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Post-Miocene Deformation in the South of the Galatean Volcanic Province, NW of Central Anatolia (Turkey)

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Abstract: Central Anatolia, located on the immense Alpine-Himalayan orogenic belt, has a complicated neotectonic evolution, and NE–SW-trending Neogene horsts-graben systems that rejuvenate pre-existing palaeostructures are among the most important structures which help us understand the tectonic evolution of Central Anatolia.

Post-Miocene deformational studies were carried out in Miocene–Quaternary sequences situated at the southeastern margin of the Galatean Volcanic Province (NW of Central Anatolia, Turkey) in order to understand the deformational history of Central Anatolia.

The structural analyses were based on bedding attitude data and fault plane slip data. Fold analysis in Miocene units gave an asymmetrical fold axis trending 046°N. Although there is a clear angular unconformity between the Upper Miocene and Plio–Quaternary sequences, similar fold analysis in the Plio–Quaternary clastics revealed a symmetrical open fold attitude trending 040°N, thus indicating an almost identical trend for all the post-Miocene folds.

Stress analyses were performed by processing fault plane slip lineation data, using the Angelier Inversion Method. In the analyses, no reliable results could be obtained for the post-Miocene–pre-Pliocene compressional period. But the results of the post-Plio–Quaternary period strongly revealed a continuous extension from NW–SE to NNE–SSW directions since the Pliocene.

Stress analyses together with the field observations showed that the area has evolved structurally in several phases of deformation since the Late Miocene. The NW–SE-directed post-Miocene compression, based on fold analysis and field observations, was followed by a regional NW–SE to NNE–SSW multi-directed extension, based on slip-data analyses, operating since the Pliocene.

Key Words: palaeostress analysis, extensional tectonics, neotectonics, Late Miocene–Plio-Quaternary, Anatolia

Galatya Volkanik Bölgesinin Güneyinde Miyosen Sonrası Deformasyon, KB Orta Anadolu (Türkiye)

Özet: Devasa Alpin-Himalaya Dağoluşum Kuşağında yeralan Orta Anadolu'nun karmaşık sayılabilecek bir neotektonik evrimi vardır. Bu karmaşık evrimde varolan eski yapıların üzerine KD–GB gidişli Neojen yaşlı yükselimler ve çöküntüleri Orta Anadolu'nun tektonik evriminin anlaşılmasında önemli yapılardır.

Orta Anadolu'nun deformasyonunun anlaşılması maksadı ile yapılan Miyosen sonrası deformasyon çalışması Galatya Volkanik Bölgesinde yeralan Miyosen–Kuvaterner sekanslarında sürdürülmüştür.

Yapısal analizler tabaka eğim ve doğrultu ve fay düzlemi kayma verileri temelinde yapılmıştır. Miyosen birimleri üzerine yapılan kıvrım analizleri 046°K yönelimli asimetrik bir kıvrım ekseni vermiştir. Her ne kadar Geç Miyosen ile Pliyo–Kuvaterner sekansları arasında net bir açısal uyumsuzluk var ise de benzer şekilde Pliyo–Kuvaterner birimlerinde yapılan kıvrım analizlerinden tüm Miyosen sonrası için 040°K yönelimli simetrik açık kıvrımlanma gözlenmiştir.

Stres analizleri 'Angelier Inversion' yöntemi kullanılarak fay düzlemi kayma verileri ile yapılmıştır. Bu analizlerden Miyosen sonrası–Pliyosen öncesi sıkışma dönemi için güvenilir sonuçlar elde edilememiştir. Fakat Pliyosen sonrası–Kuvaterner dönemi için yapılan analizler neticesinde Pliyosen den itibaren KB–GD'dan KKD–GGB'ya değişen sürekli bir genişlemenin varlığı kuvvetle ortaya konmuştur. Arazi gözlemleri ile birlikte stres analizleri alanın yapısal olarak Geç Miyosen'den itibaren pek çok deformasyon evreleri ile geliştiğini göstermiştir. Bölgenin evrimi kıvrım analizleri ve arazi gözlemlerine göre Geç Miyosen sonrası KB–GD yönelimli sıkışma, kayma verileri analizlerine göre ise Pliyosen'den itibaren KB–GD'dan KKD–GGB'ya çok yönlü genişleme rejimi ile devam etmiştir.

Anahtar Sözcükler: paleostres analizleri, genişlemeli tektonizma, neotektonik, Geç Miyosen–Pliyosen, Anadolu

Introduction

The research area is a part of the Galatean Volcanic Province (GVP) (Toprak *et al.* 1996) where important geological and tectonic events were recorded in a composite array. The GVP is situated on an Upper Cretaceous accretionary complex and bounded on the north by an intercontinental shear zone – North Anatolian Fault Zone (NAFZ) (Figure 1). Geographically, the area is located 40 km northwest of Ankara (Central Anatolia, Turkey) and contains economic mineral deposits including: (i) the Kazan trona deposit to the south, (ii) the Beypazarı trona deposit and (iii) Çayırhan coal deposit to

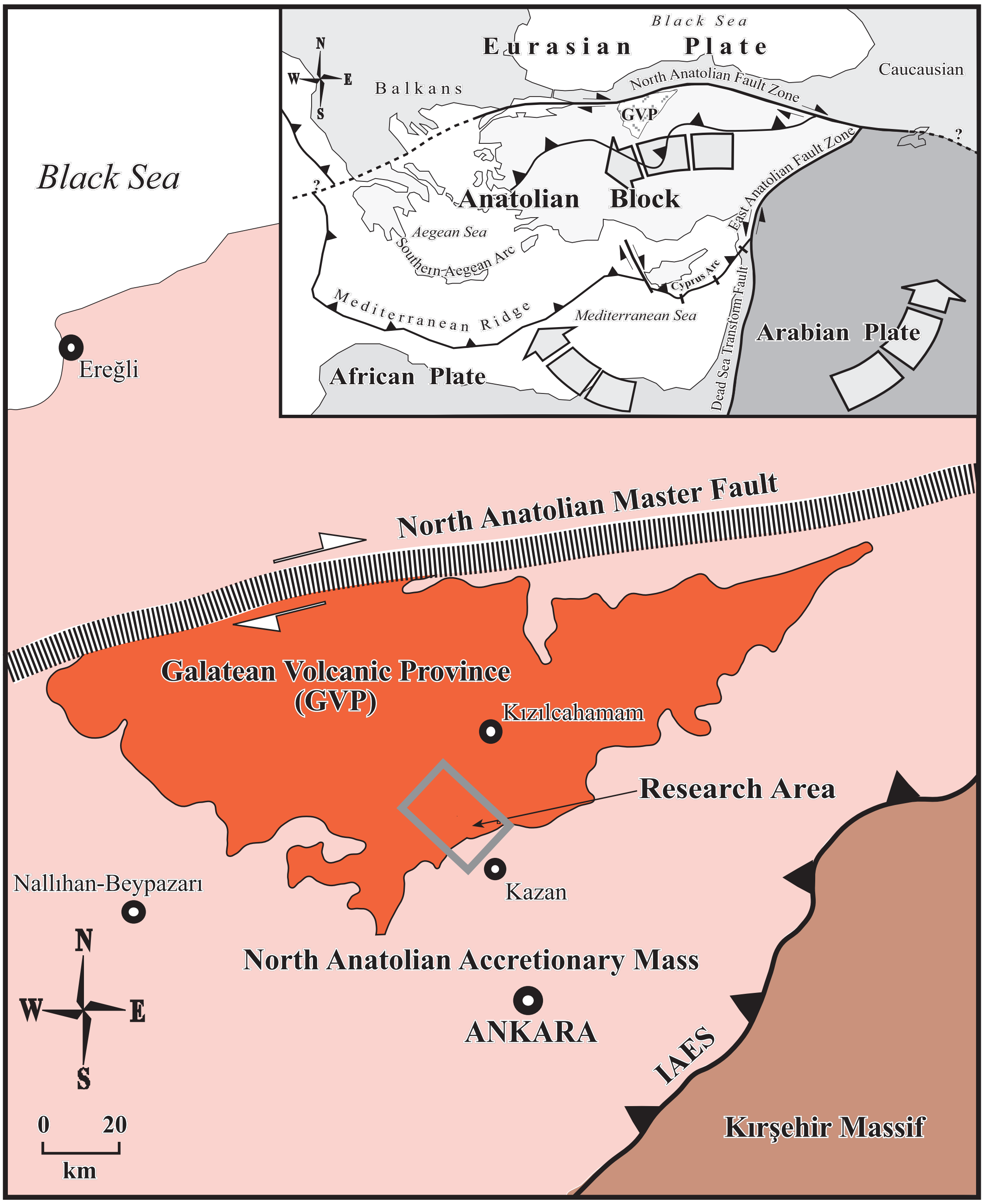


Figure 1. Neotectonic setting of Eastern Mediterranean and GVP (Inset map) with regional geological setting of the research area. İAES– southern limit of the İzmir-Ankara-Erzincan suture belt.

the southwest, (iv) the Çeltikçi (Kızılcahamam) coal deposit to the northwest and (v) the Kızılcahamam geothermal field to the northeast of the research area. Thus, the study area is situated in a geologically and economically important region.

Radiometrically well-dated volcanism and associated palaeontologically dated stratigraphic sequences make the structural analysis more meaningful. This paper aims to analyze the deformational structures since the Miocene in an area NW of Ankara (Central Anatolia, Turkey) where various views about the Neogene deformational history have been proposed.

Total consumption of the northern Neotethys oceanic crust and the collision of the Eurasia + Sakarya Continent with the Tauride-Anatolide platform took place diachronously from the Late Mesozoic until the end of the Early Palaeogene (Şengör & Yılmaz 1981). During and after the collision, continental to shallow marine conditions predominated in central Anatolia. The collision marks the end of the Neogene period and beginning of a new tectonic era – the neotectonic period– in the region where proto-Anatolia was developed (Şengör *et al.* 2004).

The complicated tectonic evolutionary history of Anatolia was then over and Anatolia acquired its present geography as a result of its overprinted geological history by the end of Miocene. It is a mixture of several amalgamated pre-Alpine and Alpine microcontinents; remnants of consumed oceans as tectonic belts (as ophiolitic slivers and tectonic mélanges), magmatic arcs, massifs (e.g., Menderes Massif, Kırşehir Massif) and finally a vast collection of tectonically controlled Neogene basins filled with sedimentary sequences that are mostly interbedded with volcanics.

The interbedded sequences of volcanics/volcaniclastics and terrestrial sediments imply that the palaeogeographic depositional setting was continental, with lakes around terrestrial volcanic vents in an inter-arc depositional system along the İzmir-Ankara Suture Belt in central Anatolia during the Neogene period (Gökten *et al.* 1988; Koçyiğit *et al.* 1988; Erol 1993). The alkaline lakes in particular covered quite large areas northwest of Ankara. Volcanism, dominantly calc-alkaline, was initiated and affected all of central Anatolia. This well-known volcanism created the Galatean Volcanic Province.

Volcanic products of this volcanism were called the 'Kızılcahamam volcanics' or 'Köroğlu volcanics' (Türkecan *et al.* 1991), or the Galatean Volcanic Massif (Gökten *et al.* 1996). However, the informal but tectonically exact name 'Galatean Volcanic Province' (Toprak *et al.* 1996) is preferred here.

