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The Stress State of The Region around İnönü-Eskişehir active fault system (Turkey); kinematic analysis accompanied with GPS Data

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ABSTRACT
The İnönü-Eskişehir Fault System (IEFS) exhibits WNW–ESE striking right-lateral strike-slip character with a normal component that extends from Uludağ (Bursa) in the west to Sivrihisar (Eskişehir) in the east and separates the west Anatolian extensional region from the central Anatolia to the northeast. This fault system consists of E–W and NW–SE trending fault sets and segments which have potential to produce destructive earthquakes. In this study, we aim to identify the stress regime of the region around İnönü-Eskişehir active fault system by correlating the fault-slip data and GPS data. The strain rates are computed using the velocity vectors from 5 Turkish National Fundamental GPS Network (TUTGA) data, acquired from the General Command of Mapping (Turkey). Fault-slip data have been analysed using the stress inversion method of Angelier. The obtained contraction rate for the studied area is about 65±15 nanostrain/yr, which corresponds to a contraction rate of 0.7±0.15 mm/yr over 10 km. The strain rate results of last ten years calculated from the TUTGA-99 data suggest approximately NW-SE trending compressional tectonic regime in the region. This strain rate and orientations are confirmed by the Plio-Quaternary slip surface data collected along the İnönü-Eskişehir Fault System.

Key words: İnönü-Eskişehir Fault System, contraction rate, Kinematic analysis, TUTGA data and Central Anatolia.

INTRODUCTION

The Central parts of the Anatolian block plays the role of stress transferring zone between East Anatolian contractional province and West Anatolian Extensional region in the west during its drive towards west along North and East Anatolian Fault systems. Together with this tectonic escape of the Anatolian block towards to the west, new small plate boundaries and related neotectonic elements are created with several intra-block strike slip faults (Gökten et al., 2013). The rotations of the blocks bounded by these intra-block strike slip faults (Sarıbudak et al., 1990; Tatar et al., 1995; Kaymakçı 2000; Kaymakçı et al., 2003 a,b; Gökten et al., 2013) during the westward movement of the Anatolian block as a whole, caused the rising of various stress regimes which characterize and control different sub-regions of the Central Anatolia giving rise to regional seismicityin the region. Besides, the relative movements of the small blocks are characterized by different stress orientations, although most of the sub-region boundaries are controlled by the strike-slip faults. In this context, IEFS is one of the major neotectonic structures of the central Anatolia which separates the southwestern Turkey Extensional and the North Anatolian strike-slip neotectonic domains (Özsayın and Dirik, 2007) (Figure 1). Regarding active tectonic regimes and related structures in the Central Anatolian region, IEFS has a considerable role in the stress distribution in the region. The IEFS, extending from Uludağ (Bursa) to the west and Lakesalt(Konya) to the east, is a 400-km long and 15-25-km wide right-lateral transtensional strike-slip fault belt (Koçyiğit 2003; Koçyiğit 2005) (Figure 1). In general, the fault belt is mainly composed of WNW-ESE trending right-lateral strike-slip faults and also includes NE-SW trending left-lateral strike-slip and NW-SE trending dip-slip normal faults.

During the time interval between late Pliocene and recent the central Anatolia deformed at a low velocity strain rate (>20 cm/yr) under two diverse cogenetic neotectonic regimes (Reilinger et al., 2006). Recent GPS studies indicate that there are velocity differences between eastern and western parts of central Anatolia and deformation type of the region is not uniform; while the western part of the Anatolia has been shaping under the extensional-dominated tectonic regime, the eastern part has been deformed under the contractional tectonic regime (Aktuğ et al., 2013). Deformation rate on the IEFS is estimated as 0.15 mm/yr using GPS data (Aktuğ et al., 2013). The rate in the western sector is 0.1 μstrain/yr which sharply falls to 0.02 μstrain/yr to the east (Kahle et al., 1998). Based on geologic observations, Koçyiğit et al., (2000) suggest a deformation rate of 0.07 – 0.13 mm/yr for this region. However, some recent works on dating of terrace deposits (Ocakoğlu, 2007; Ocakoğlu and Açıkalın 2009) yield a strain rate of 1 mm/yr. The IEFS has undertaken different roles at different periods in the tectonic evolution of Central Anatolia. The segmentation of this fault system around Kaymaz was

