenvalues presenting an intermediate (non-negative, non-positive) fold test (Figure 5). This could be interpreted as synfolding acquisition of the NRM, but we believe that this non-positive fold test is caused by the normal polarity being a secondary overprint. This causes one part to be unfolded correctly, but the other, normal part *is* already unfolded.

5.2. Tuz Gölü Domain (TGD)

The Tuz Gölü Domain comprises the southwestern flank of the Kırşehir Block and straddles the Inner-Tauride Suture Zone. It is delimited by the Menderes-Tauride Block in the west. The sampled horizons range from middle Miocene to Pliocene. Except for one disregarded

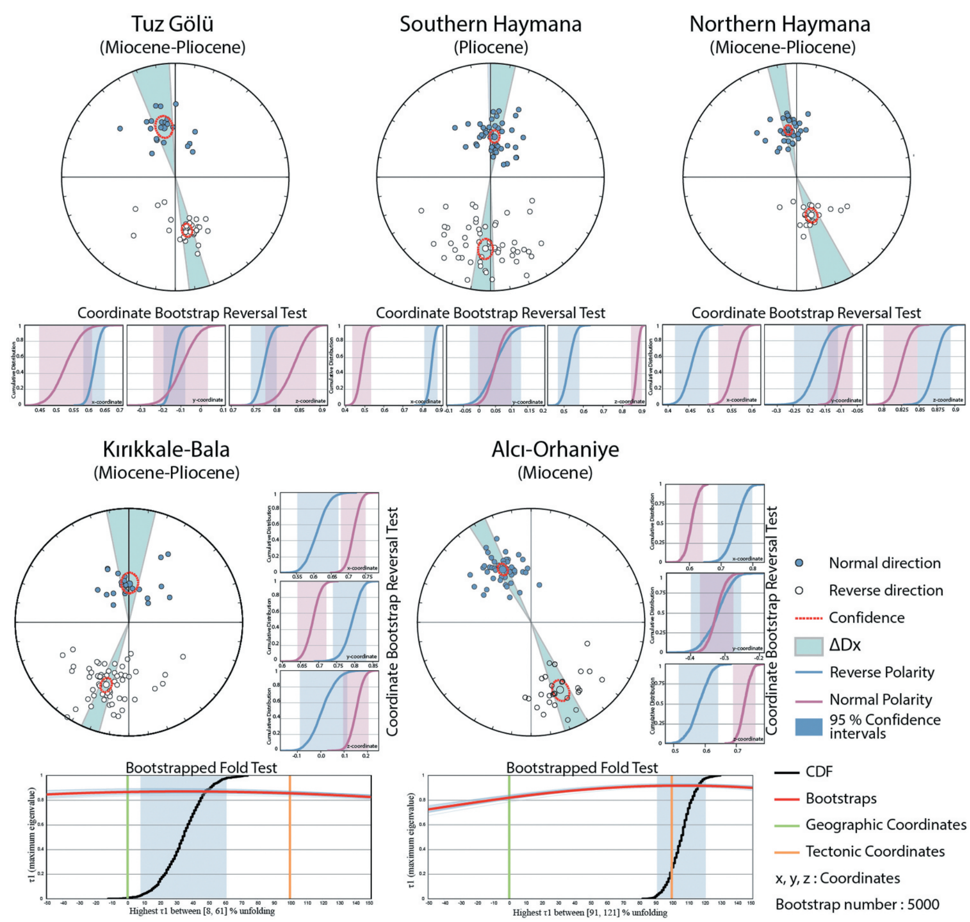

Figure 5. Equal area projection of the ChRM directions for each domain. Closed (open) symbols indicate projection on lower (upper) hemisphere. Red dashed circles denote the mean directions and their cone of confidence (α95). Reversals test results are calculated by the coordinate bootstrap method of Tauxe (2010). Bootstrapped fold tests performed for the Kırıkkale-Bala and Alcı-Orhaniye.

site (R 78) with low number of samples (N = 3) and random directions (k < 10), all other three sites produced statistically meaningful results. In addition, one site (TT8, Oligo. -Miocene in age) is added to the domain from literature (Çinku 2017) and it was parametrically resampled and then combined with our results (Figure 4). The Oligo-Miocene site (TT8, N = 8) shows 327.0 ± 12.9°/60.5 ± 8.3°, declination/inclination values, which indicates an approximately 33° CCW rotation of the site. The remaining two Miocene to Pliocene sites shows normal (R 18, TT8) and reversed (R 84) polarities, all of which indicate coherent CCW rotations. The combined result suggests that the Tuz Gölü Domain underwent ~15 ± 5° average CCW vertical-axis rotation since the Miocene (Figure 4, Supp. Table 1). Considering the limited number of sites for each age, we cannot discriminate differential rotation from Miocene to Pliocene times. However, the reversal test of all three sites produced a positive result (Figure 5), suggesting that no significant differential rotation took place within that age interval and main rotation took place by the end of Miocene – Pliocene.