The geodynamic-volcanic evolution of the GVP is extensively discussed with radiometric dating and geochemical analyses. The age of volcanism ranges from Paleocene to latest Miocene (Keller *et al.* 1992; Koçyiğit *et al.* 2003a) or may be solely Miocene (Türkecan *et al.* 1991; Tankut *et al.* 1995; Wilson *et al.* 1997).

Two stages of volcanism with different tectonic settings in the GVP are recorded by various researchers (Türkecan *et al.* 1991; Tankut *et al.* 1995; Gökten *et al.* 1996; Wilson *et al.* 1997; Adıyaman *et al.* 2001; Koçyiğit *et al.* 2003a). The volcanism is interpreted as being generated from a subducting slab and a rifting process related to subduction in two intermittent or successive stages. The older volcanic cycle, which is the major phase, is calc-alkaline in composition, ranging from K-rich basaltic trachyandesite to rhyolite with minor occurrences of alkali-basalts (Türkecan *et al.* 1991). The main volcanic cycle occurred between 25 Ma and 10 Ma (Early–Late Miocene) (Türkecan *et al.* 1991; Wilson *et al.* 1997), but other volcanics may be much older (e.g., Paleocene, 65 Ma: Koçyiğit *et al.* 2003a) or post-Lutetian (Gökten *et al.* 1996)). The older volcanism is interpreted as sourced from lithospheric mantle that was modified by earlier subduction during the first volcanic cycle of the GVP in the northern Neotethys. The parental magmas of this volcanism in the Galatean province were generated in a post-collisional tectonic setting from a previously subduction-modified mantle source (asthenospheric mantle) (Tankut *et al.* 1990, 1998; Gökten *et al.* 1996; Adıyaman *et al.* 2001). This latest cycle, erupted between 11–8.5 Ma, consists of a small volume of alkali basaltic flows capping the older volcanic sequences (Türkecan *et al.* 1991). These Upper Miocene alkaline basalts of the latest phase in the GVP simply correspond to typical rift volcanism related to extensional tectonics. Hence the Mid-Miocene hiatus in volcanic activity in the area strongly suggests a major change in geodynamic setting as manifested by changes in both eruptive style and geochemical characteristics of the volcanics.

The other feature of the Neogene evolution of the GVP is the stratigraphy of Neogene sedimentary sequences. The sedimentary rocks intercalated with volcaniclastics/volcanics accumulated between the Early and Late Miocene in a region where some of the researchers proposed continuous Miocene to Pliocene sedimentation (e.g., Akyol 1968; Tatlı 1975; Turgut 1978; Yağmurlu *et al.* 1988).

Following the classical work of Erol (1961) (reporting that a gradual weakening in the Alpine orogenic movements in the region during the Neogene and Quaternary, with the faults and folds generally having WSW to ENE trends in the west and SW to NE trends to the east of Ankara) nothing was done on the tectonic evolution of the central Anatolia until the 1980s. Following the 1980s, the tectonics of the Central Anatolia gained in importance because of the discovery of industrial ore deposits in the region. The studies mostly focused on the evolution of the Neogene basins that enclose these deposits and the neotectonics of the region (e.g., Yağmurlu *et al.* 1988; Türkecan *et al.* 1991; İnci *et al.* 1988; İnci 1991; Koçyiğit 1991, 1992; Koçyiğit *et al.* 1995; Gökten *et al.* 1988, 1996; Seyitoğlu *et al.* 1997; Helvacı 1998; Süzen & Toprak 1998; Rojay *et al.* 2002; Özsayın *et al.* 2005).

Moreover, much more solid data came from palaeostress analyses done in the region in order to clarify the order of Neogene to Quaternary deformational events (Toprak *et al.* 1996; Demirci 2000; Kaymakcı 2000; Toprak & Rojay 2000, 2001; Demirci *et al.* 2001; Yürür *et al.* 2002; Koçyiğit *et al.* 2003b). These studies covered a vast area of central Anatolia between Çayırhan-Beypazarı in the west and Çankırı in the far east. Demirci (2000) proposed three main deformational phases during the Miocene in the Beypazarı-Kızılcahamam area: (1) Early Tortonian E–W compression; (2) Tortonian to Late Tortonian (radiometric age dating: 7.7 Ma) N–S compression; (3) Post-7.7 Ma E–W extension between Çayırhan and Kızılcahamam. However, Kaymakcı (2000) and Kaymakcı *et al.* (2000, 2003) proposed an Early–Middle Miocene extensional system, followed by Late Miocene–Recent transpression in the Çankırı area (in the far NE of the Ankara region). In another study, Yürür *et al.* (2002) produced evidence for (i) two basic deformational periods, with almost N–S (NNE–SSW and NW–SE to NNW–SSE) extension throughout the Miocene, and (ii) a deformation linked to the activation of the NAF during the Pliocene in the Kızılcahamam area. They interpreted the Miocene extension in the GVP and the Aegean Extensional Province as a single linked event. Toprak & Rojay (2000, 2001) proposed three deformational phases occurred since the Late Miocene in the Kazan area (northwest of Ankara). They interpreted the first two deformational periods as overprinted, almost E–W compression and almost N–S compression, with the younger showing purely N–S compression, and noted a post-Miocene clockwise rotation. The last deformational period was interpreted as Plio–Quaternary NNE–SSW extension. Finally, Koçyiğit *et al.* (2003b) proposed a wide range of (NE–SW to NW–SE-oriented) extension (oblique-slip normal faulting) for the last deformational period (Late Pliocene–Quaternary) across the entire Ankara region.

The Kazan sector was chosen as a research area in order to add more solid data to the history of deformation in Central Anatolia where the Neogene sequences are clearly dated.

Stratigraphy and Age

Unconformity bounded stratigraphic units of the research area were lithologically differentiated, stratigraphically reconstructed and classified into four major rock groups: (1) pre-Miocene basement rocks, (2) Miocene units, (3) Plio–Quaternary clastics and (4) Quaternary clastics (Figures 2 & 3).

Pre-Miocene rocks, classified as basement, are composed of chaotically associated schist, calc-schist, quartzite, phyllite and Jurassic limestones, unconformably overlain by Eocene conglomerates and nummulitic limestones.

Neogene units are divided into two distinctive groups, basically depending on their colours, deformational intensities and the presence of volcanics as: (1) Miocene and (2) Plio–Quaternary units (Figure 3) (Karaca 2004). However, Neogene dating and stratigraphy is still not well-established and that cause conflicts, especially in calibration in NW Central Anatolia. Thus, it is not convenient to use an 'Early' or 'Late' terminology with regard to ages of Neogene stratigraphic packages in NW central Anatolia. Therefore, the age relations were established using stratigraphic relationships, rather than by absolute dating, and age determinations were interpreted on this basis.

Dominant lithologies of the pale Miocene succession are mudrocks, silicified carbonates and volcanics. The thickness of units is around 250 m. Miocene units are calibrated as Middle–Late Miocene by correlating a mammalian fossil site in the research area with palaeontologically and lithologically equivalent levels in the type locality (Ozansoy 1961; Gürbüz 1981). It corresponds to a Middle–Late Miocene age (MN-9 to MN-13 time interval in the mammalian time scale which is 11.1 Ma to 6.8 Ma; Agusti *et al.* 2001). However, age calibrations done by palynological and radiometric age datings vary widely, although the results of the palynological analyses done on coal layers alternating with mudrocks reveal a Middle to Late Miocene age (Akyol 1968; Turgut 1978).

Because of missing of coal-bearing units in the research area, the age correlation is based on age dating of the tuff beds in the region. Age dating analyses on tuff samples alternating with lacustrine units yielded an age interval of 25 Ma to 21 Ma (Türkecan *et al.* 1991), 16.2 Ma (Ercan

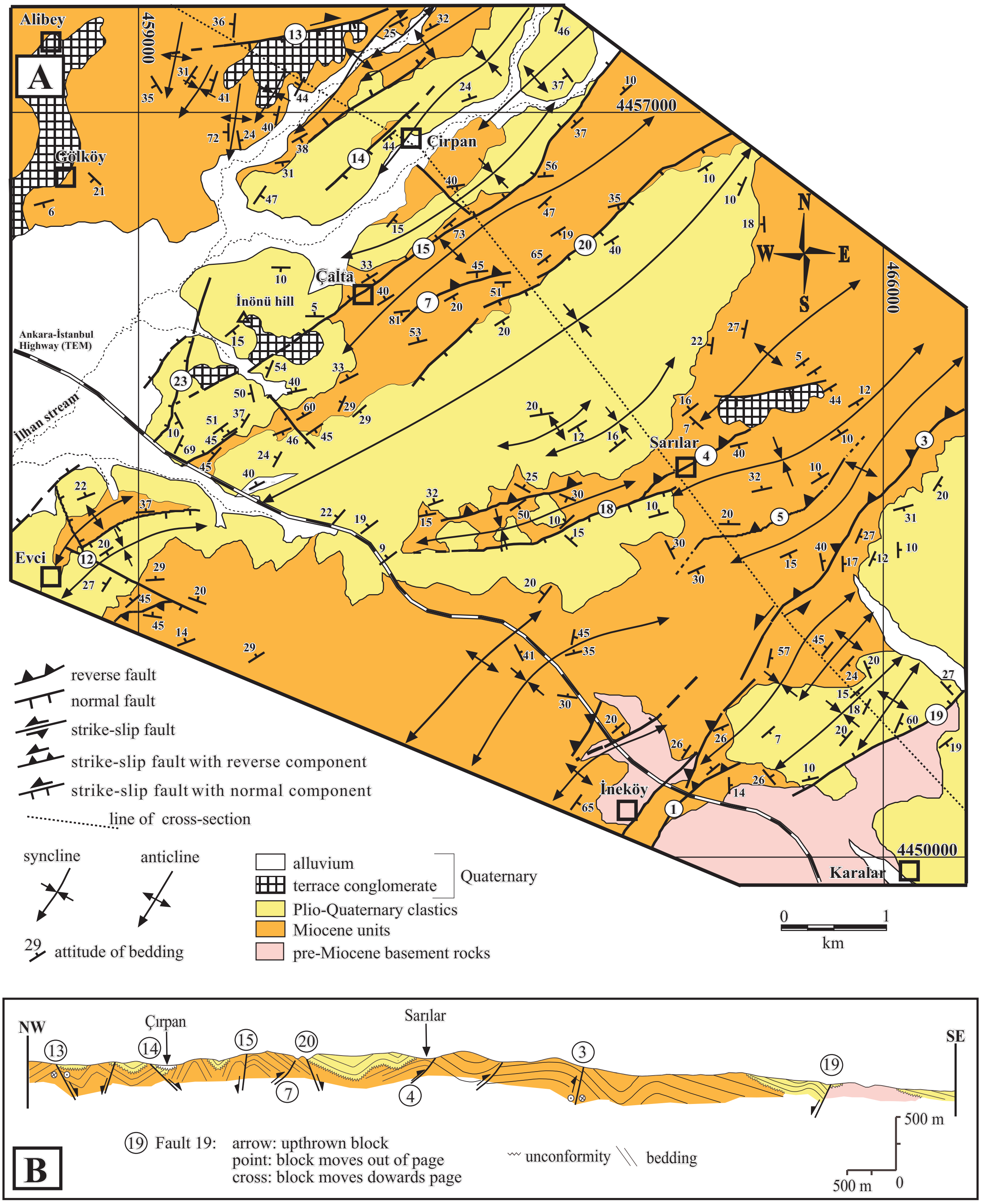


Figure 2. Geological Map (a) (simplified from Karaca 2004), and geological cross-section (b) of the research area.