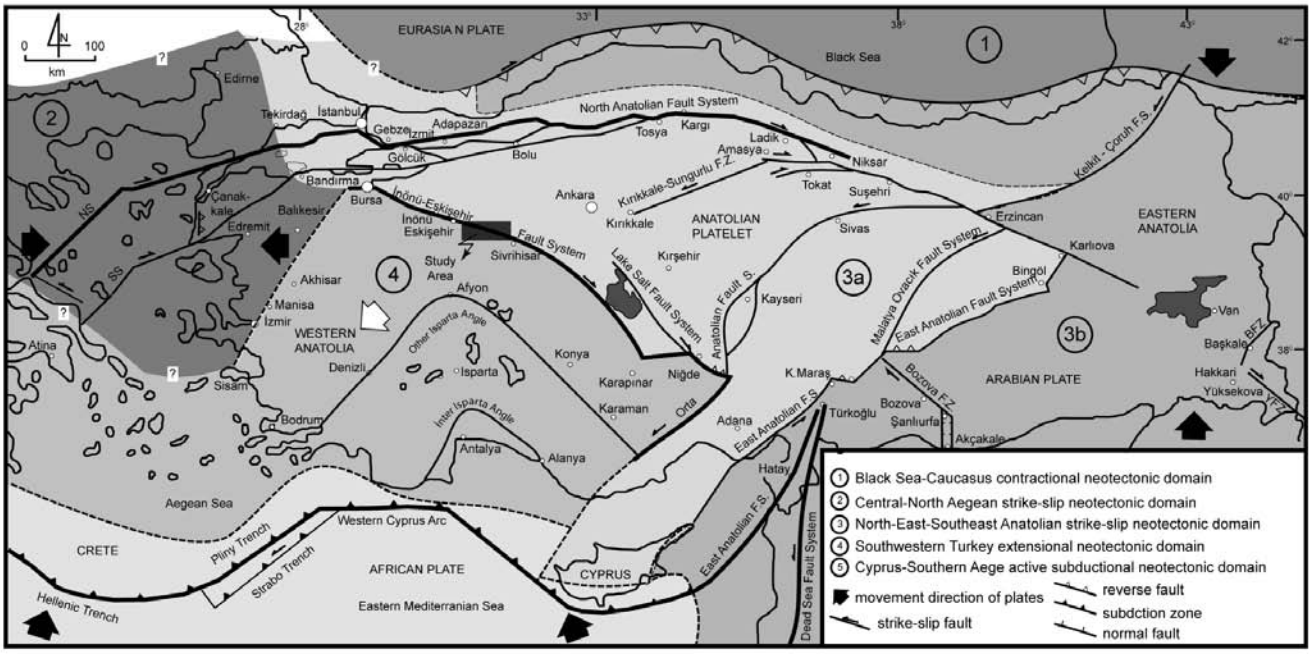

Figure 1. Simplified tectonic map of Turkey and surrounding areas showing major tectonic structures and neotectonic provinces (Koçyiğit and Özacar, 2003).

developed in three different zones which are Alpu fault zone, Eskişehir fault zone and Orhaniye fault zone from north to the south (Figure 2) (Sağlam Selçuk and Gökten, 2012). Tectonic analyses of the faults are made with the help of slip vectors measured on the fault planes. These analyses are based on stress-shearing relation developed by Wallace (1951) and Bott (1959). If the slip vector on each fault plane is in the same direction of effective resolved shear stress (Bott, 1959), then the most suitable stress tensor can be computed from the inversion of the fault slip vectors measured from fault (Carey and Brunier, 1974; Angelier 1984). Angelier's direct inversion method, one of the mostly used methods in the inversion solutions, is based on functions established by mathematical approaches. This technique using the fault properties enables the calculation of principle stress vectors and their ratio. These properties include character, strike and dip of the fault and the fault striae with rake angles. In this study, we aim to identify the stress regime of the region around İnönü-Eskişehir active fault system by correlating the fault-slip data and GPS data by using the stress inversion method of Angelier and TUTGA network data.