5.3. Alcı-Orhaniye Domain (AOD)

This Alcı-Orhaniye Domain is located in the northwestern part of the study area, within the Pontide Block. From this domain, we sampled 10 sedimentary sites, of which 6 belong to upper Miocene and 4 to Pliocene sequences. The sites display both normal and reversed polarities. Two sites were disregarded, since they produced no meaningful results, either because of lightning (S 2), a recent remagnetization as indicated by too steep inclination after tilt correction (S 3). Since the domain has a sufficient number of reliable site results for different time intervals, the results are divided into two different time intervals, i.e. for the Miocene and Pliocene ages. The Miocene normal polarity sites indicate a well clustered VGP distribution (K = 19.4, A_{95} = 4.3) and mean ChRM direction of D = 318.4 ± 5.0°/I = 42.1 ± 6.0° after tilt correction (Supp. Table 1), which indicates approximately 42° CCW rotation. Furthermore, the reversed polarity sites (S5 and R30) also present a significant CCW mean rotation (~24° CCW). The reversal test, however, is negative because of very shallow inclinations of the reversed sites (Figure 5). Although they become significantly steeper after tilt correction, the reversal test remains negative. The shallow inclinations are likely caused by insufficient removal of a secondary overprint, but declinations are still indicative of considerable CCW rotation. Combining the normal and reversed Miocene sedimentary sites shows mean direction of D = 325.2 ± 4.2°/I = 40.1 ± 5.4°. This indicates that the Alcı-Orhaniye Domain has rotated about 35° CCW since the Miocene. Furthermore, the remaining three Pliocene sites (S 4, R 28, R 29) have normal magnetization directions, and they also produced significant rotations, around 22° CCW (D = 337.7 ± 5.5°). In addition, the fold test is positive and shows a 95% interval of [91–121%] unfolding for maximum eigenvalues (Figure 5). Additionally, three volcanic localities from Piper *et al.* (2010) of Miocene (Tekke, Mamak) and-Pliocene (Bozdağ) age also indicate CCW rotation (Supp. Table 1). The mean of the combined analysis of volcanic sites of Piper *et al.* (2010) and our single basalt site (R13) indicate approximately 14° CCW rotation. However, the error in declination values is quite large (D = 345.8 ± 33.7°) implying that the rotation can be considered as similar – within error – to the sedimentary sites. In conclusion, all these results indicate that the mean of Pliocene sites are slightly lower than the Miocene sites implying that rotation started during the Late Miocene and continued throughout the Pliocene.

5.4. Northern Haymana Domain (NHD)

The Haymana Basin is traversed by the Yenimehmetli Fault (Figure 1), a strike-slip fault that compartmentalized the basin into two domains. Therefore, the northern and southern parts of the basin are analysed separately. The Northern Haymana Domain is delimited in the northeast by the Hirfanlar Hacıbektaş Fault and in the south by the Yenimehmetli Fault (Figure 1). In the west, it is covered with Late Miocene-Pliocene gypsum bearing lacustrine deposits. It comprises four palaeomagnetic sites; one site (R 31) from the Miocene and three sites (R 24, R 27) from the Pliocene. The Miocene site mean yields a ~ 10° CCW rotation with a small error (D = 350.2 ± 4.9°). The three Pliocene sites have both normal (R 27 and R32) and reversed (R 24) polarities. The combined Mio-Pliocene directions resulted in D = 347.9 ± 3.8°, which indicate approximately ~12° CCW mean rotation for the domain, contrary to the results obtained from the Pliocene localities in the Southern Haymana Domain (Figure 4, Supp. Table 1), see below. The reversal test was applied to tilt corrected data, but it is found to be negative (Figure 5).