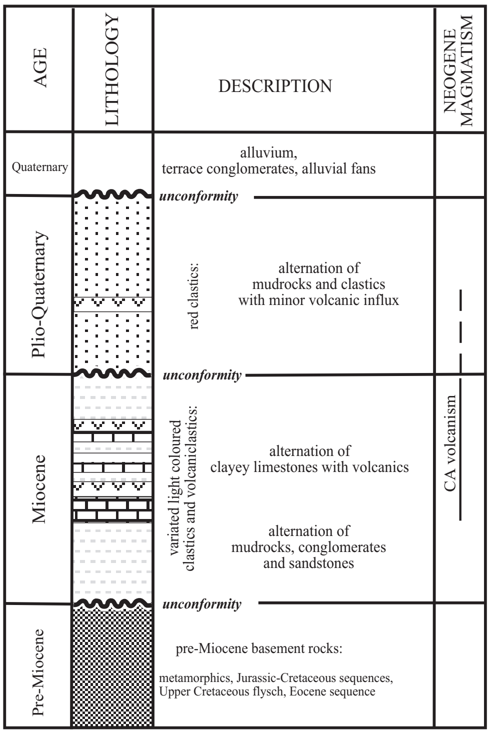


Figure 3. Stratigraphic columnar section of the research area.

et al. 1990), 20.9 to 9.6 Ma (Keller *et al.* 1992), 19.7 to 16.9 Ma and 9.51 Ma (Tankut *et al.* 1995). Altogether, the age of the Miocene sequence alternating with volcanics is accepted as Early (?) to Late Miocene.

The pinkish red Plio–Quaternary clastics can easily be recognized by their colour and soft morphologies, with gentle dip angles except in intensely faulted areas. The dominant lithologies are polygenetic clastics, clayey/silty limestones and silicified limestones without gypsum horizons. The maximum thickness of the Plio–Quaternary clastics is around 150 m. The Plio–Quaternary units unconformably overlie the Miocene units. The age of the unit, thought to be post-Miocene, and Plio–Quaternary, was dated as Early Pliocene using mammalian fossils (Ozansoy 1961; Tekkaya 1973, 1974a, b; Tatlı 1975; Şen & Rage 1979) at its type locality (SE of the research area). The Neogene calibration and palaeoenvironmental evolution of the terrain are well-described and addressed where international Neogene –especially the uppermost Late Miocene to Pliocene– stratigraphic calibration is set (Ozansoy 1961; Tekkaya 1973; 1974a, b; Şen & Rage 1979; Gürbüz 1981).

Quaternary units include alluvium and older terrace deposits. The age of these units is assumed to be Quaternary since they overlie the Plio–Quaternary clastics with a clear angular unconformity on the hilltops and valley floors (Figure 2). The observed thickness of the units is not more than 20 metres.

Structural Analysis

Methods of Study

Principally, two types of structural data were collected: (i) dip-strike measurements of bedding planes and (ii) slip-lineation measurements from fault planes.

Bidirectional rose diagrams of the strike data at 10º class intervals were created by Rockworks-2002 software (http://www.rockware.com/rockworks) for the analysis of bedding planes. The same program was also used for creating contoured stereonet diagrams of the bedding data for the fold analysis.

For the analyses of the slip data, the software Angelier Direct Inversion Method version 5.42 was used (Angelier 1979, 1984, 1991). Different deformational phases affecting the research area were clarified by using this software.

Attitude of Bedding Planes and Folding

A total of 213 dip-strike measurements of the bedding planes were recorded (Figure 2). 157 measurements were from the Miocene units and 56 measurements were from the Plio–Quaternary clastics. For the analysis of bedding planes, rose diagrams were prepared by using RockWorks-2002 software for rocks of the same age. In order to better understand the bedding attitudes, dip-strike data were elaborated for each rock package except for those Quaternary units where there were insufficient measurements to conduct reliable bedding plane analysis.

The unconformity between Plio–Quaternary clastics and Miocene units is of key importance in understanding the post-Miocene tectonic evolution of the region. However, in some places, the angular difference between the bedding plane attitudes of the Plio–Quaternary clastics and Miocene units is so small that their angular relationship is poorly exposed (Figure 2).

Since the Miocene units are older and have undergone more deformation than the younger units, large numbers of measurements were recorded from them. The rose diagram of the bedding plane measurements from the Miocene units with 10° class intervals indicates that the most prominent strike trend is between N40°E and N60°E (average 050°N; around 14.6% of the 157 measurements) (Figure 4a).

The Plio–Quaternary units were relatively less deformed and their bedding plane attitudes seem to be more consistent throughout the research area. The rose diagram of the bedding plane measurements from the Plio–Quaternary clastics reveals that there are two prominent strike directions (Figure 4b): firstly between N20°E – N30°E (average N25°E; around 18.2% of 56 measurements), and secondly between N40°E – N50°E (average N45°E), with a slightly lower abundance of around 16.2%. However, overall statistical analysis done with different class intervals shows a dominant strike trend of 040°N.

Folds are one of the most distinguishing post-Miocene geological structures in the study area (Figure 2). To better understand the folding in the area, folds were examined in two groups; (i) post-Miocene folding (folds developed within Miocene units) and (ii) post-Plio–Quaternary folding (folds developed within Plio–Quaternary clastics).

Miocene units are more intensely folded and deformed than Plio–Quaternary clastics. The size of the structures ranges from outcrop scale to 1:25 000 map-scale. This is well-observed along the belts of thrust faults and overturned structures (Figures 2 & 5). Fold axes generally trend NE–SW in the Miocene units (Figure 2). When the resulting contoured stereonet diagram is examined, bedding plane measurements of Miocene units are clearly quite consistent throughout the research area with two prominent bedding planes indicated by two maximum concentrations on the diagram (Figure 6a). The first is inclined at N45°E/27°SE and has about 7% abundance, while the other is inclined at N60°E/16°NW with about 6% abundance. The presence of these two dominant bedding plane trends, which are more or less parallel, but with opposing dip directions, suggests that there are large-scale asymmetrical folds, whose axes have fairly consistent trends all over the region. The common fold axis of those structures is perpendicular to the best fit circle calculated by the program and trends 046°N.

Plio–Quaternary clastics commonly display open folding. However, when the contoured stereographic plot of dip-strike measurements is examined, it is clear that the bedding planes of the Plio–Quaternary clastics are quite consistent throughout the research area. The diagram is

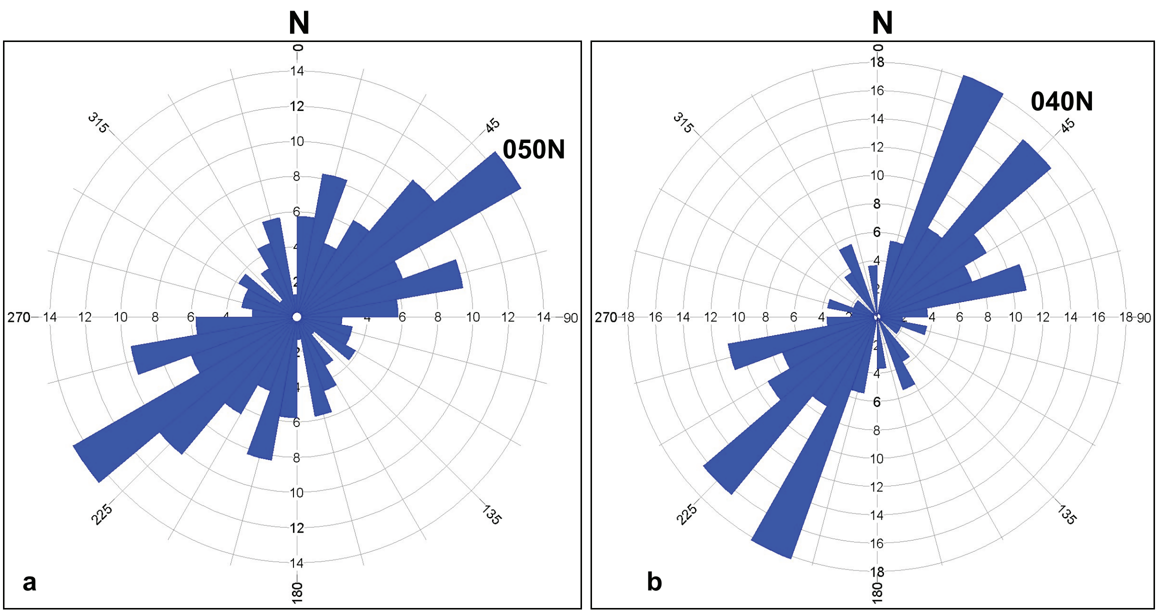


Figure 4. Rose diagrams showing strike measurements taken from bedding planes of (a) the Miocene units (n= 157) and (b) the Plio–Quaternary clastics (n= 55).

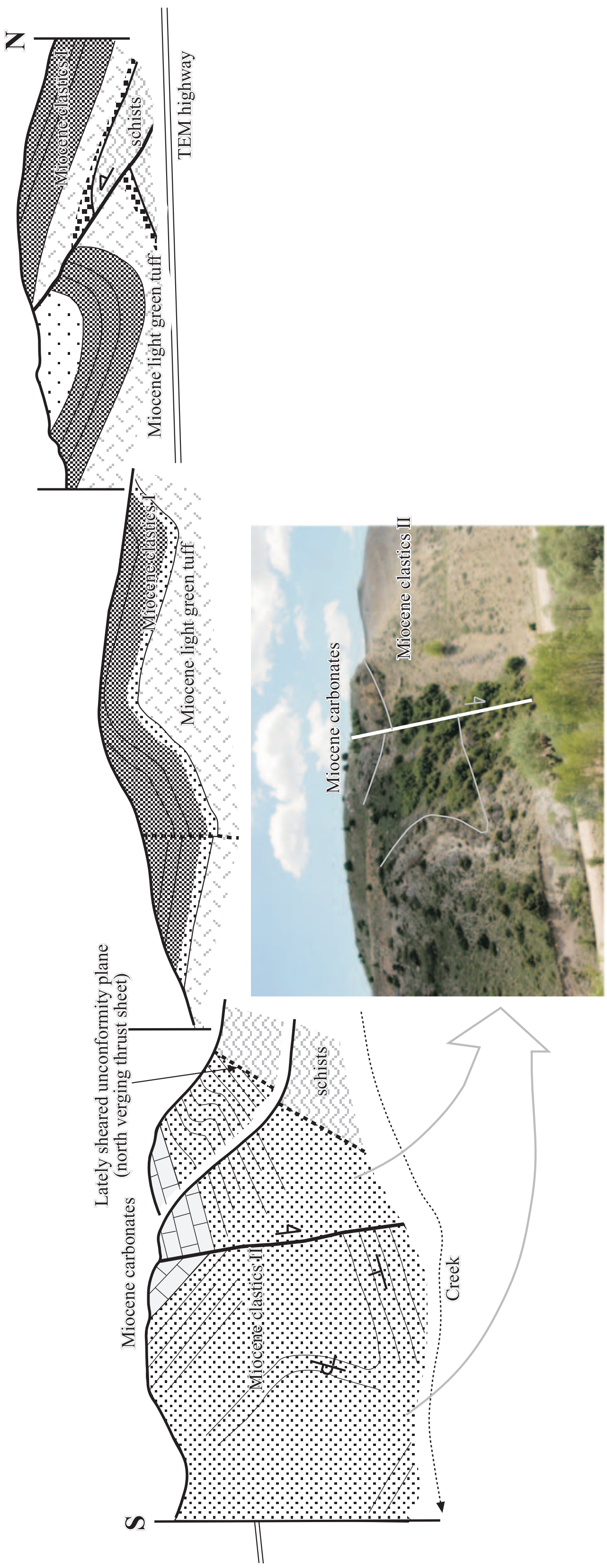


Figure 5. Tentative combined geological cross-sections of overturned, intensely deformed and folded Upper Miocene sequences depicting post-Late Miocene–pre-Pliocene deformation. Location: north of Karalar village.

