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Crustal Stress States associated with the surface ruptures of the 2023 Pazarcık and Ekinözü Earthquakes

2023 Pazarcık ve Ekinözü depremlerinin yüzey kırıklarının yerkabuğu gerilimleri ile ilişkisi

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ABSTRACT

The doublet disastrous earthquakes occurred on February 6, 2023, in the south-east part of Türkiye. These earthquakes caused a total of more than 500 km long surface ruptures with distinct ground deformations and striations. This study infers the crustal stress state at selected sites along the surface ruptures. The inferred crustal stress states differ depending upon location and the fault system. The inferred stress states of each segment of the fault system are presented and compared with those inferred focal plane solutions and the previous studies. Although the stress states inferred from the fault striations imply very complex stress states for the earthquake-affected region, they provide some insight to the stress state of the earthquake-affected region as well as that of Türkiye.

Keywords: crustal stress, surface rupture, 2023 Pazarcık and Ekinözü earthquake, striation

ÖZ

Türkiyenin güney doğusunda 2023 Şubat 6'sında ikiz 2 büyük oldukça yıkıcı deprem meydana gelmiştir. Bu depremlerde oluşan yüzey kırıkları 500 km'yi aşmakta ve belirgin kalıcı yüzey deformasyonları oluşturmuştur. Bu çalışmada yazar yüzey kırıklarından yerkabuğuna etkiyen gerilme durumunu belirlemektedir. Belirlenen yerkabuğu gerilmeleri fay sistemine göre değişim göstermektedir. Fay sistemlerinin segmentleri için belirlenen gerilme durumu ile deprem oluşum mekanizmasından tahmin edilen gerilme durumları sunulmuş ve daha önceki çalışmalarda belirlenenleri de içerecek şekilde birbirleri ile karşılaştırılmıştır. Bölgenin gerilme ortamı oldukça karmaşık olmasına rağmen, elde edilen gerilme durumu depremden etkilenen bölgenin ve Türkiyenin genelinde gerilme ortamına ışık tutmaktadır.

Anahtar Kelimeler: *yerkabuğu gerilmesi, yüzey kırıkları, 2023 Pazarcık ve Ekinözü depremleri, fay çiziğii*

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INTRODUCTION

Two disastrous earthquakes occurred on February 6, 2023 in the south-east part of Türkiye. The first earthquake is named as the Pazarcık earthquake occurred at 4:17 and the second earthquake is named as Ekinözü (Elbistan) earthquake occurred at 13:24 after about 9 hours on the same day (e.g. Aydan and Ulusay, 2023; Goldberg et al. 2023). The first earthquake ruptured the segments of East Anadolu Fault Zone(EAFZ) and Dead Sea Fault Zone. The Pazarcık earthquake was initiated at Narlı fault segment belonging the Dead Sea Fault Zone and triggered the Pazarcık segment and Amanos segment belonging to East Anadolu Fault Zone, subsequently. While some forking of the East Anadolu Fault segments were observed at Gölbaşı City, another rupture started from Ozan passed over Harmanlı (H) and ruptured Erkenek Gölet (EG) dam body and extended towards Çelikhan (Ç). However, it should be noted this fault intermittently ruptured and it does not exactly follow the Erkenek fault trace depicted in the active fault map by MTA (Emre et al. 2013). The estimated total rupture length was about 330 (50+280) km while it was much shorter at the time of the earthquake occurrence (i.e. 250-270 km).

The Ekinözü earthquake involved E-W trending Çardak segment of the Çardak and Sürgü fault, which was 120-130 km long part initially, and later extended a total rupture length of 180 km. The focal mechanisms of both earthquakes implied sinistral slip with slight vertical component. The Ekinözü earthquake initially ruptured the fault segments between Göksun and Nurhak and later bended at Kullar and extended towards Doğanşehir. Figure 1 shows the fault ruptures together with seismicity and focal mechanisms reported by KOERI (2023) and the active faults prepared by MTA (Emre et al. 2013).