Eskişehir Fault Zone

Eskişehir fault zone which has been active possibly since Pliocene (Sağlam Selçuk and Gökten, 2012) generated moderate size earthquakes during the instrumental period. The most recent destructive earthquakes occurred on Eskişehir fault zone in1956, with a magnitude of M=6.4 (Öcal, 1956) is an important one with reference to Neotectonic and seismicity of the region (Figure 3).

This fault zone exhibits right-lateral strike-slip character with a normal component and extends between Uludağ (Bursa) to the west and Sivrihisar (Eskişehir) to the east. In the study area, this fault zone is composed of three distinct segments, namely Yörükkaracaören segment (YF) (between Yörükkaracaören and Sarıkavak), Bardakçı-Kaymaz segment (BKF) (between Sarıkavak and Kaymaz) and Paşakadın segment (PF) (between Kaymaz and Sivrihisar) (Figure 2). The basement rocks consisting of mostly Mesozoic marbles and Quaternary units comprising alluvial sediments are tectonically juxtaposed along these segments. Furthermore, morphotectonic structures such as fault terraces, hanging alluvium fans, and several kinematic data on the fault planes are also observed. While we were not able to observe slip surface data along the Yörükkaracaören segment, we observed and measured some kinematic indicators along the Bardakçı-Kaymaz and Paşakadın segments. The 28-km-longBardakçı-Kaymaz segment is a N25°W trending right-lateral strike-slip fault with a normal component. 14 slip data were measured at three locations along the Bardakçı-Kaymaz segment. Fault-slip data have been analysed, using the stress inversion method of Angelier (1990, 1994). From the direct inversion method the orientations of the stress tensors are σ_1=138°/7°, σ_2=20°/76° and σ_3=230°/12° and

Figure 2. Simplified structural map of Mahmudiye-Çifteler-Emirdağ basin. Abbreviations: OF: Orhaniye fault, İF: İskankuyu fault, Ak: Akçalıtepe fault, SKFT: Sakaryabaşı fault, IF: Ilıcabaşı fault, KF: Kızıltep fault, KÖF: Kötütepe fault, TF: Tepecik fault, BF: Bardakçı fault, UF: Uyuzhamam fault, İF: İncecik fault, ALF: Alpu fault.

Φ is 0.524 (Table 1). The computed results of the inverse analysis of fault-slip measurements are consistent with the behavior of principal stresses, as expected in strike-slip faults, while σ_2 is vertical and σ_1 and σ_3 are nearly horizontal. These results revealed a NW-SE trending compression and NE-SW trending extension on Bardakçı-Kaymaz segment (Figure 3). In the study area, the eastern segment of Eskişehir fault zone is Paşakadın fault. The N85°W trending and 65°SW dipping Paşakadın fault is a 16-km long right-lateral strike-slip fault with a dip slip component. The stress field orientations along the fault suggest an approximately NW-SE trending compression and NE-SW trending extension.

Alpu Fault Zone

Alpu fault zone is a structural contact between the Kaymaz uplift and Alpu basin while the southern side of the Kaymaz uplift is bordered by the Eskişehir fault zone (Figure 4). Tepecik, Uyuzhamam, and İncecik faults are the main segments within the Alpu fault zone. Kinematic properties of these structural elements define the characteristics of recent stress field in the region.

Data obtained along the fault surfaces of Tepecik fault indicate that IEFS has a significant right-lateral character. The N80°W trending and 45°SW dipping Tepecik fault is