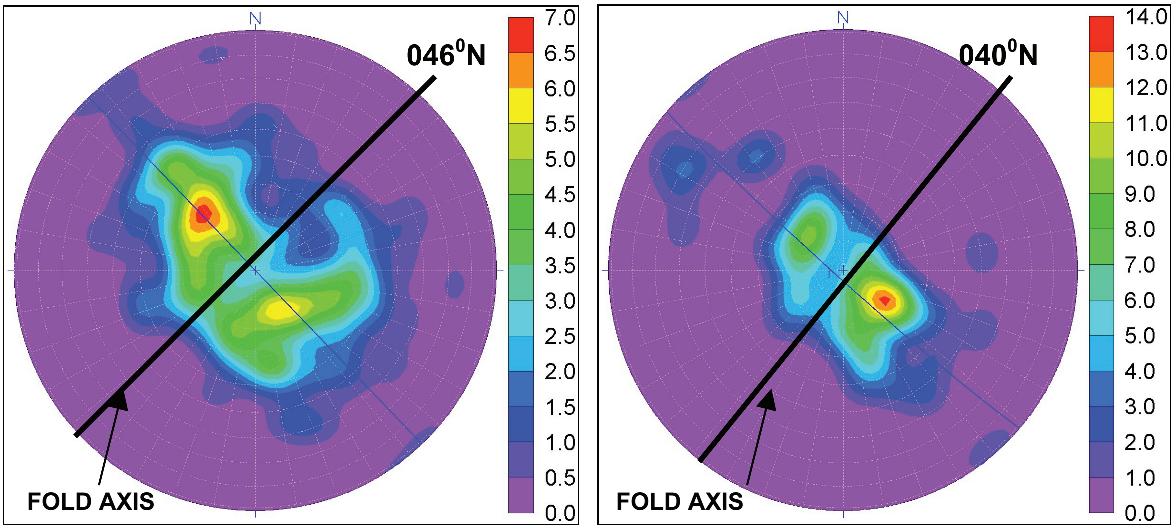


Figure 6. Stereographic contoured plot of the bedding plane measurements from (a) the Miocene units (n= 157) manifesting an asymmetrical folding with a trend of 046°N, (b) the Plio–Quaternary clastics (n= 55) manifesting almost a symmetrical folding with a trend of 040°N.

not scattered at all and there are two maximum concentrations of beddings. The first is inclined at N45ºE/17ºSE and has 11% abundance, while the second is inclined at N35ºE/19ºNW and has 14% abundance (Figure 6b). These results, which give more or less parallel strike trends with opposing dip directions, suggest that the folds are almost symmetric. The common fold axis of these structures is perpendicular to the best fit circle calculated by the program and trends 040ºN. Moreover, the clustering of data points close to the centre of the stereographic plot suggests that the inter-limb angles are not steep, so the folds are broad and gentle.

Faults

The possible estimated age of faulting is based on the age of unconformity-bounded stratigraphic units and cross-cutting relations. Types of individual faults were determined either by using the slickenlines, where available, or other field observations such as drag folds, offsets, juxtaposition, cross-cutting relations or shear sense indicators.

It is clearly seen that most of the structures strike NE–SW- with a few NW–SE- and N–S-trending faults.

The faults that are mostly confined to the Miocene units are reverse faults with dextral components trending NE–SW (Figure 2). Therefore it is suggested that these faults are the relics of the oldest (post-Miocene, pre-Plio–Quaternary) deformational phase that affected the region and controlled the folding and Plio–Quaternary basin evolution. The faults between Karalar and Sarılar villages in particular display reverse-thrust faulting closely associated with overturned folds, folds and 'monoclines' (Figures 2 & 5). The age of these faults and folds are presumed to be post-Miocene – pre-Plio–Quaternary. In the region, the series of anticlines and synclines is strongly controlled by those compressional structures both here and in the Kazan to Beypazarı sector (Demirci 2000).

However, there are also low- to high-angle normal faults with almost the same attitude (NE–SW trend) (Figure 2). These faults, with a maximum offset of 216 cm (Figure 7), bound the Plio–Quaternary basins on their northern margin and cut the Plio–Quaternary and Quaternary units (Figure 2).

N–S- and NW–SE-trending faults are small-scale and usually perpendicular to the strikes of the stratigraphic units and folds (Figure 2). They are either oblique-slip (having both dextral strike-slip and dip-slip components) or dextral strike-slip faults.

N–S- to NNW–SSE-trending small-scale to outcrop-scale syn-depositional faults are high-angle normal faults (60º to 85º). These faults display conjugate structures. No slip data could be obtained from the fault surfaces due to the soft and non-clayey nature of the sediments. However,

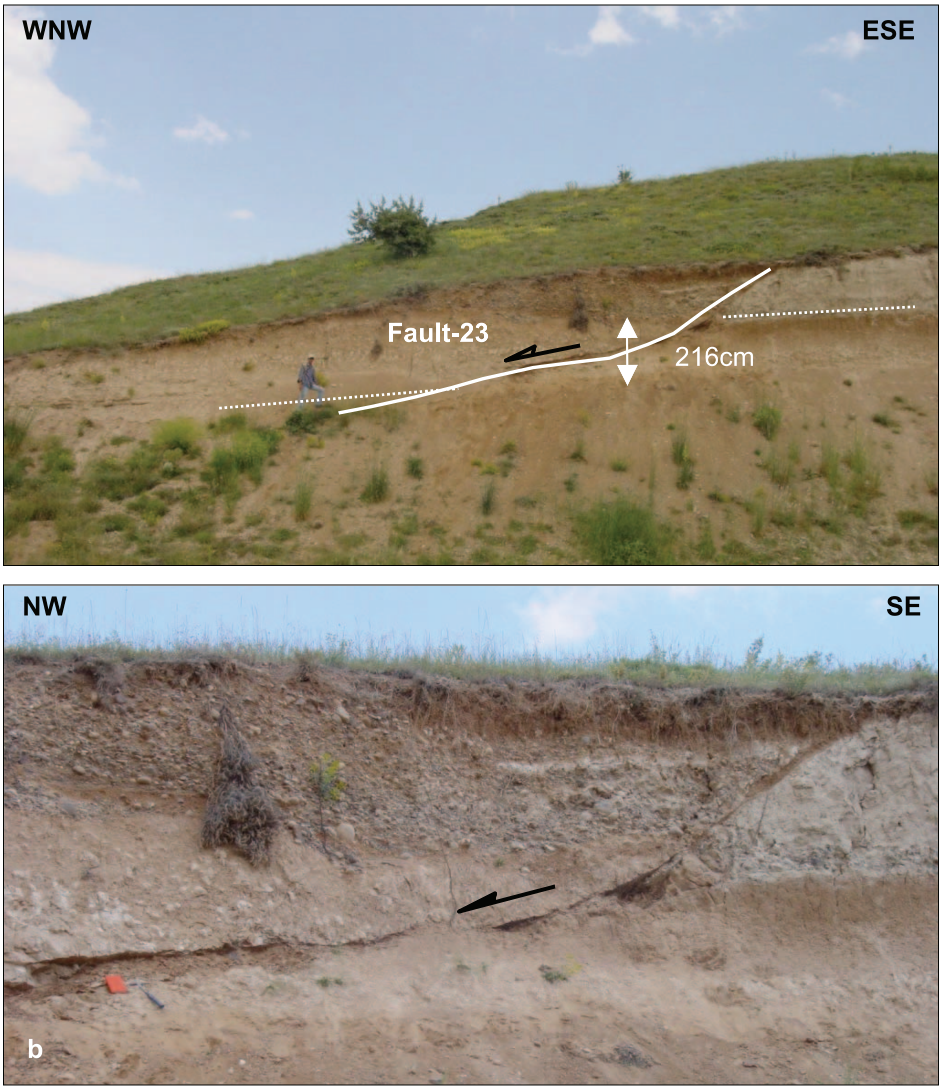


Figure 7. (a) A normal fault, Fault-23, having a listric profile in the Plio–Quaternary units. Note: 1.73-m-long Aykut Karaca (Location: N: 44 54 000, E: 04 59 250); (b) close-up view of Fault-23 cross-cutting the soil. Note: 33-cm-long hammer.

the faults are interpreted as normal faults with their normal offsets, en échelon open veins/calcite veins, drag folds, sediment thickness changes (thickening on hanging wall) and conjugate pairs. Offset amounts range from 6 cm to 27 cm. The age of the faulting must be coeval with the age of the units, which is Plio–Quaternary. However, some of the syn-depositional faults were re-activated during the Quaternary as shown by unfilled *en échelon* fractures and or recent clastic fills within them.

Slip-data Analysis

204 slip lineation data were measured at 39 locations to differentiate the deformational phases and to calculate the directions of principal stresses which acted in the area. 24 of those locations are situated on the major faults mapped in the area. Others are located on the minor faults developed within the post-Miocene outcrops. In total, 179 out of 204 slip data were analyzed (Table 1) (Figures 8 & 9).

Table 1. Field information on slip data measurements.

Site #	Easting	Northing	# of Slip Data	Some Field Observations
1	465750	4452375	12	Fault 3: Inversion of a normal fault as reverse fault with strike slip component. Normal drags on the fault.
3	465380	4454538	3	Bed parallel normal slip (N71°E/36°S) in Miocene mudrocks. Controlled the deposition of the Quaternary terraces.
16	464250	4450750	9	1st reverse, 2nd right-lateral, 3rd left-lateral and 4th is normal faulting.
22	464123	4450689	4	Fault-2: Monoclinal structure developed in the Miocene clastics.
44	465769	4453146	39	Fault-3: Normal faults offset reverse faults.
44/2	465769	4453146	27	Fault-3: Normal faults offset reverse faults.
49	464555	4453863	4	Fault-4: Monoclinal structure developed in the Miocene cherty limestones.
65	459354	4453882	4	Conjugate faults developed in the Plio–Quaternary conglomerates.
80	460605	4457160	4	Faults developed in the Plio–Quaternary clastics.
90	460700	4456950	10	Faults developed in the Plio–Quaternary clastics.
191	460334	4453793	10	Syn-depositional normal faulting, offset from 6 cm to 27 cm in the Plio–Quaternary clastics.
196	462215	4455187	4	Fault 20: controlled the deposition of the Plio–Quaternary clastics.
204	459315	4454066	18	Fault-23 offsets Recent soil, same as the site-65. It has a listric character with dip amounts changing from 50° to 30°. Vertical offset 216 cm (Figure 7).
207	460882	4457758	3	Fault-13: controlled the Quaternary terrace conglomerates situated at 750 meters.
211	461382	4456825	13	Fault-14: developed in Plio–Quaternary clastics.
227	462989	4453423	4	Fault 18: controlled deposition of the Plio–Quaternary clastics.