The author surveyed the entire surface ruptures caused by the 2023 Pazarcık and Ekinözü from March 24 until May 3, 2023 as a member of the reconnaissance team of the International Consortium on Geo-disaster Reduction (ICDdR) dispatched to the disaster region. Figure 2 shows the locations and views of selected scarps and the traces of fault surface ruptures caused by the 2023 Pazarcık and Ekinözü earthquakes. In this study, the crustal stresses inferred from the striations on the fault scarps using the method of Aydan (2000, 2003, 2013, 2015, 2016, 2019) are presented and the stress states of the earthquake affected regions are evaluated. These evaluations are also compared with those inferred from focal plane solutions released by several domestic and international seismological institutes (KOERI, USGS, ERD (AFAD), Harvard (GCMT), IGPT). The stress states of the Dead-Sea Fault Zone, East

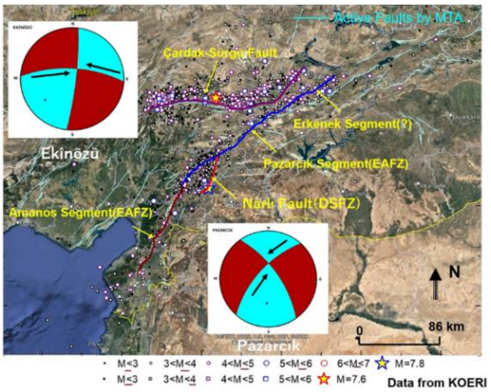

Figure 1. Locations of epicenters and focal mechanism of the earthquakes together with seismicity data from KOERI (2023) and the active faults prepared by MTA (Emre et al. 2013).

Şekil 1. *KOERI (2023) deprem verilerine göre depremlerin merkez üsleri ve faylanma mekanizmaları. Aktif fay haritası MTA (Emre vd. 2013).*

Anadolu Fault Zone and the Çardak and Sürgü Fault differ from each other and imply a very complex stress state. The author presents the inferred stress state of each segment of the fault zones and compares it with those inferred focal plane solutions and the previous studies.