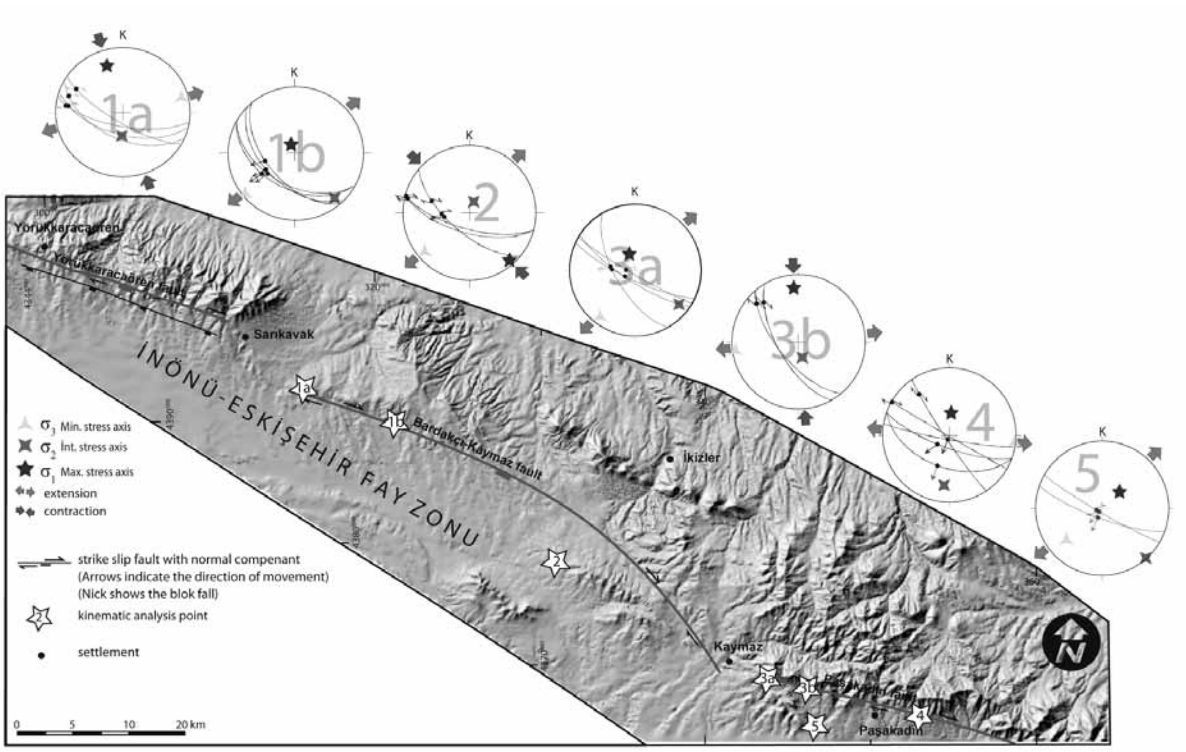

Figure 3. Digital Elevation Model (DEM) showing general outline of the Eskişehir fault zone (Sağlam Selçuk and Gökten, 2012). Numbers in stars refers to location of fault slip data (see, Table 1 for slip data).

Table 1. Results of paleostress analysis from measurement of slickensides in the Eskişehir fault zone. (see Figure 3 for locations).

Name of fault	Location no	Nature of fault	Number of slip data	σ_1	σ_2	σ_3	ϕ
Bardakçı-Kaymaz F.	1a	Oblique-slip	4	337°/23°	181°/67°	076°/02°	0.527
Bardakçı-Kaymaz F.	1b	Oblique-slip	5	339°/78	140°/11°	231°/04°	0.191
Bardakçı-Kaymaz F.	2	Oblique-slip	5	138°/07°	20°/76°	230°/12°	0.524
Paşakadın F.	3a	Oblique-slip	7	357°/67°	126°/15°	221°/17°	0.103
Paşakadın F.	3b	Oblique-slip	2	357°/07°	157°/83°	265°/09°	0.101
Paşakadın F.	4	Oblique-slip	5	005°/63°	186°/27°	096°/01°	0.346
Paşakadın F.	5	Oblique-slip	2	045°/63°	138°/02°	229°/29°	0.342

a 13-km long right-lateral strike-slip fault with a dip slip component. A total of 8 measurements were taken from fault planes as fault striae and deviation angle at two stations along Tepecik fault. From the direct inversion method, following values are estimated, σ_1=8°/65°, σ_2=152°/21° and σ_3=247°/13° and Φ is 0.282 (Table 2). Regarding the behavior of three principal stresses, σ_1 is vertical, σ_2 and σ_3 are almost horizontal indicating the dip slip normal faulting character of Tepecik fault. The stress field orientations along the Tepecik fault suggest an approximately NE–SW-directed extension (Figure 4).