Overprinting relations of the slip lines on fault planes are rare. However, before running the data during the collection of slip lineation, it was clearly observed that normal faults cut reverse ones in several locations, especially along Fault 3 (Figure 2). Therefore, the normal faulting post-dates the reverse faulting in this study area. Indeed no compressional slip data were observed in any of the faults cutting the Plio–Quaternary outcrops.

In view of those geological considerations, the slip data were prepared to run the analyses by using the direct inversion method in Angelier's 'TENSOR' software (Angelier 1979, 1984, 1991). Lately, sites with fewer than 4 slip data were excluded from the analyses (Figure 8). The data were grouped so that the populations did not have fewer than 20 data or more than 60. At the end of the analyses, although unfortunately no reliable result was obtained for the post-Miocene compressional phase, the results obtained for the post-Pliocene extensional regime were quite reliable (Figure 9).

The reliability of results of the analysis were based on (i) the orientation of σ_1 and σ_3 axes, and (ii) the ratio between the principal axes (Φ). When the ratio is less than 0.4, but over 0.2, the σ_1 axis is clear and the quality of the result was accepted as good. However, when the ratio exceeded 0.7, the orientation of σ_3 axis was clear. In our analysis, the orientation of σ_1 is clear where σ_3 presumed to be reliable in relation to the angular relationship with σ_1 and σ_2. The subperpendicular σ_1 axis shifts from the perpendicular by about 6º to 23º on some of the normal faults that display an oblique character resulting from a strike slip component in the field (Figure 9).

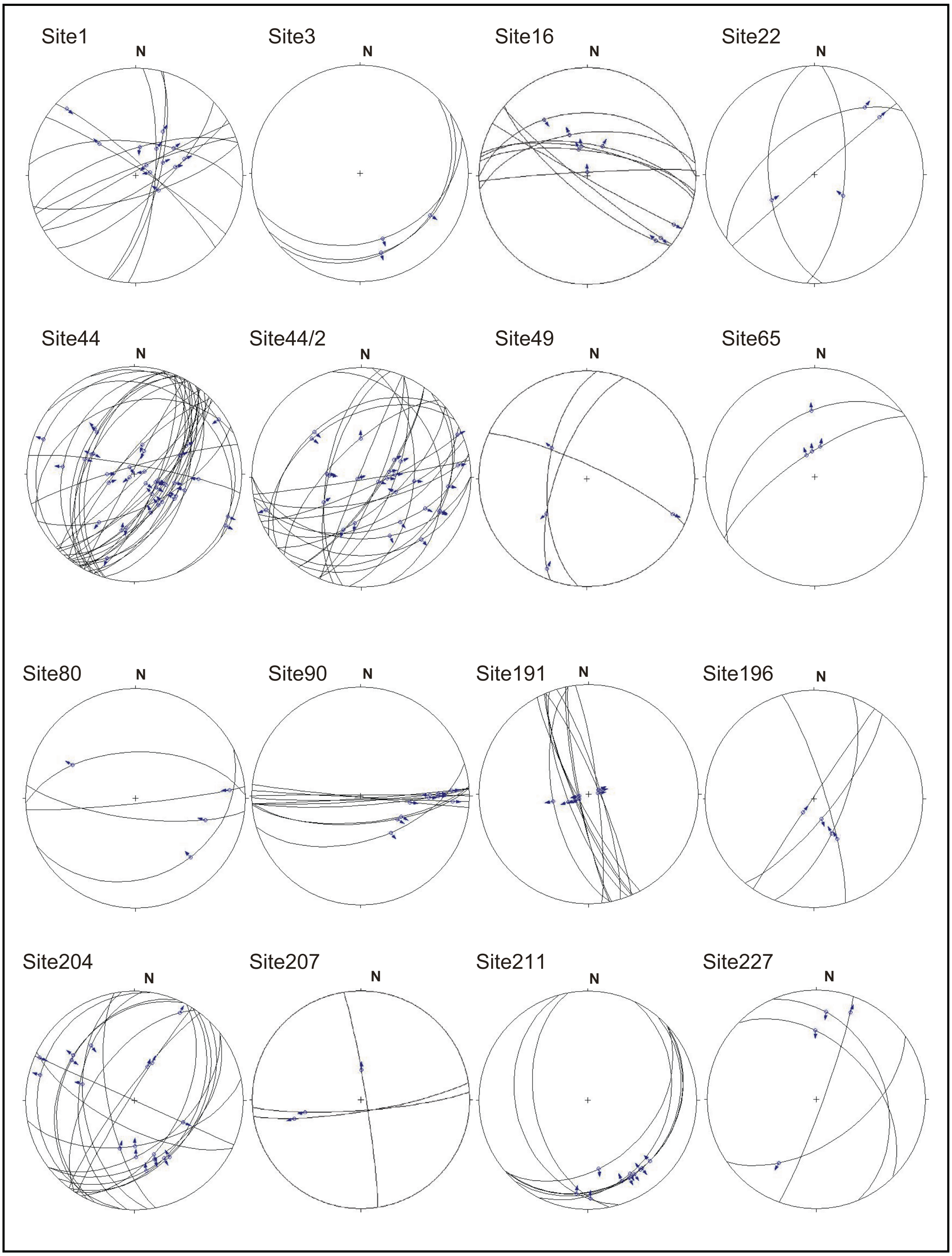
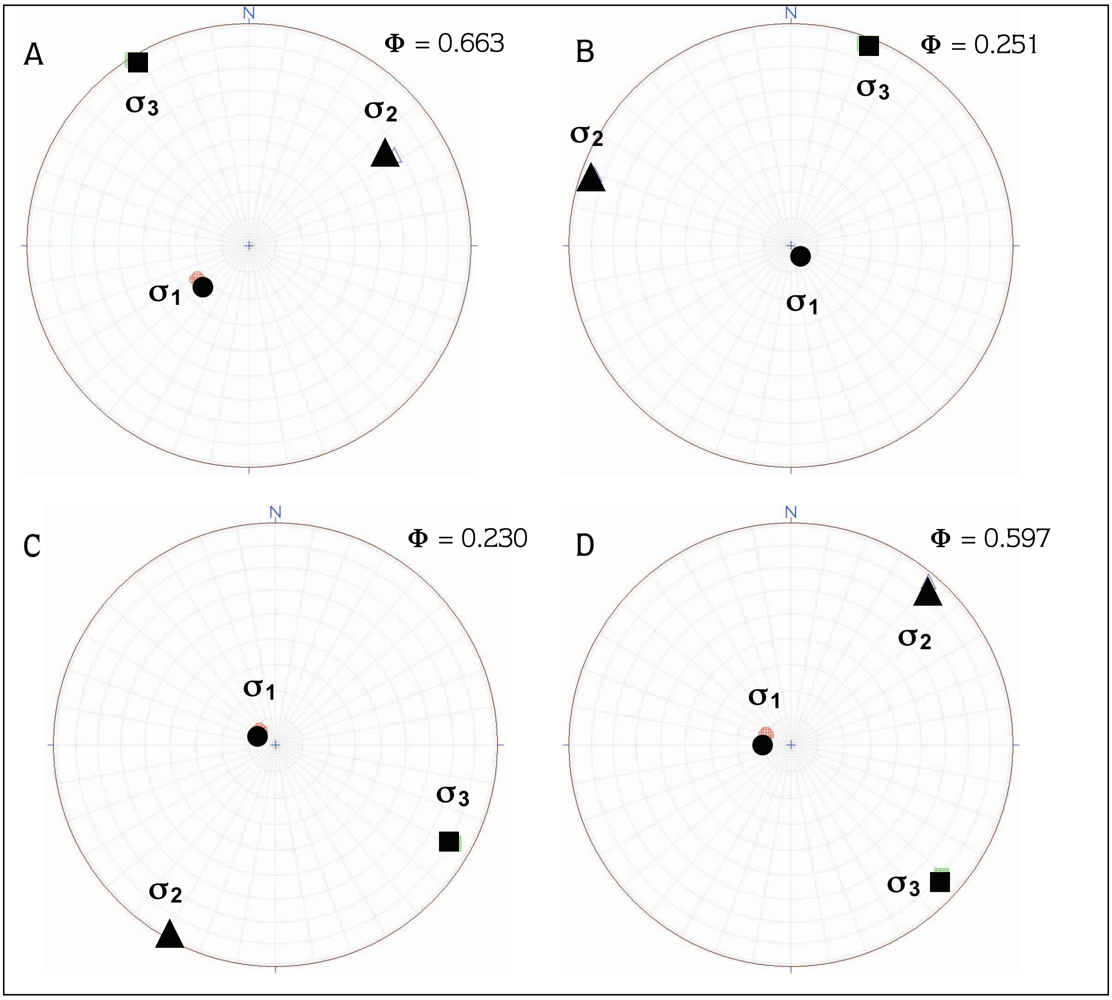


Figure 8. The stereoplots of the slip data used in analysis measured from different 16 sites.



Solution	Φ	σ_1		σ_2		σ_3	
		Trend	Plunge	Trend	Plunge	Trend	Plunge
A	0.663	237^0N	67^0	058^0N	23^0	328^0N	0^0
B	0.251	135^0N	84^0	290^0N	05^0	20^0N	02^0
C	0.230	312^0N	82^0	209^0N	02^0	119^0N	08^0
D	0.597	292^0N	80^0	40^0N	03^0	131^0N	10^0

Figure 9. The stereoplots of the principal stress directions obtained by analyses of the slip data for the post-Plio–Quaternary NW–SE to NE–SW extensional phase (out of 179 data) and summarized results of slip analyses in the table.

It clearly reveals a multi-directed extension in a NW–SE to NNE–SSW direction, when the angular relation between σ_1 and σ_3 axes is clearly figured out (Figure 9). To sum up, multi-directional extension has operated in the region since the Pliocene where σ_1 is vertical to subvertical, σ_2 and σ_3 are radial and concentric, and σ_3 migrates from NW–SE to NNE–SSW orientations.

Results of the Structural Analyses

There is a clear deformational difference in the intensity and style of deformation between the Miocene and Plio–Quaternary sequences. Whereas the Miocene rock units are intensely folded and faulted, the Plio–Quaternary clastics are gently folded, with broad open folding characteristic, and less faulted, with poorly-preserved slickensided fault planes.

The Plio–Quaternary conjugate faults and associated en échelon veins indicate NW–SE extension (σ_1 which is almost vertical where σ_3 is in 305°N). Unfilled fractures and recent clastic fills within en échelon fractures show that these faults were re-activated as normal faults during the Quaternary.

To sum up, NW–SE compressional regimes acted on the Miocene units during the post-Miocene – pre-Pliocene period. This is well shown by NE–SW-trending asymmetric-close folds, NE–SW-trending overturned folds and closely associated NE–SW-striking reverse-thrust faults. In contrast, Pliocene to Quaternary time was characterized by a NW–SE to ENE–WSW multi-directed extensional regime manifested in NNW–SSE- and NE–SW-trending normal faulting, active since the Pliocene (Figure 9). One deformational phase recognized, with palaeostress configurations for Pliocene–Quaternary time, is characterized by vertical to subvertical σ_1, and radial σ_2 and σ_3, typically indicative of extension.

Discussion

Although there are contradictory views on the neotectonic evolution of the Central Anatolian terrane, most researchers support an extensional or transtensional during the neotectonic period since the Pliocene.