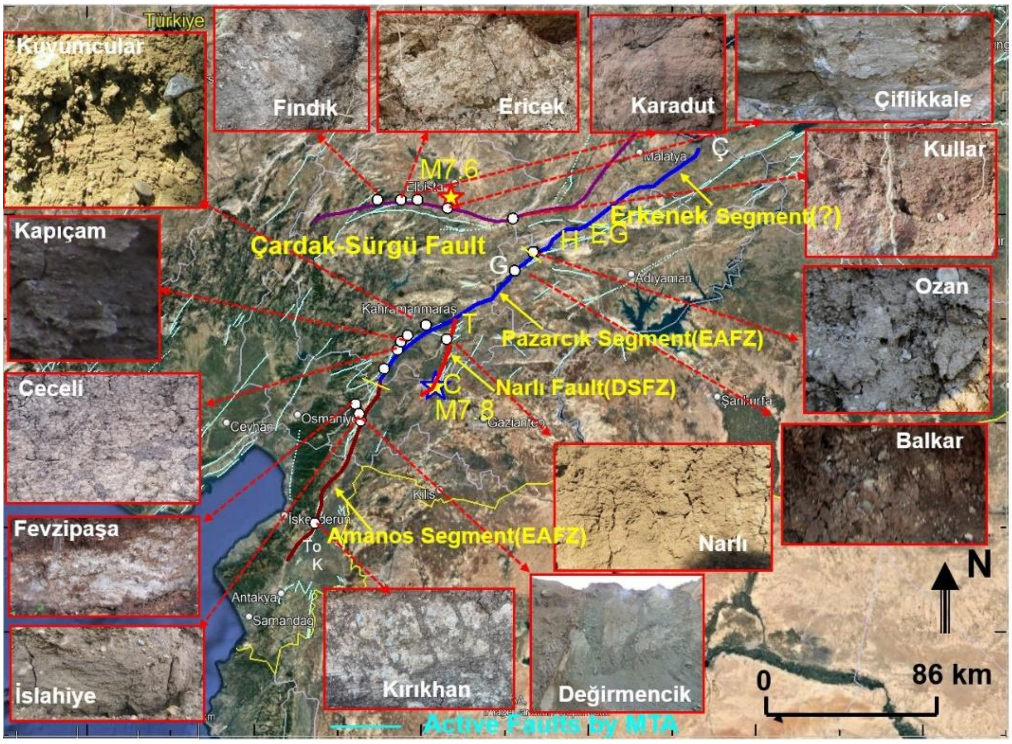

Figure 2. Views of the outcrops of scarps of the faults and their locations. C, T, G, H, Ç, K and To denote localities of Çöcelli, Tetirlik, Gölbaşı, Harmanlı, Çelikhan, Kumlu and Topboğazı mentioned in the text, respectively.

Şekil 2. *Yüzey kırıklarının yerleri ve görünümleri. C, T, G, H, Ç, K ve To Çöcelli, Tetirlik, Gölbaşı, Harmanlı, Çelikhan, Kumlu ve Topboğazı'nın özlenene yüzey kırıklarına karşılık gelmekte ve yerlerini göstermektedir.*

THE METHOD OF INFERENCE OF STRESS STATE

Aydan (2000a) proposed a new method to infer the crustal stresses from the striations of the faults or other structural geological features, which is powerful and accurate to study the stress state associated with paleo and modern-day earthquakes (Aydan 2013, 2015, 2016, 2023; Aydan and Tokashiki, 2003). While the details of the method can be found in the publications of Aydan (2000a, 2016, 2020), it is the most complete solution in view of the physics of rocks and fault mechanics. Furthermore, it is superior to any of available methods without any arbitrary assumption. Figure 3 illustrates the notation used in this method. Aydan (Aydan and Kim, 2002; Aydan, 2003; Aydan and Tokashiki, 2003) applied this method to infer the stress state of the earth crust from focal plane solutions with the utilization of rake angle obtained in focal plane solutions. However, it should be noted that the focal plane solutions used in geo-science are derived by assuming that the pure-shear condition holds. As a result of this assumption, one of the principal stresses is always compressive (P) while the other one is tensile (T) in focal plane solutions. This condition may further imply that the friction angle of the earthquake fault is nil.

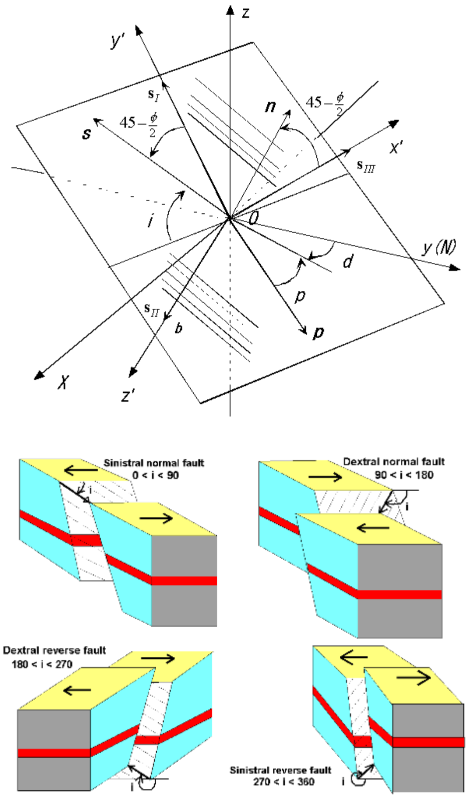

Figure 3. Illustrations of notation for fault striation method (from Aydan 2000a).