5.5. Southern Haymana (SHD)

The Southern Haymana Domain is delimited in the NE by the Hirfanlar-Hacıbektaş Fault Zone, Yenimehmetli Fault in the NW and Inner-Tauride Suture in the west and Ankara-Erzincan Suture in the east. The domain comprises 13 sedimentary sites, 5 of which belong to the Middle Miocene and the remaining 8 sites belong to

Pliocene sequences (Supp. Table 1). In addition, two volcanic layers (R 45 and R 46, Miocene basalt lavas, Temel *et al*. 2010) were also sampled in the domain. Each volcanic site contains at least seven different lava layers. All of the Miocene sedimentary sites show normal polarities. Four of them were disregarded for final analysis since they present scattered NRM directions in three sites (SF 2, SF3 and SF 5) and site SF 6 seems to be remagnetized by the recent magnetic field after deposition. The remaining site R 4 is located in the southwesternmost of the study area and shows a well-clustered distribution ((Figure 4, Table 1) which gave a quite large mean rotation after tilt correction compared to in-situ rotation result. The site yielded D = 326.0 ± 8.0°/ I = 57.2 ± 5.9° indicating an approximately 34° CCW rotation since the Miocene. The South Haymana Domain includes two volcanic sites, but site R 46 shows nearly horizontal inclinations after tilt correction and is disregarded. The remaining site (R 45) indicates reversed polarity with mean directions of D = 209.1 ± 8.3°/ I = −23.7 ± 14.3°. This indicates approximately 30° CW rotation, opposite to the nearby sedimentary site (R 4).

For the Pliocene rotation history of the domain, 8 sites are sampled. They show both normal and reversed polarities. Two sites (SF 1, SF 3) were disregarded due to the scattered nature of the NRM directions (Figure 4). The site R 3 shows normal polarity with a mean direction of D = 16.3 ± 12.5°, which indicate approximately ~16° CW rotation for the domain. The remaining 5 sites have reversed polarity, and similarly, they also show CW rotation (D = 4.1 ± 5.9°) after tilt correction. This is almost in line with the results from the Pliocene Polatlı lavas (Piper *et al*. 2010, Supp. Table 1) which show a small CW rotation. As a conclusion, the Southern Haymana Domain indicates, on average, no significant rotation (D = 4.0 ± 4.9°) since the Pliocene. The only successful Middle Miocene site (R4) is most likely not representing the Miocene rotation history of the domain, since it is west of the IASZ.

6. Evaluation of published data

Magmatic rocks are primary palaeomagnetic recorders because of their nature. On the other hand, their paleohorizontal in uncertain and because of rapid cooling they represent only a spot reading of the magnetic field, requiring a long sequence of lava flows to average out PSV. Clastic rocks contain low magnetic mineral content, but provide an advantage in continuous recording of the field. Therefore, the results obtained by taking samples from both magmatic and clastic rocks can in practice not really be compared (the results of one lava flow counts as one sedimentary specimen).

Several palaeomagnetic results have been published in the study area. Most of these studies are based on magmatic rocks except for a few sedimentary studies. The studies on the magmatic rocks are mainly concentrated on two large Neogene volcanic provinces, namely Central Anatolian Volcanic Province and Galatean Volcanic provinces, and the granitic rocks (of much older Upper Cretaceous age) within the Kırşehir Block. The studies on the sedimentary rocks are concentrated mainly on the Çankırı Basin. We have evaluated each rock type and tectonic domain in detail below.

6.1. Central Anatolian Volcanic Province (CAVP)

In the south-easternmost part of the study area, the Central Anatolian Volcanic Province consists of Neogene to Quaternary ignimbrites, basalt flows covered by epiclastic lacustrine sequences (Aydar *et al*. 2013). Miocene to Quaternary palaeomagnetic results from the CAVP belongs to three different studies (Gürsoy *et al*. 1998; Platzman *et al*. 1998; Özçep 2010). These studies include various lava levels from three different sites spanning from Middle Miocene to Quaternary. They produced very consistent CCW results. The integrated results from all sites indicate that the region has rotated about 12 ± 6° CCW since the middle Miocene to Quaternary (Figure 6, Supp. Table 2).