Viewed in an Eastern Mediterranean-wide neotectonic framework, Central Anatolia is interpreted as a continuation of the Aegean Graben System, with N–S extension weakening eastwards from the Aegean to Central Anatolia (Şengör 1980). Following Şengör's (1980) neotectonic classification of Turkey, which opened a special gateway in understanding the neotectonics of Anatolia, researchers started to fit their observations into that neotectonic framework. Later, a different interpretation, involving N–S to NNE–SSW shortening and anticlockwise rotation during the neotectonic period was proposed for Central Anatolia (Barka & Reilinger 1997). Following these two basic classifications, the control and record of the effects of NAFZ started to be discussed (Bozkurt 2001; Şengör *et al.* 2004).

The studies of neotectonics in central Anatolia cover a vast area, extending from Çayırhan-Beypazarı in the west to Çankırı in the far east and from the North Anatolian Fault Zone in the north to Tuzgölü in the south (e.g., Koçyiğit 1991, 1992; Koçyiğit *et al.* 1995; Toprak *et al.* 1996; Seyitoğlu *et al.* 1997; Demirci 2000; Dirik & Erol 2000; Kaymakcı 2000; Kaymakcı *et al.* 2000, 2003; Koçyiğit 2000; Toprak & Rojay 2000, 2001; Koçyiğit *et al.* 2001; Koçyiğit *et al.* 2000, 2003b; Rojay *et al.* 2002; Yürür *et al.* 2002; Özsayın *et al.* 2005).

Collectively, the Pliocene (Koçyiğit 1991, 1992; Koçyiğit *et al.* 1995, 2003b; Gökten *et al.* 1996; Seyitoğlu *et al.* 1997; Toprak & Rojay 2000, 2001; Yürür *et al.* 2002) or the Late Miocene (Demirci 2000; Kaymakcı 2000) has been accepted as the initiation time of the neotectonic period in Central Anatolia, where, in almost all the studies, the time of deformation is based on regional lithological correlations. In such an approach, important care should be given to the application of the Neogene-time scale used for lithologies. The timing of most deformational structures in the region is based on the age of these lithologies by correlation with lithological units, instead of by absolute age dating. Age determinations have been accepted on this basis. In the Galatean area, the unconformity between the Late Miocene and Plio–Quaternary units reflects a change in the tectonic setting in the region.

Taking geological considerations and our field observations into account, the compressional regime that affected the Miocene units was caused by almost NW–SE- to NNW–SSE-directed compression. It is reflected by NE–SW-trending reverse-thrust faults with strike slip components and NE–SW-trending folds/overturned folds. In contrast, in the Plio–Quaternary units, while there are open folds developed, no compressional features were noted. During the Plio–Quaternary, the extensional regime operated firstly in an ENE–WSW direction, recorded by almost N–S- to NNW–SSE-directed syn-depositional normal faults. Then the extension direction changed to NW–SE during the post-Plio–Quaternary period, as recorded by NE–SW-trending normal faults controlling the configuration of the Plio–Quaternary basins and cross-cutting the Plio–Quaternary units. The normal faulting post-dated the reverse faulting and post-Late Miocene folding in the research area, and no compressive structures were observed in the Plio–Quaternary rock units. Therefore the compression was pre-Pliocene.

Syn-depositional normal faults were discovered in the Plio–Quaternary rock packages, so the age of N–S- to NNW–SSE-trending normal faulting must be coeval with the age of the units, namely Plio–Quaternary. To conclude, the initiation time of normal faulting is accepted as post-Late Miocene – pre-Quaternary. Since the fault with striae data cross-cuts Quaternary alluvium, the extension must be part of the recent tectonic activity in Central Anatolia.

Analysis of slip measurements related to Plio–Quaternary time yielded a NW–SE to NNE–SSW extension, while the continuation of this period, which might be still going on, is represented by NW–SE-directed extension as manifested in NE–SW-trending normal faults.

To support the region-wide extension, seismic activity and active fissure travertines were analyzed (Figure 10). The Central Anatolian deformational terrain is situated in an area between the dextral North Anatolian Fault Zone in the north, the normal Eskişehir-Cihanbeyli fault zone in the southwest and south and the sinistral Korgun-Bala fault zone in the east. The areas of deformation are well-marked with a series of earthquakes with epicentre solutions, and field data. The northern deformational boundary, the NAFZ, is a highly seismic dextral fault zone (Şengör *et al.* 2004) (Figure 10). The eastern deformational boundary that trends almost N–S from Korgun to Kalecik to Bala is a sinistral strike-slip boundary (Kaymakcı 2000; Kaymakcı *et al.* 2000) where the eastern sector (Kırşehir sector) is elevated. The southwestern and southern boundary displays a WNW–ESE-trending normal faulted margin development with a minor dextral component as exemplified by the 1956 Eskişehir earthquake (Kiratzi 2002) and field observations (Koçyiğit *et al.* 2003b). The eastern and southwest to western boundaries display much less seismic activity than the northern boundary.

In the region, various earthquakes bigger than magnitude three have been recorded, such as the Yeniceoba-Cihanbeyli (April 1973), Kulu-Köşker (April 1983), Kızılcahamam (June 1992), Ayaş (April 1995), Yenimehmetli-Haymana (August 1999), Orta (June 2000), Güdül- Uruş-Beypazarı (August 2000), Ankara (May 2005) and Kazan (October 2006) earthquakes (http://www.koeri.boun.edu.tr). However, there are such limited data about the epicentre fault plane solutions of these earthquakes plus data which are not even published (e.g., Baran 1996; Kaplan 2004) that only limited numbers of seismic events may shed light on the internal deformation history of the Central Anatolian sector.

The existence and orientation of travertine fissures from Malıköy and Cihanbeyli in the far south of the research area indicates active E–W extension in Central Anatolia (Figure 9). However, there is almost N–S extension, based on the field slip data in the research area and its close vicinity stating a different extension orientation to the south (Figure 10). It was observed in the field that the region experiences normal faulting with minor dextral component (Yenikent to Kazan) as seen after the 2006 Kazan earthquakes. Therefore, it can be proposed that the terrain experience a multi-directed extension.

The slip and field survey analyses may be backed up by the results of previous researchers. The Miocene extensional regime, probably caused by gravity collapse, is well-recorded by Seyitoğlu *et al.* (1997) and Yürür *et al.* (2002). Following the Miocene extension, the post-Late Miocene – Early Pliocene NW–SE compression was well-recorded by most researchers and is either linked to the initiation of the NAFZ in the north (e.g., Gökten *et al.* 1988, 1996; İnci 1991; Koçyiğit 1992; Koçyiğit *et al.* 1995, 2003b; Toprak *et al.* 1996; Seyitoğlu *et al.* 1997; Kaymakcı 2000; Yürür *et al.* 2002; Kaymakcı *et al.* 2003), or to the changes in orientation of the compressional direction of the contractional stress regime because of the progressive collision in Central Anatolia (e.g., Koçyiğit 1991), or to the existence of so called two co-operating shear couplets, the North Anatolian Fault Zone and Eskişehir fault (e.g., Yağmurlu *et al.* 1988). However, there is no record of post-Pliocene – pre-Plio–Quaternary N–S compression in the research area, as proposed by some of the previous researchers in the region (e.g., Gökten *et al.* 1988; Koçyiğit 1991, 1992; Koçyiğit *et al.* 1995).

However, palaeomagnetic results showing a small but significant clockwise rotation in the GVP (Gürsoy *et al.* 1999) does not supported with our palaeostress analysis well. It can be deduced from our results that there is a shift from NW–SE to NNE–SSW trends, where the principal stress migrated clockwise or counterclockwise. The timing of clockwise rotation is not well constrained and rotation might be local, as stated by Gürsoy *et al.* (1999, p. 16–21). Although the counterclockwise rotation is well displayed in the areas lying between NAFZ in the north and the Tauride collision and the EAFZ in south (Tatar *et al.*

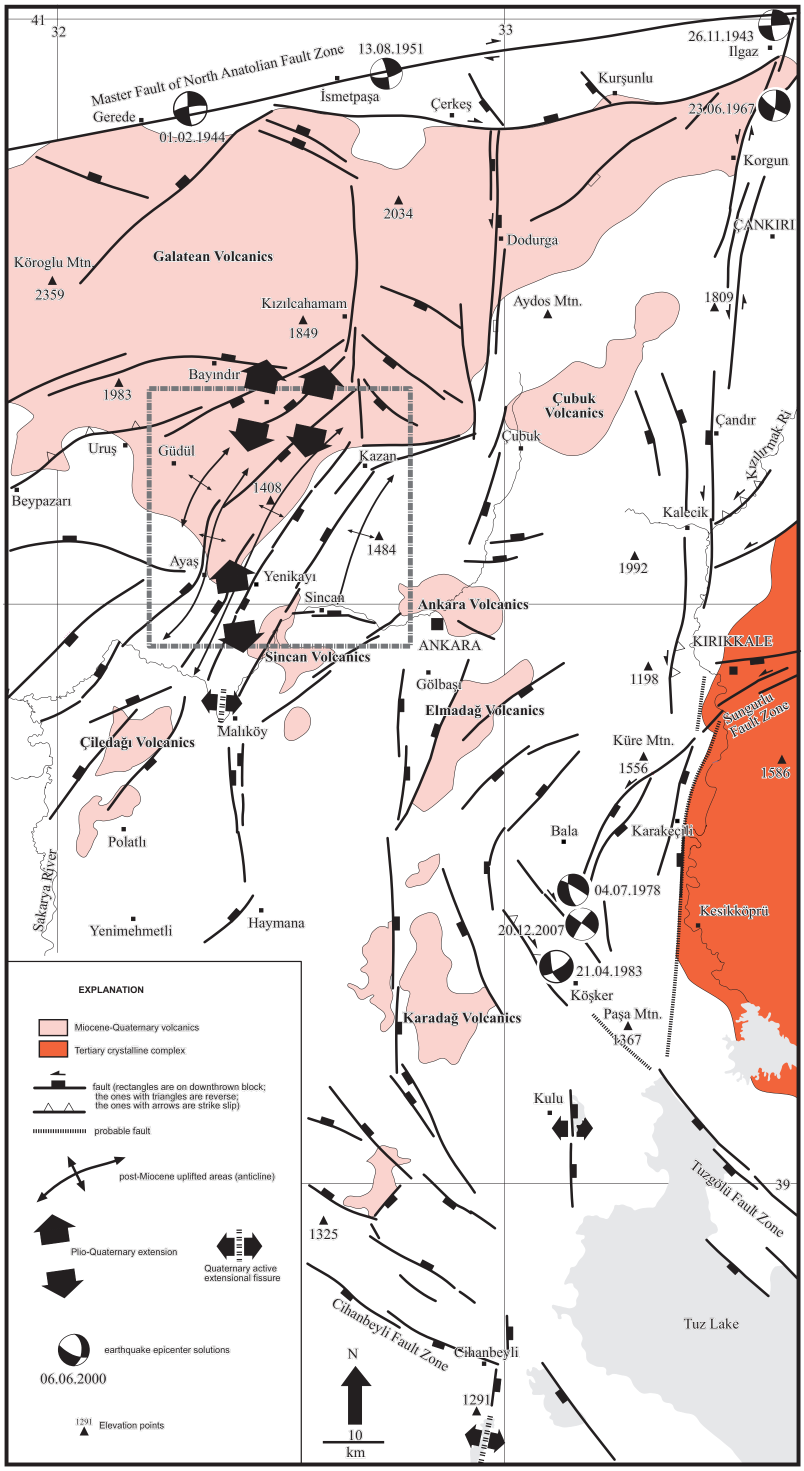


Figure 10. Simplified neotectonic map of Central Anatolia showing fault plane solutions of earthquakes bigger than magnitude 4 (Canıtez & Üçer 1967; Jackson & McKenzie 1984; Gençoğlu *et al.* 1991; Kalafat 1998; Taymaz & Tan 2001); the spatial distribution of the Miocene–Quaternary volcanic areas and Tertiary Crystalline Complex terrains (1: 500 000 scaled geology map, MTA); and major post-Miocene structurally uplifted terrains (within the framed area).