Şekil 3. *Fay çiziği yönteminde kullanılan notasyon (Aydan 2000a'dan).*

THE INFERRED STRESS STATE FOR SURFACE RUPTURES OF THE 2023 PAZARCIK EARTHQUAKE

Narlı Segment of Dead Sea Fault Zone

The surface ruptures associated with the Narlı Segment were observed between Çöcelli (C) and Tetirlik (T) villages denoted in Figure 2. A clear fault scarp with an offset of 250cm was observed east of Narlı town (Figure 4a). Table 1 gives the computed stress state parameters for the fault scarp of the Narlı Segment (d_1, d_2, d_3 and p_1, p_2, p_3 stand for dip directions and plunges of principal stresses ($\sigma_1, \sigma_2, \sigma_3$) in Table 1 and other tables hereafter). Furthermore, the friction angle of faults are assumed to be 30 degrees in view of experiments on the samples obtained in Değirmencik, Ericek and Çiftlikkale fault rupture outcrops by the author and his group (Aydan et al. 2024) and studies by Byerlee (1978). Figure 4b shows a view of the fault surface striation while Figure 5 shows the inferred stress state and focal mechanism solutions. The maximum horizontal stress is orientated N39W and its ratio (σ_H/σ_v) to the vertical stress (σ_v) is 1.361.

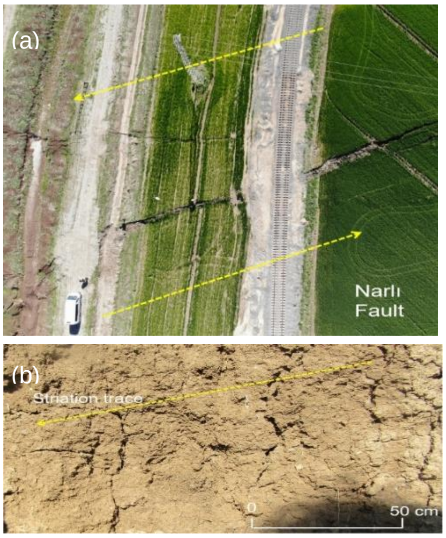

Figure 4. Views of the surface rupture (a) and the striation (b) of Narlı fault.

Şekil 4. *Narlı fay yüzey kırığı (a) ile fay yüzleğinin (b) görüntüleri.*

Table 1. Computed results for Narlı Segment.

Tablo 1. *Narlı fayı segmenti için hesaplanan gerilme sonuçları*

σ_1			σ_2			σ_3			$\frac{\sigma_h}{\sigma_v}$	$\frac{\sigma_H}{\sigma_v}$	d_{σ_H}
$\frac{\sigma_1}{\sigma_v}$	d_1	p_1	$\frac{\sigma_2}{\sigma_v}$	d_2	p_2	$\frac{\sigma_3}{\sigma_v}$	d_3	p_3			
1.398	142	17	0.963	315	73	0.466	51	2	1.361	0.467	321

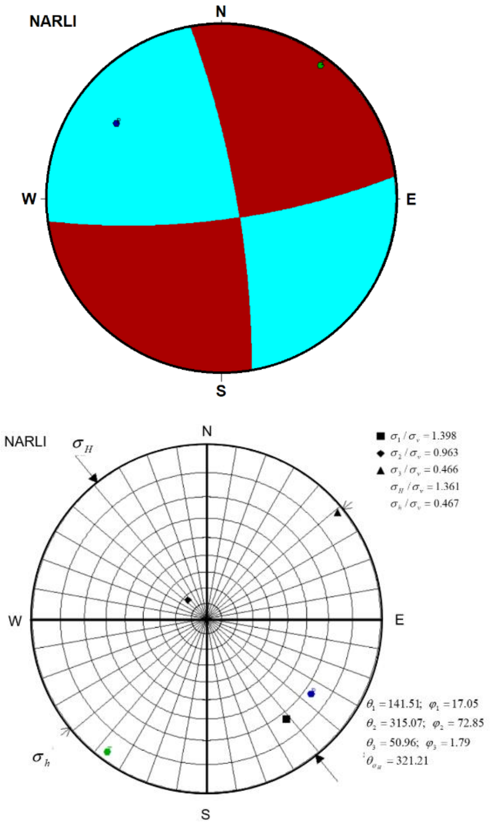

Figure 5. Stereo projections of inferred focal mechanism and stress tensor for the surface rupture of Narlı fault