6.2. Galatean Volcanic Province (GVP)

The Galatean Volcanic Province is located at the northwest of the study area and comprises Neogene volcanic rocks (Toprak 1994, 1998; Wilson *et al*. 1997; Tankut *et al*. 1999). Gürsoy *et al*. (1999), Çinku and Orbay (2010) have studied the region and they reported results from five different localities belonging to Neogene rocks (Figures 1 and 6). The locality (AYS) comprises two different sites and shows anomalously low inclinations and large declination differences (D = 247.0 ± 3.3°/I = 7.2 ± 6.5°), due to potentially paleohorizontal and/or secular variations problem. Therefore, we rejected these sites for further analysis from our database (Table 2). The BYP locality includes 3 distinct lava levels and their combined results produced D:65.6°, I = 63.6°, implying a very large (~65°) CW rotation. The KBR locality contains 9 lava levels and 2 andesitic suits, combined results of which indicate ~18.5° CW rotation (Table 2). Unlike other localities in the region, site ST has reversed polarity but it also indicates a CW rotation of 31° (Table 2). The KCH locality has 8 different lava levels and mean rotation results indicate a very significant CCW rotation amount (~36.5°) unlike other sites in the GVP. Combined analysis of only CW sites indicates

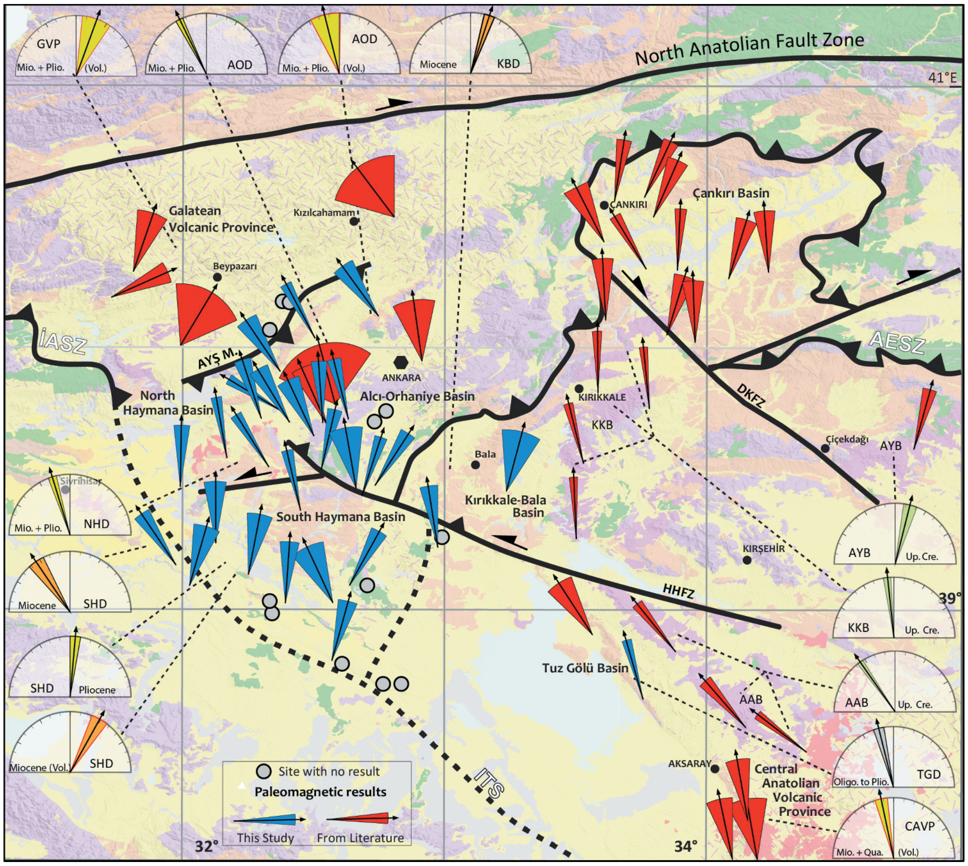

Figure 6. Arrows show individual site results both from this study (blue) and literature (red). Domains and associated vertical axis rotations are denoted as arrows on equal area projection with their 95% error envelope (ΔDx).

27° CW rotation while combination of all four sites indicate ~20.0° CW rotation in the GVP since the Upper Miocene-Pliocene (Table 2, Figure 6).

6.3. Çankırı Basin (ÇB)

The Çankırı Basin is located at the northeasternmost part of the study area, at the northern tip of Kırşehir Block, where Ankara-Erzincan Suture Zone makes an omega-shaped northwards convex bend. The area comprises 11 sedimentary sites ranging from Middle to Upper Miocene belonging to three different studies (Kaymakcı *et al*. 2003a; Lucifora *et al*. 2013; Çinku *et al*. 2016). According to Kaymakcı *et al*. (2003a), prior to Middle Miocene, the basin underwent CCW and clockwise (CW) rotations in its western and eastern margins, respectively, due to the indentation of the Kırşehir Block. We have parametrically resampled the results of these studies and found out that 5 of the 11 sites show reversed polarity, and their mean rotation amount is changing from ~27° CCW to ~22° CW (Supp. Table 2). Similarly, the remaining 6 normal polarity sites show both CW (max = 25.6°) and CCW (max = 30.8°) rotations. The internal deformation and its changes in rotations preclude a meaningful reversal test,