The N25°E trending, 60° to 85° southward dipping Uyuzhamam fault is an 8-km long strike slip fault. The fault is located between Esenler village to the north and Uyuzhamam village to the south. The striation set has an average rake of 18°N. Kinematic analysis indicates that the Uyuzhamam fault operates as a left-lateral strike slip fault. A total of 4 measurements were taken from fault planes at one station as fault striae and deviation angle at one station on the Uyuzhamam fault. From the direct inversion method, σ_1=227°/12°, σ_2=346°/67° and σ_3=133°/20° and Φ is 0.353 (Table 2). At station 9, where the left-lateral strike slip character of the fault is clearly seen, a deformation domain of NW-SE trending compression and NE-SW trending extension is suggested (Figure 4).

İncecik fault starts from just northeast of the Beylikova village, and changes its direction from N60°W to N30°W along its 6 km long length. A total of 4 measurements were taken from fault planes, fault striae and deviation angle at one station on the İncecik fault. From the direct inversion

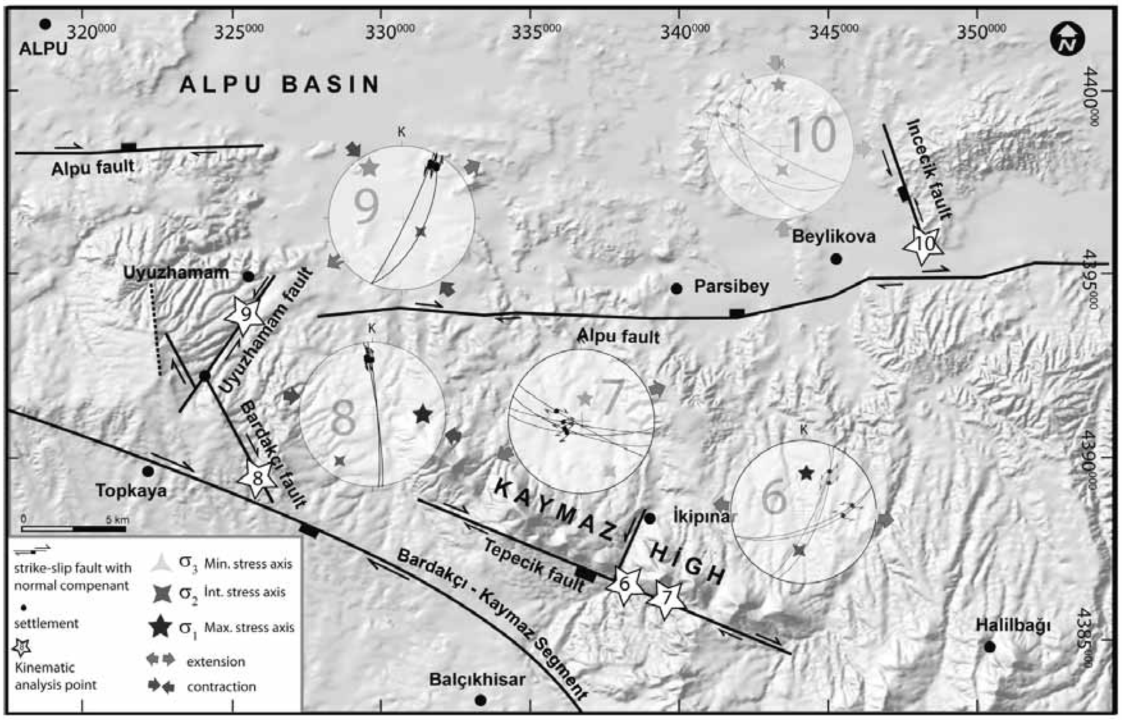

Figure 4. DEM showing general outline of the Alpu fault zone (Sağlam Selçuk and Gökten, 2012). Nick shows the block fall, arrows indicate local compression and extension directions respectively (see, Table 2 for slip data).

Table 2. Results of paleostress analysis from measurement of slickensides in the Alpu fault zone. (see Figure 4 for locations).

Name of fault	Location no	Nature of fault	Number of slip data	σ_1	σ_2	σ_3	ϕ
Tepecik F.	6	Oblique-slip	4	337°/65°	170°/21°	074°/06°	0.444
Tepecik F.	7	Oblique-slip	4	327°/71°	162°/19°	071°/05°	0.770
Uyuzhamam F.	8	Strike-slip	4	098°/28°	204°/29°	303°/38°	0.289
Alpu F.	9	Oblique-slip	4	326°/14°	138°/58°	233°/04°	0.613
İncecik F.	10	Oblique-slip	5	357°/26°	175°/64°	266°/01°	0.253

method, σ_1=357°/26°, σ_2=175°/64° and σ_3=266°/01°and Φ is 0.653 (Table 2). At station 10, the NE-SW trending right-lateral strike slip character of the fault is analysed. The result suggests a N–S compression associated with an E–W extension (Figure 4).