1996; Gürsoy *et al.* 1997, 1998), the rotation of Ankara and its close vicinity in the Central Anatolian block is still unclear.

On the scale of the Eastern Mediterranean, the convergence was accommodated by displacement on the North and East Anatolian fault zones and resulted in the extension (Hempton 1987) and anticlockwise rotation of the Central Anatolian block between these two transcurrent faults (Rotstein 1984). There are thus two possibilities for the extensional neotectonic evolution of the Ankara region (Central Anatolia); one is that control by the NAFZ (researchers op. cit.), resulted in establishment of a transtensional regime in the region since the Pliocene; and the other is the link between the graben system of the Aegean and Ankara regions (Şengör 1980). Based on our regional observations, the principal compressive stress orientations on NAFZ and Central Anatolia, and the latest earthquakes, the stress regime acting on the NAFZ clearly does not fully penetrate into Central Anatolia. The results support an active NW–SE to NNE–SSW multi-directional extension after the Plio–Quaternary which is probably the continuation of the NE–SW-trending Aegean grabens in Central Anatolia. Therefore the Aegean-Western Anatolia area and NW Central Anatolia acted as parts of the same block since the Miocene.

Conclusions

The age of deformation, the sequence of deformational events and the context of the regional deformation are discussed and lead to the following conclusions: (1) The Miocene rock package is relatively more folded than the Plio–Quaternary rock package, where there is a clear unconformity between Late Miocene and Plio–Quaternary that pre-dates the later deformation; (2) since the normal fault with striae data cross-cuts the reverse faults and Quaternary alluvium, extension is thought to be the most recent tectonic activity in Central Anatolia; (3) results of the overall tectonic analyses indicate three main tectonic phases; (i) post-Miocene, almost NW–SE-directed compression (from field survey analysis done on the attitude of beds), (ii) Pliocene, almost E–W-directed extension (from syn-depositional faults developed within Plio–Quaternary clastics), and (iii) post-Plio–Quaternary NW–SE to NNE–SSW multi-directional extension (from fault slip data analyses). Only the last deformational phase was recognized by palaeostress analysis, as it is characterized by vertical-subvertical σ_1, radial σ_2 and σ_3, indicative of extension for the post-Pliocene period.

Collectively, post-Miocene compression was followed by a regionally continuous progressive extension since the Pliocene. The Plio–Quaternary is when continuous and continuing extension was initiated in the region. This should also be when the NAFZ was activated as a single shear, equivalent to the time of the last phase of ‘rifting’ (or, in other words, initiation of sea-floor spreading; 4.5 Ma) in the Red Sea (Hempton 1987) which is eased by the drift of the Eastern Mediterranean-Anatolian plate sliding along the East Anatolian and North Anatolian fault zones onto the African plate along the Mid Mediterranean Ridge (inset map, Figure 1). The convergence is accommodated by the displacement on the North and East Anatolian faults and has lately resulted in the extension of the Central Anatolian and Aegean regions between these two transcurrent fault zones.

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References

Adiyaman, Ö., Chorowicz, J., Arnaud, O.N., Gündoğdu, M.N. & Gourgaud, A. 2001. Late Cenozoic tectonics and volcanism along the North Anatolian Fault: new structural and geochemical data. *Tectonophysics* **338**, 135–165.

Agusti, J., Cabrera, L., Garces, M., Krijgsman, W., Oms, O. & Pares, J.M. 2001. A calibrated mammal scale for the Neogene of Western Europe: State of the art. *Earth-Science Reviews* **52**, 247–260.

Akyol, E. 1968. *Ankara-Kızılcahamam, Çeltikçi Civarında Bulunan Kömür Zuhurlarının 1/25000 Ölçekli Detay Jeolojik Etüdü Hakkında Rapor.* Mineral Research and Exploration Institute (MTA) of Turkey report no. **4405** [in Turkish, unpublished].

Angelier, J. 1979. Determination of the mean principal directions of stresses for a given fault population. *Tectonophysics* **56**, T17–T26.

Angelier, J. 1984. Tectonic analysis of fault slip data sets. *Journal of Geophysical Research* **80**, 5835–5848.

Angelier, J. 1991. Inversion of field data in fault tectonics to obtain regional stress. III: A new rapid direct inversion method by analytical means. *Geophysical Journal International* **103**, 63–76.

Baran, B. 1996. *Ankara Batısının Sismotektonik İncelenmesi [Seismotectonic Investigation of West of Ankara]*. MSc Thesis, Ankara University [in Turkish with English abstract, unpublished].

BARKA, A. & REILINGER, R. 1997. Active tectonics of the Eastern Mediterranean region: deduced from GPS, neotectonic and seismicity data. *Annali di Geofisica* **XI/3**, 587–610.

BOZKURT, E. 2001. Neotectonics of Turkey – synthesis. *Geodinamica Acta* **14**, 3–30.

CANITEZ, N. & ÜÇER, B. 1967. *A Catalog of Focal Mechanism Diagrams for Turkey and Adjoining Areas*. İstanbul Technical University Publication no. **25**, İstanbul.

DEMİRCİ, C.Y. 2000. *Structural Analysis in Beypazarı-Ayaş-Kazan-Peçenek Area, NW of Ankara (Turkey).* PhD Thesis, Middle East Technical University, Ankara [unpublished].

DEMİRCİ, C., TOPRAK, V. & ROJAY, B. 2001. Neogene deformational phases from slip lineation data, North of Ankara (Turkey). *4th International Turkish Geology Symposium, Abstracts*, p. 189.

DIRİK, K. & EROL, O. 2000. Tuzgölü ve civarının tektonomorfolojik evrimi, Orta Anadolu, Türkiye [Tectonomoprhological evolution of Tuzgölü and its surroundings, Central Anatolia, Turkey]. *Haymana-Tuzgölü-Ulukışla Basenleri Uygulamalı Çalışma (Workshop), Proceedings,* 27–46.

ERCAN, T., YEĞİNGİL, Z., BIGAZZI, G., ODDONE, M. & ÖZDOĞAN, M. 1990. Kuzeybatı Anadolu obsidiyen buluntularının kaynak belirleme çalışmaları [Source area investigation of obsidian findings from northwest Anatolia]. *Jeoloji Mühendisliği Bülteni* **9**, 5–11 [in Turkish with English abstract].

EROL, O. 1961. Orogenic phases of the Ankara region. *Türkiye Jeoloji Kurumu Bülteni* **7**, 57–85 [in Turkish with English abstract].

EROL, O. 1993. Ankara yöresinin jeomorfolojik gelişimi [Geomorphological evolution of Ankara region]. *A. Suat Erk Geology Symposium, Proceedings*, 25–35 [in Turkish with English abstract].

GENÇOĞLU, S., İNAN, E. & GÜLER, H. 1990. *Türkiye'nin Deprem Tehlikesi* [*Earthquake risk of Turkey*]. Jeofizik Mühendisleri Odası Publications, Ankara [in Turkish].

GÖKTEN, E., KAZANCI, N. & ACAR, Ş. 1988. Ankara kuzeybatısında (Bağlum-Kazan arası) Geç Kretase–Pliyosen serilerinin stratigrafisi ve tektoniği [Stratigraphy and tectonics of Late Cretaceous–Pliocene sequences in the northwest of Ankara (the area between Bağlum and Kazan)]. *Maden Tetkik Arama (MTA) Dergisi* **108**, 69–81 [in Turkish with English abstract].

GÖKTEN, E., ÖZARKSOY, V. & KARAKUŞ, K. 1996. Tertiary volcanic and tectonic evolution of the Ayaş-Güdül-Çeltikçi region, Turkey. *International Geology Review* **38**, 926–934.

GÜRBÜZ, M. 1981. İnönü (KB Ankara) Orta Miosendeki Hemicyon sansaniensis (Ursidae) türünün tanımlanması ve stratigrafik yayılımı [Description and stratigraphic range of Hemicyon sansaniensis (Ursidae) from the Middle Miocene of İnönü (NW Ankara) area]. *Türkiye Jeoloji Kurumu Bülteni* **24**, 85–90 [in Turkish with English abstract].

GÜRSOY, H., PIPER, J.D.A., TATAR, O. & TEMİZ, H. 1997. A paleomagnetic study of the Sivas Basin, Central Turkey: crustal deformation during lateral extrusion of the Anatolian Block. *Tectonophysics* **271**, 89–105.

GÜRSOY, H., PIPER, J.D.A., TATAR, O. & MESCİ, L. 1998. Paleomagnetic study of the Karaman and Karapınar volcanic complexes, central Turkey: Neotectonic rotation in the south-central sector of the Anatolian Block. *Tectonophysics* **299**, 191–211.

GÜRSOY, H., PIPER, J.D.A. & TATAR, O. 1999. Paleomagnetic study of the Galatean Volcanic Province north-central Turkey: Neogene deformation at the northern border of the Anatolian Block. *Geological Journal* **34**, 7–23.

HELVACI, C. 1998. *The Beypazarı Trona Deposits, Ankara Province, Turkey.* Wyoming State Geological Survey Public Information Circular **40**, 67–103.

HEMPTON, M.R. 1987. Constraints on Arabian Plate motion and extensional history of the Red Sea. *Tectonophysics* **6**, 687–705.

İNCI, U. 1991. Miocene alluvial fan-alkaline playa lignite-trona bearing deposits from an inverted basin in Anatolia: sedimentology and tectonic controls on deposition. *Sedimentary Geology* **71**, 73–97.

İNCI, U., HELVACI, C. & YAĞMURLU, F. 1988. Stratigraphy of the Beypazarı Neogene Basin, Central Anatolia, Turkey. *Newsletter Stratigraphy* **18**, 165–182.

JACKSON, J.A. & MCKENZIE, D.P. 1984. Active tectonics of the Alpine-Himalayan belt between Turkey and Pakistan. *Geophysical Journal of Royal Astronomical Society* **77**, 185–264.

KALAFAT, A. 1998. Anadolu'nun tektonik yapılarının deprem mekanizmaları açısından incelenmesi [Investigation of Anatolian tectonic elements on the basis of earthquake mechanisms]. *Deprem Araştırma Bülteni* **77**, 1–218 [in Turkish with English abstract].

KAPLAN, T. 2004. *Neotectonics and Seismicity of Ankara Region: A Case Study in the Uruş Area.* MSc Thesis, Middle East Technical University [unpublished].

KARACA, A. 2004. *Post-Miocene Deformation of the Area Between Alibey (Kızılcahamam) and Karalar (Kazan) Villages, NW Ankara (Turkey).* MSc Thesis, Middle East Technical University, Ankara-Turkey.

KAYMAKCI, N. 2000. *Tectono-stratigraphical Evolution of the Çankırı Basin (Central Anatolia, Turkey).* PhD Thesis, Universiteit Utrecht, Utrecht.