6.4. Kırşehir Block

The Kırşehir Block is one of the largest metamorphic terranes in Central Turkey and is bordered by the Ankara-Erzincan Suture Zone in the north, the Tuz Gölü Fault Zone in the west, and the Inner-Tauride Suture Zone in the south and east. Lefebvre *et al*. (2013) studied the plutonic rocks of the block and proposed 3 different rigid fault blocks that deformed independently during the Late Cretaceous to Tertiary. These three fault blocks of the Kırşehir Block are separated by approximately NW-SE striking fault zones developed possibly by the end of Cretaceous as normal faults providing accommodation space for Çiçekdağı and Ayhanlar basins (Figure 1). The fault blocks of the Kırşehir Block, from south to north include Ağaçören-Avanos Block (AAB). It is delimited in the north by the Haymana-Hirfanlar Fault Zone. Kırşehir-Kırıkkale Block (KKB) constitutes the middle part of the

Kırşehir Block and it is delimited in the north by the Haymana-Hirfanlar Fault Zone while Delice-Kozaklı FZ delimits it in the north. The northern block of the Kırşehir Block is the Akdağ-Yozgat Block (AYB). It is separated from the other blocks of the Kırşehir Block by the Delice-Kozaklı FZ in the south. Lefebvre *et al*. (2013) proposed 35° CCW for the AAB, 6° CCW rotations for the KKB and 15° for the AYB (Supp. Table 2, Figure 6).

7. Discussion

7.1. Neogene Block rotations in Central Anatolia

The new palaeomagnetic results from more than 900 specimens collected from 40 new sites are documented here, as well as existing literature data reported from 27 sites, which we assessed and parametrically resampled in order to homogenize and unify them with our data. They are altogether used to developed rotational evolutionary scenarios of central Anatolia and to reconstruct the Neogene geometry of Neotethyan sutures in Turkey.

All palaeomagnetic results covering Miocene to Quaternary sedimentary and volcanic rocks are considered to be of primary magnetization demonstrated by demagnetization results, consistency between sites after tilt correction, rock magnetic analysis, PSV check). Of the 40 analysed sites, 11 (~27%) were rejected due to scattered ChRM directions, lightening effect, and inconsistent demagnetization behaviour marked in Supp. Table 1.

The remaining 73% of the data meet the criteria, and we regard them as reliable and interpretable. The reliable data are separated into subgroups based on the tectonic domain they belong. Eighth domains are recognized in this study. These are Kırıkkale-Bala Domain (KBD), Tuz Gölü Domain, (TGD), Alcı-Orhaniye Domain (AOD), Northern Haymana Domain (NHD), Southern Haymana Domain (SHD), Central Anatolian Volcanic Province (CAVP), Galatian Volcanic Province (GVP), and Çankırı Basin (Supp. Table 1 and 2, Figures 6 and 7). The boundaries of these domains are defined by a major structure such as suture zones or a well-developed fault zones (Özsayın and Dirik 2007; Lefebvre *et al*. 2013; Gülyüz *et al*. 2019).

The Kırıkkale-Bala Domain partly belongs to Kırşehir-Kırıkkale Block (KKB) while Tuz Gölü Domain lies within the Ağaçören-Avanos Block (AAB) (Lefebvre *et al*. 2013).

According to our rotation results, two of our localities (R 18 and R 71, Figure 1) located within the KKB of Lefebvre *et al*. (2013) indicate CW and CCW rotation. It is possible that these two localities are caught within the Hirfanlar-Hacıbektaş Fault Zone (Lefebvre *et al*. 2013) and produced opposite rotations (Figure 6). The combined results from Kırıkkale-Bala Domain indicate a mean CW rotation of ~18° by the Late Miocene (Supp. Table 1), contrary to the approximately ~6° CCW (negligible) rotation obtained from the Late Cretaceous-Palaeogene intrusive suits of the KKB (Lefebvre *et al*. 2013).