Orhaniye Fault Zone

The Orhaniye fault zone (OFZ) is composed of faults with dissimilar character extending in varying directions. They are OFZ, Sakaryabaşı fault, İskankuyu fault, Akçalıtepe fault, Ilıcabaşı fault, Kötütepe fault and Kızılkaya fault. Among them, Orhaniye fault set, Kötütepe and Kızılkaya faults are the younger ones and yield important kinematic data (Figure 5). OFZ consists dominantly of NW-SE striking fault segments with an average length of 40 km between Dede area and Sünnürüz hill (Figure 5). It is mostly composed of normal faults with a right-lateral component. During the field studies, a total of 9 measurements were taken from the fault planes of Orhaniye fault zone, fault striae and deviation angle at one station. From the direct inversion method, σ_1=326°/13°, σ_2=185°/74° and σ_3=28°/10° and Φ =0.196, are obtained. Regarding the behavior of three principal stresses, σ_2 is vertical and σ_1 and σ_3 are nearly horizontal. In the fault plane solution, it indicates the NNW-SSW trending compression and NNE-SSW trending extension (Figure 5).

The N70°E trending Kötütepe fault, located around the İskankuyu village, is a normal fault with an oblique slip component. During the field studies, 4 measurements were taken from fault planes, fault striae and deviation angle at one station. Based on the results from direct inversion method, σ_1=204°/72°, σ_2=310°/5° and σ_3=41°/17° and Φ =0.373are obtained (Table 3). Regarding the behavior of three principal stresses, σ_1 is vertical and σ_2 and σ_3 are nearly horizontal indicating dip slip normal character of