KAYMAKCI, N., WHITE, S.H. & VANDIJK, P.M. 2000. Paleostress inversion in a multiphase deformed area: Kinematic and structural evolutionof the Çankırı Basin (Central Turkey), part 1 – northern area. *In:* BOZKURT, E., WINCHESTER, J.A. & PIPER, J.D.A. (eds), *Tectonics and Magmatism in Turkey and the Surrounding Area.* Geological Society, London, Special Publications **173**, 295–323.

KAYMAKCI, N., WHITE, S.H. & VAN DIJK, P.M. 2003. Kinematic and structural development of the Çankırı Basin (Central Anatolia, Turkey): a paleostress inversion study. *Tectonophysics* **364**, 85–113.

KELLER, J., JUNG, D., ECKHARD, F.J. & KREUZER, H. 1992. Radiometric ages and chemical characterization of the Galatean andesite massif, Pontus, Turkey. *Acta Vulcanologica* **2**, 267–276.

KIRATZI, A. 2002. Stress tensor inversions along the western North Anatolian Fault Zone and its continuation into the North Aegean sea. *Geophysical Journal International* **151**, 360–376.

KOÇYIĞIT, A. 1991. Changing stress orientation in progressive intracontinental deformation as indicated by the neotectonics of the Ankara region (NW Central Anatolia). *Türkiye Petrol Jeologları Derneği Bülteni* 3, 43–55.

KOÇYIĞIT, A. 1992. Southward-vergent imbricate thrust zone in Yuvaköy: A record of the latest compressional event related to the collisional tectonic regime in Ankara-Erzincan Suture Zone. *Türkiye Petrol Jeologları Derneği Bülteni* 4, 111–118.

KOÇYIĞIT, A. 2000. Orta Anadolu'nun genel neotektonik özellikleri ve depremselliği [Neotectonic characteristics and seismicity of Central Anatolia]. *Haymana-Tuzgölü-Ulukışla Basenleri Uygulamalı Çalışma (Workshop), Proccedings*, 1–26 [in Turkish with English abstract].

KOÇYIĞIT, A., ÖZKAN, S. & ROJAY, B. 1988. Examples from the forearc basin remnants at the active margin of northern Neo-Tethys; development and emplacement ages of the Anatolian Nappe, Turkey. *METU Journal of Pure and Applied Sciences* 21, 183–210.

KOÇYIĞIT, A., ROJAY, B. & KAYMAKCI, N. 2003b. *Kazan (Ankara) Soda Proje Sahası ve Çevresinin (İç Anadolu) Sismotektonik Araştırması* [*Seismotectonic Investigation of Kazan (Ankara) Soda Project Area and its Surroundings*]. Middle East Technical University–RioTur project report [unpublished].

KOÇYIĞIT, A., TÜRKMENOĞLU, A., BEYHAN, A., KAYMAKCI, N. & AKYOL, E. 1995. Post-collisional tectonics of Eskişehir-Ankara-Çankırı segment of İzmir-Ankara-Erzincan Suture Zone (İAESZ): Ankara Orogenic Phase. *Türkiye Petrol Jeologları Derneği Bülteni* 6, 69–86.

KOÇYIĞIT, A., WINCHESTER, J.A., BOZKURT, E. & HOLLAND, G. 2003a. Saraçköy Volcanic Suite: implications for the subductional phase of arc evolution in the Galatean Arc Complex, Ankara, Turkey. *Geological Journal* 38, 1–14.

KOÇYIĞIT, A., ROJAY, B., CIHAN, M. & ÖZACAR, A. 2001. The June 6, 2000, Orta (Çankırı, Turkey) earthquake: sourced from a new antithetic sinistral strike-slip structure of the North Anatolian Fault System, the Dodurga Fault Zone. *Turkish Journal of Earth Sciences* 10, 69–82.

OZANSOY, F. 1961. Ankara bölgesi fauna teakubu etüdünün esaslı sonuçları [Results of the Study on the faunal essamblages of Ankara region]. *Maden Tetkik Arama (MTA) Dergisi* 56, 86–95 [in Turkish with English abstract].

ÖZSAYIN, E., YÜRÜR, T. & DIRIK, K. 2005. Yuva ve Yakacık köyleri (Ankara kuzeybatısı, İç Anadolu) çivarındaki Üst Kretase ofiyolitik karmaşığı ile Miyosen birimlerinin dokunak ilişkileri ile ilgili yeni gözlemler (Technical note) [New observations on the contact relationships between the Upper Cretaceous ophiolitic mélange and Miocene units near Yuva and Yakacık villages (northwest of Ankara, Central Anatolia)]. *Yerbilimleri* 26, 55–59 [in Turkish with English abstract].

ROJAY, B., TOPRAK, V., BOZKURT, E. & ARCASOY, A. 2002. *Final Core Analysis Report Kazan Trona Project*. Middle East Technical University-SRK project report [unpublished].

ROTSTEIN, Y. 1984. Counterclockwise rotation of the Anatolian Block. *Tectonophysics* 108, 71–91.

ŞEN, Ş. & RAGE, J. C. 1979. Çalta (Ankara) Pliyosen Omurgalı Faunası [Pliocene vertebrate fauna of Çalta (Ankara)]. *Türkiye Jeoloji Kurumu Bülteni* 22, 155–160 [in Turkish with English abstract].

ŞENGÖR, A.M.C. 1980. *Türkiye'nin Neotektoniğinin Esasları [Fundamentals of Neotectonics of Turkey]*. Geological Society of Turkey, Conference Series 2 [in Turkish].

ŞENGÖR, A.M.C. & YILMAZ, Y. 1981. Tethyan evolution of Turkey: a plate tectonic approach. *Tectonophysics* 75, 181–241.

ŞENGÖR, A.M.C., TÜYSÜZ, O., İMREN, C., SAKINÇ, M., EYIDOĞAN, H., GÖRÜR, N., LE PICHON, X. & RANGIN, C. 2004. The North Anatolian Fault: A New Look. *Annual Review of Earth and Planetary Sciences* 33, 1–75.

SEYİTOĞLU, G., KAZANCI, N., KARAKUŞ, K., FODOR, L., ARAZ, H. & KARADENİZLİ, L. 1997. Does continuous compressive tectonic regime exist during Late Palaeogene to Late Neogene in NW Central Anatolia, Turkey? Preliminary observations. *Turkish Journal of Earth Sciences* 6, 77–83.

SÜZEN, M.L. & TOPRAK, V. 1988. Filtering of satellite images in geological lineament analyses: an application to a fault zone in Central Turkey. *International Journal of Remote Sensing* 19, 1101–1114.

TANKUT, A., WILSON, M. & YIHUNIE, T. 1998. Geochemistry and tectonic setting of Tertiary volcanism in the Güvem area, Anatolia, Turkey. *Journal of Volcanology and Geothermal Research* 85, 285–301.

TANKUT, A., AKIMAN, O., TÜRKMENOĞLU, A., GÜLEÇ, N. & GÖKER, T.T. 1990. Tertiary volcanic rocks in Northwest-Central Anatolia. *In:* SAVAŞÇIN, Y. & ERONAT, A.H. (eds), *International Earth Sciences Colloquium on the Aegean Regions, 1990, Proceedings* 2, 450–466.

TANKUT, A., SATIR, M., GÜLEÇ, N. & TOPRAK, V. 1995. *Galatya Volkaniklerinin Petrojenezi [Petrogenesis of Galatean Volcanics]*. Middle East Technical University-TÜBİTAK project report [in Turkish with English abstract, unpublished].

TATAR, O., PIPER, J.D.A., GÜRSOY, H., & TEMİZ, H. 1996. Regional significance of neotectonic counterclockwise rotation in Central Turkey. *International Geology Review* 38, 692–700.

TATLI, S. 1975. *Kızılcahamam Doğu Alanının Jeolojisi ve Jeotermal Enerji Olanakları [Geology and Geothermal Energy Potential of East of Kızılcahamam Area]*. Maden Tetkik Arama Enstitüsü (MTA) report no. 5749 [in Turkish, unpublished].

TAYMAZ, T. & TAN, O. 2001. Source parameters of June 6, 2000 Orta-Çankırı and December 15, 2000 Sultandağı-Akşehir earthquakes (Mw=6.0) obtained from inversion of teleseismic P- and SH wave forms. *Symposia on Seismotectonics of the North-Western Anatolia-Aegean and Recent Turkish Earthquakes, Extended Abstracts, İstanbul Technical University,* 96–107.

TEKKAYA, İ. 1973. Orta Sinaptaki yeni bir Gazella türü [A new Gazella species in Middle Sinap]. *Maden Tetkik Arama (MTA) Dergisi* 80, 113–136 [in Turkish with English abstract].

TEKKAYA, İ. 1974a. The Bovidae fauna of middle Sinap of Turkey. *Türkiye Jeoloji Kurumu Bülteni* 17, 173–186.

TEKKAYA, İ. 1974b. A new species of Tortonian Anthropoid (primate, mammalia) from Anatolia. *Maden Tetkik Arama (MTA) Dergisi* 83, 148–165.

TOPRAK, V. & ROJAY, B. 2000. *Geology Baseline Study for the Kazan Soda Project Area, Ankara, Turkey.* Middle East Technical University–RioTur project report [unpublished].

TOPRAK, V. & ROJAY, B. 2001. *Geological Investigation in Kazan Soda Project Area, Ankara, Turkey.* Middle East Technical University–RioTinto project report [unpublished].

TOPRAK, V., SAVAŞÇIN Y., GÜLEÇ, N. & TANKUT, A. 1996. Structure of the Galatean volcanic province. *International Geology Review* **38**, 747–758.

TURGUT, T. 1978. *Kızılcahamam (Ankara-Çeltikçi) ve Çamlıdere Neojen Havzalarının Linyit Olanakları [Lignite Potential of Kızılcahamam (Ankara-Çeltikçi) and Çamlıdere Neogene Basins].* Maden Tetkik Arama Enstitüsü (MTA) Report no. **6173** [in Turkish, unpublished].

TÜRKECAN, A., HEPŞEN, N., PAPAK, İ., AKBAŞ, B., DİNÇEL, A., KARATAŞ, S., ÖZGÜR, İ., AKAY, E., BEDİ, Y., SEVİN, M., MUTLU, G., SEVİN, D., ÜNAY, E. & SARAÇ, G. 1991. *Seben-Gerede (Bolu)-Güdül- Beypazarı (Ankara) ve Çerkeş-Orta-Kurşunlu (Çankırı) Yörelerinin (Köroğlu Dağları) Jeolojisi ve Volkanik Kayaçların Petrolojisi [Geology and Petrology of Volcanic Rocks in Seben-Gerede (Bolu)-Güdül-Beypazarı (Ankara) and Çerkeş-Orta-Kurşunlu (Çankırı) Areas (Köroğlu Mountains)].* Maden Tetkik Arama Enstitüsü (MTA) Report no. **9193** [in Turkish, unpublished].

WILSON, M., TANKUT, A. & GÜLEÇ, N. 1997. Tertiary volcanism of the Galatia province, north-west Central Anatolia, Turkey. *Lithos* **42**, 105–121.

YAĞMURLU, F., HELVACI, C., İNCİ, U. & ÖNAL, M. 1988. Tectonic characteristics and structural evolution of the Beypazarı and Nallıhan Neogene basin, Central Anatolia. *METU Journal of Pure and Applied Sciences* **21**, 127–143.

YÜRÜR, M. T., TEMEL, A. & KÖSE, O. 2002. Evidences of extensional tectonics at the southern boundary of the Galatean Volcanic Province, NW Central Anatolia. *Türkiye Jeoloji Bülteni* **45**, 85–98.

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