According to Lucifora *et al*. (2013), the Çankırı Basin shows various normal and reversed directions indicating CW as well as a few CCW rotations. However, Kaymakcı *et al*. (2003a) argued that there is no net rotation during the Middle Miocene onwards in the Çankırı Basin, despite some sites with rotations and they are mostly related to local structures. Therefore, we combined all the sites from the Çankırı Basin and analysed them. The normal polarities indicates no net rotations (D:1.6 ± 5.1°) while reversed polarity sites indicate approximately ~8° CW rotations. Nevertheless, combined analysis of all sites indicates approximately no net rotation in the Çankırı Basin (Supp. Table 2, Figure 6) as suggested by Kaymakcı *et al*. (2003a). The Çankırı Basin is associated with the Akdağ-Yozgat Block (AYB) of Lefebvre *et al*. (2013), and they reported that the Upper Cretaceous intrusive suits within the block rotated ~15° CW. Having no net rotations in the Çankırı Basin indicate that the rotation of AYB took place prior to late Miocene.

Among the four sites from the Tuz Gölü Domain, only three sites produced reliable results. Combined analysis of these sites indicates that approximately ~14° CCW rotation of the domain. The Tuz Gölü Domain is located within the Ağaçören-Avanos Block of (Lefebvre *et al*. 2013) Late Cretaceous intrusive suits of which rotated approximately ~35° in CCW sense. Our results indicate a similar sense of rotation, whereas they are almost half the rotation of the AAB. Similarly, palaeomagnetic studies carried out in the Central Anatolian Volcanic Province (e.g. Gürsoy *et al*. 1998; Platzman *et al*. 1998; Özçep 2010), which is located within the AAB also shows approximately ~ 12° CCW rotation since the middle Miocene. All these results indicate that almost half of the amount of CCW rotations of the AAB took place since the Miocene and onwards and the remaining −20° CCW rotation took place prior to Miocene.

The results of Alcı-Orhaniye Domain indicate ~35° CCW rotations for the upper Miocene and ~22 CCW rotations for the Pliocene sequences. This relationship indicates that the rotations in the domain started in the Late Miocene and only about ~13° CCW rotation took place. However, the main rotation took place by the Pliocene.

The Northern Haymana Domain rotated ~12 in CCW sense while rotation amounts in the Southern Haymana Domain range from ~34°CCW since the Miocene, though only based on one site only, to almost no net rotation (4.6 ± 5°) since the Pliocene.

The results from Galatean Volcanic Province indicate ~20° CW rotations (Gürsoy *et al*. 1999; Çinku and Orbay 2010) contrary to the nearby Alcı-Orhaniye and Haymana domains (Supp. Table 2, Figure 6).

7.2. Temporal relationships

Our palaeomagnetic data combined with parametrically bootstrapped literature data show that rotational deformation in Central Anatolia is a continuous process since late Cretaceous times and various rotation amounts and senses took place in different domains of the region. There are significant variations both in the senses, and the amounts of the vertical-axis block rotations since the early Miocene, and in some domains rotations took place during the Early Miocene and lasted until Pliocene while some took place after the Pliocene (Figure 7).

For the Kırıkkale-Bala Domain, there is only data for the Upper Miocene to Pliocene time interval because available age data do not allow better age resolution for the sampled horizons in the domain. However, TT8 site of Tuz Gölü Domain (Çinku *et al*. 2016) indicate 33° CCW rotation of the Oligo-Miocene sequences while our Miocene and Pliocene sedimentary sites indicate ~12° CCW rotations. This relationship indicates that CCW rotation started before the Late Miocene and continued afterwards. Rotation amount of the TT8 site is almost equal to the rotation amount of AAB of Lefebvre *et al*. (2013), implying that the rotation of the block took place by the Miocene and continued onwards.

Rotation amounts in the Alcı-Orhaniye Domain are virtually the same, considering the error margins for Miocene (D:332.4°± 4°) and Pliocene (D:337.7°± 5.5°) sequences. This relationship indicates that the main rotations in the domain took place after the Late Miocene.

The Northern Haymana Domain comprises three Pliocene and one middle Miocene sites. The results of all sites are virtually equal to each other, implying that rotations took place post-Miocene times. Combined analysis of all sites indicates ~12° CCW rotation for the Northern Haymana Domain during Pliocene.

Only one Miocene site produced reliable results from the Southern Haymana Domain which indicates an ~34° CCW rotation, while Pliocene sites indicate no significant rotation, implying that rotations took place prior to Pliocene.

In conclusion, obtained rotation amounts, senses, and their timing indicate that rotational deformation of the Central Anatolia is diachronous and it cannot be constrained to a specific single time interval.