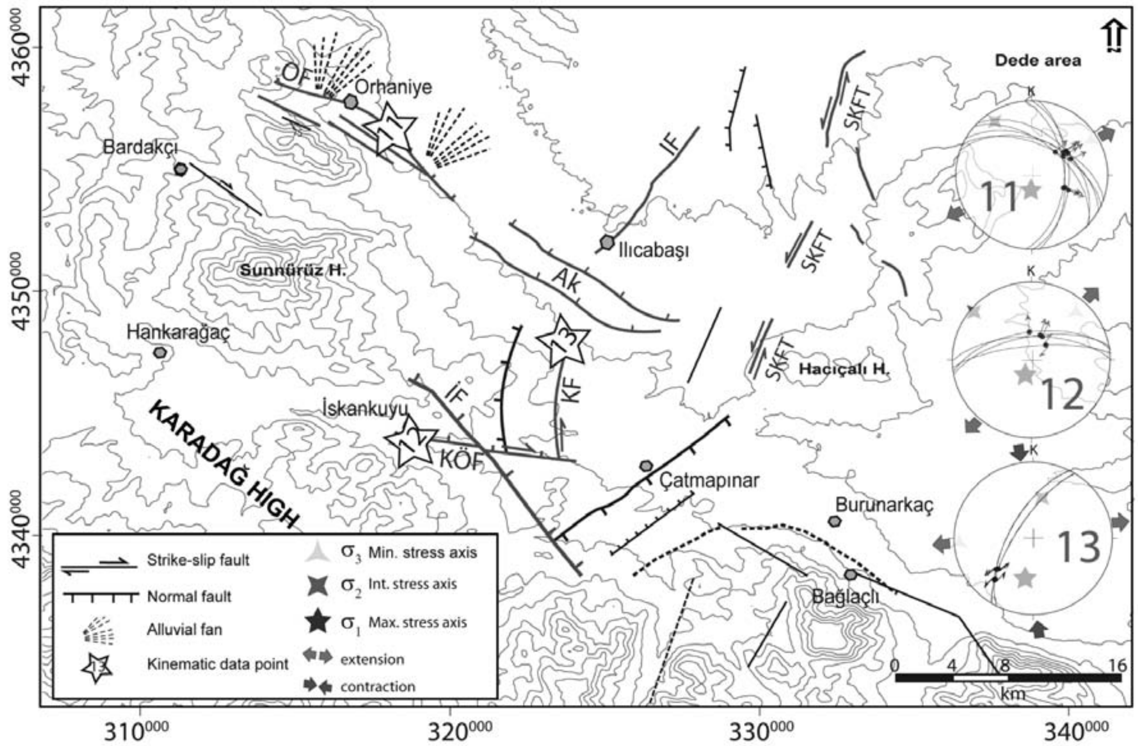

Figure 5. General outline of the Orhaniye fault zone. Numbers 11 through 13 shows the locations of the fault slip data, (see, Table 3 for slip data), OF: Orhaniye fault, KÖF: Kötütepe fault, KF: Kızıltepe fault, İF: İskankuyu fault, SKFT: Sakaryabaşı fault.

Table 3. Results of paleostress analysis from measurement of slickensides in the Orhaniye fault zone. (see Figure 5 for locations).

Name of fault	Location no	Nature of fault	Number of slip data	σ_1	σ_2	σ_3	ϕ
Orhaniye F.	11	Normal	9	185°/74°	326°/13°	048°/10°	0.196
Kötütepe F.	12	Oblique-slip	4	204°/72°	310°/05°	041°/17	0.373
Kızıltepe F.	13	Strike-slip	2	171°/34°,	001°/46°	261°/00°	0.315

Kötütepe fault. Fault plane solutions indicate the presence of a NE-SW trending extension (Figure 5). The N28E trending Kızıltepe fault is a left-lateral strike-slip. During the field studies conducted on the Kızıltepe fault, measurements were taken from fault planes, fault striae and deviation angle at only one station. Based on the results from direct inversion method, σ_1=191°/44°, σ_2=12°/46° and σ_3=281°/0° and Φ=0.315 (Table 3) are obtained. Another fault approximately parallel to Kızıltepe fault was determined in this part of the field which is a NE-SW trending normal fault with a left-lateral strike slip component, and as a whole the region is characterized by a NW-SE trending compression and NE-SW trending extension (Figure 5).

Stress Analysis of the Region and Relative Velocity Vector

TUTGA network has been established between 1997 and 1999, covering the Anatolian block, and considering the deformation due to active tectonic movements of Turkey, the GPS sites have been selected. The coordinate variations of the particular points via tectonic plate movements are caused by inter seismic, co seismic, and post seismic effects. The coordinates and the velocities of five fundamental stations (MIH, KRCT, EMRD, KYMZ, TRMN and ESKI) located in the study area were obtained from the national mapping agency of Turkey (General Command of Mapping). The interseismic velocities of the sites along with formal uncertaincites are shown in Figure 6. To determine the strain rates, Delaunay Triangulation algorithm and a linear estimation methodology were employed in which the rigid body rotations and the translations were estimated simultaneously with the strain parameters (Feigl et al., 1990; Turcotte and Schubert, 1982).rain axes are shown in Figure 7.

The results obtained from the kinematic data Angelier (1990, 1994) and the analysis in the study area show NNW-SSE compression and ENE-WSW extension. Other

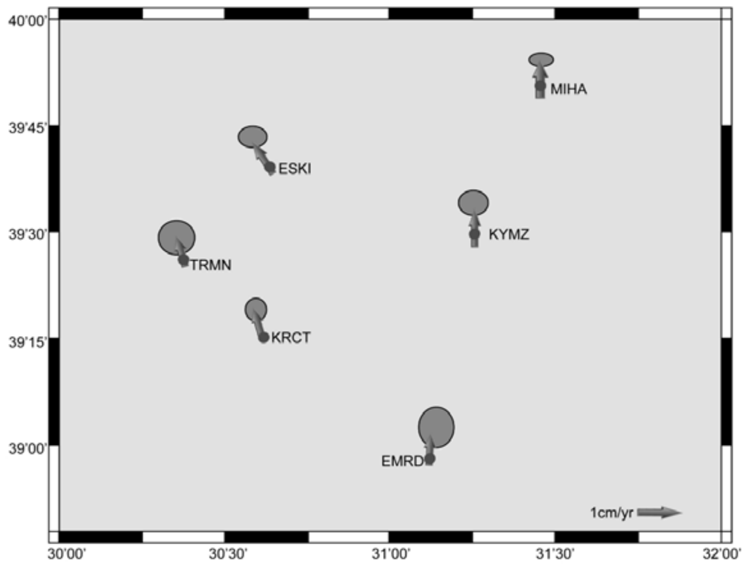

Figure 6. The study area and obtained velocity vectors in ITRF96.