7.3 Regional implications and kinematic restorations

The main elements of the continental collision in the Central Anatolia include Kırşehir, Pontide, and Menderes-Tauride blocks. Various scenarios related to collision and further convergence of the region have been proposed in the literature. These scenarios can be classified into two groups; 1) Collision of Kırşehir Block as a rigid indenter into the Pontides along the İzmir-Ankara -Erzincan Suture Zone (Kaymakcı *et al*. 2003b; Meijers *et al*. 2010; Çinku *et al*. 2011, 2016), 2) collision and fragmentation of non-rigid magmatic arc model (Lefebvre *et al*. 2013).

Among these, the rigid Kırşehir Block models generally emphasize how and when the subduction and collision occurred in Central Anatolia and considered the deformation at the southern margin of the Pontides (Kaymakcı *et al*. 2003a; Meijers *et al*. 2010; Çinku *et al*. 2011, 2016) and folding of the Tauride-Menderes Block around rigid Kırşehir Block (Çinku *et al*. 2016). The non-rigid Kırşehir model of Lefebvre *et al*. (2013) nicely illustrated how the Kırşehir Block was segmented and deformed during N-S shortening. Still, it fails to explain the timing of deformation and rotation of the basins around each block.

One of the main outcomes of this study is documentation of the diachronous nature of the rotational deformation in Central Anatolia and providing temporal and spatial constraints on the matter. Clearly, a uniform rotational history model with consistent CCW rotations for Central Anatolia since the Late Miocene (Kissel *et al*. 2003; Piper *et al*. 2010; Koçbulut *et al*. 2013; Çinku *et al*. 2016) is not a valid simplification since the region was subdivided into smaller tectonic domains that have undergone variable rotation amounts and senses since the Miocene.

The obtained results are used to restore the geometry of central Anatolia and the Neotethyan Suture Zones. As seen in Figure 7, the İzmir-Ankara Suture Zone (İASZ) becomes almost E-W oriented compared to its present configuration, while the Inner-Tauride and Ankara-Erzincan suture zones become N-S oriented, although the change in the geometry of the suture zones is very small, but they are significant in term of the activity and timing of the block bounding faults. The results show that Delice-Kozaklı (DKFZ), Hirfanlar-Hacıbektaş fault zones (HHFZ) were active during the Pliocene, and possibly they are still active until present, while the Yenimehmetli Fault (Gülyüz *et al*. 2019) was deactivated by the Pliocene. The deformation of the basin at the periphery of the pieces of Kırşehir Block seems to be

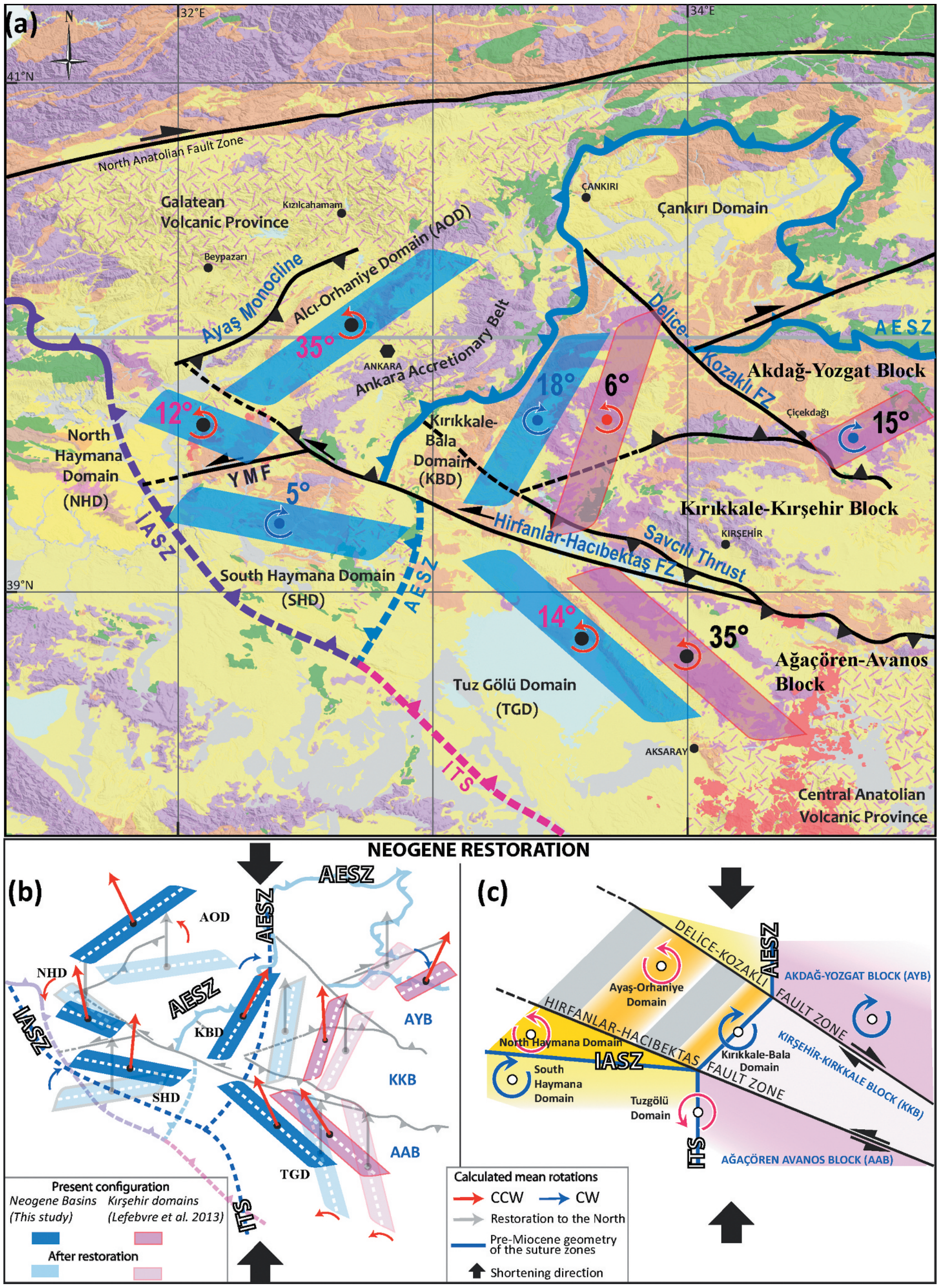

Figure 7. Kinematic restorations of Central Anatolia and Neotethyan Suture in central Anatolia. a) Rotation amounts and representative blocks for each domain with before and after restoration. Restoration scenario for b) Miocene and c) Pliocene time intervals with major faults and fault blocks that controlled the deformation in the region. Highlighted domains are present-day configuration, and three purple blocks are after Lefebvre *et al*. (2013). Faint blocks are configurations before rotation took place. Red arrows indicate CCW rotation. Blue arrows show CW rotation. Faint black arrows represent the present-day geographic north direction. IASZ: İzmir-Ankara Suture Zone, AESZ: Ankara-Erzincan Suture Zone, ITS: Inner-Tauride Suture.

related to the relative motions of these blocks. For example, Kırıkkale-Bala and Alcı-Orhaniye domains clearly deformed internally and rotated due to relatively westwards movement of the Kırşehir-Kırıkkale Block (Figure 7(b)); a V-shaped block (c.f. Yin and Taylor 2011) moving along sinistral HHFZ and dextral in an NW direction while it is being squeezed in an N-S direction (Figure 7(c)).

8. Conclusions

Palaeomagnetic results from 40 new sites and 27 previously published sites show evidence for a significant amount of rotations in Central Anatolia since Miocene. The main findings of this study are summarized as follows:

In addition to the previously published three separate fault blocks of the Kırşehir Block, five new tectonically distinctive domains are determined in this study. 1) Late Miocene strata in the Kırıkkale-Bala Domain rotated ~14° CW by the Late Miocene, 2) the late Miocene strata in the Tuz Gölü Domain rotated ~15° CCW by the Miocene, 3) Late Miocene sequences rotated approximately ~27° CCW in the Alcı-Orhaniye Domain while Pliocene sequences rotated approximately ~22 CCW indicating that the main CCW rotation phase took place after the Miocene in this domain, (4) Late-Miocene to Pliocene sequences in the Northern Haymana Domain rotated ~12° CCW, and (5) only one site produced reliable results from the Miocene sequences in the Southern Haymana basin, and Pliocene sequences underwent no significant rotation.

The orientation of the Neotethyan Suture Belts in the region prior to the late Miocene is restored. It is found that the orientations of the Inner-Tauride and Ankara-Erzincan suture zones become almost N-S.

Highlights

- Block rotation in Central Anatolia was revealed by paleomagnetic analysis.
- Five new distinct tectonic domains were proposed in the region.
- The main factor causing these rotational differences is the deformation of the Kırşehir Block which was active since Neogene.

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Disclosure statement

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