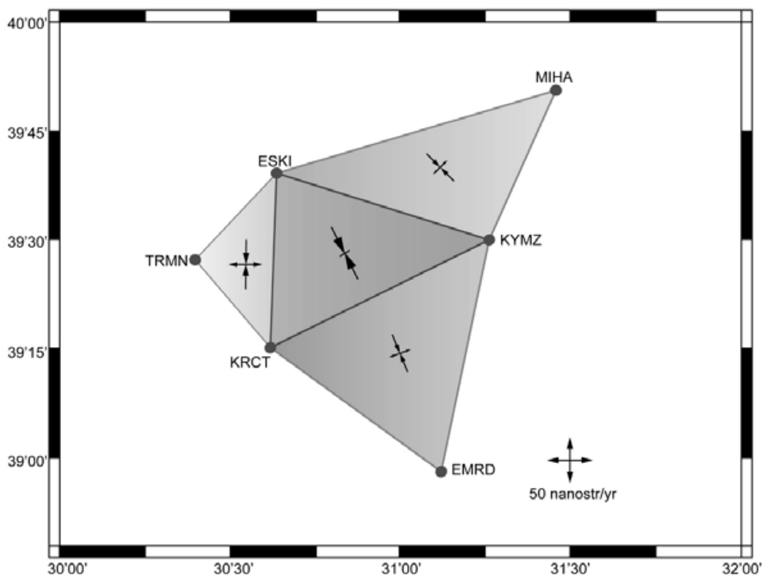

Figure 7. The elements of main warp calculated for study area.

kinematic analyses based on GPS data also support in general the same conclusion, although with a slightly more dominant regional NNW-SSE compression. On the other hand, Kaymakçı et al., (2003a) showed that this region has experienced a NNW-SSE compression from Late Paleocene to Early Miocene in their paleomagnetic studies carried out in the Çankırı basin located east of study area. This study confirms that the same stress conditions are continuing in a broad part of central Anatolia today.

GPS-derived strain rates in the ESKI-KRCT-KYMZ main warp block which lies in the southern part of the NW-SE striking Eskisehir Fault Zone exhibits some differences in the orientation, which is possibly due to the variations in the direction of the faults located in the in this western part of the basin On the other hand, the results of the ESKI-MIH-KYMZ and KRCT-EMRD-KYMZ blocks show that they have nearly the same compression and extension orientations. Especially, TRMN-ESKI-KRCT block, which is in the southern part of the province of Eskisehir, shows N-S compression and E-W extension. ESKI-KRCT-KYMZ block shows a contraction of about 65 ± 15 nanostr/yr which approximately corresponds to a quantity of 0.7 mm/yr over 10 km. ESKI-MIH-KYMZ and KRCT-EMRD-KYMZ blocks have strain rates of approximately 50 ± 15 nanostr

/ yr, corresponding a contraction of 0.6 mm/yr over 10 km. KRCTTRMN-ESKI block has a strain rate of 60 ± 15 nanostr / yr, which corresponds to 0.75 mm / yr over 10 km.

CONCLUSIONS

Six GPS sites of TUTGA-99 in the region of interest have been used for calculating the strain rate of the central Anatolia. These data comprise the measurements of 10 years of period starting from 1999. According to the TUTGA data from the region, the average strain rate along the 10 km length of the zone is 0.7 mm/year which corresponds to the compression in the region. The NW-SE direction of a compression is consistent with the fault plane kinematic data.

It is considered that such stress system is responsible for the westward escape of the Anatolian block in the late Pliocene time. With the advent of the Neotectonic period, several kinds of tectonic regimes have also been effective in the overall region including the study area. However, it is shown that the study area is under the influence of a compression in NNW-SSE trend in a simple-shear system, and an expansion raised in NNE-SSW trend related to this compression.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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