Şekil 5.*Narlı fayı yüzey kırığı ve gerilme ortamı için elde edilen faylanma mekanizması ve gerilme tensörünün stereo izdüşümleri*

Amanos Segment of East Anadolu Fault Zone

Major ruptures of the Amanos segment appeared between Kırıkhan and Nurdağı. However, the surface ruptures also appeared at the south and runway of Hatay Airport. The offsets of surface ruptures at Kumlu (K) and Toboğazı (To) villages were less than 10-20cm. The stress inferences were done on the striation observations of the surface ruptures in Kırıkhan, Değirmencik, İslahiye and Fevzipaşa and they are reported herein. The fault observed at Değirmencik was spectacular in terms of fault orientation, the fault gouge and the fracturing within the fault zone near the ground surface. The host rock mass was highly fractured serpantine while the fault gouge was hydro-magnesite due to hydro-thermo-chemical metamorphism (Kumsar, 2023). Table 2 gives the computed stress state parameters for the fault scarps of the Amanos Segment at several localities mentioned above.

Pazarcık Segment

The striations on fault scarps at Ceceli, Türkoğlu, Kuyumcular, Kapıçam, Şekeroba, Balkar and Ozan were investigated and Table 3 gives the computed parameters of the stress state at each locality (see Figure 2 for locations). However, it should be noted that the

Erkenek segment of the EAF is said to start at Ozan, north of Gölbaşı (Duman and Emre, 2013). Furthermore, the two fault segments, namely, Pazarcık and Erkenek, join and forking occurred in this locality and in Gölbaşı City. In Şekeroba, there was more than 100 cm settlement of soft ground at a stone quarry about 800 m away east from the fault trace. The striations on the old fault surface in the stone quarry were also measured. This site also implied that the fault zone may have a wider zone of ground deformation without any distinct surface rupture. The maximum horizontal stress direction at Ozan Tunnel was highly rotated and it acts almost in the N70E direction, which implies the rotation and alteration of stress state from south to north.

Table 2. Computed results for Amanos Segment

Tablo 2. *Amanos segmenti için elde edilen sonuçlar*

Location	σ_1			σ_2			σ_3					
	$\frac{\sigma_1}{\sigma_v}$	d_1	p_1	$\frac{\sigma_2}{\sigma_v}$	d_2	p_2	$\frac{\sigma_3}{\sigma_v}$	d_3	p_3	$\frac{\sigma_h}{\sigma_v}$	$\frac{\sigma_H}{\sigma_v}$	d_{σ_H}
Kırıkhan	1.456	360	4	1.003	237	83	0.485	90	6	1.454	0.490	354
Değirmencik	1.452	332	16	1.000	197	68	0.484	66	15	1.415	0.521	334
Fevzipaşa	1.451	350	5	0.999	210	84	0.484	80	4	1.448	0.486	354
İslahiye	1.502	316	12	1.035	196	68	0.501	50	19	1.481	0.556	340

Table 3. Computed results for Pazarcık Segment

Tablo 3. *Pazarcık segmenti için elde edilen sonuçlar*

Location	σ_1			σ_2			σ_3					
	$\frac{\sigma_1}{\sigma_v}$	d_1	p_1	$\frac{\sigma_2}{\sigma_v}$	d_2	p_2	$\frac{\sigma_3}{\sigma_v}$	d_3	p_3	$\frac{\sigma_h}{\sigma_v}$	$\frac{\sigma_H}{\sigma_v}$	d_{σ_H}
Ceceli	1.427	5	19	0.983	145	66	0.476	270	14	1.378	0.507	2
Türkoğlu	1.452	332	16	1.000	197	68	0.484	66	15	1.415	0.521	334
Kuyumcular	1.452	350	3	1.000	124	86	0.485	260	3	1.451	0.485	350
Kapıçam	1.469	18	8	1.033	263	72	0.500	110	16	1.490	0.541	19
Şekeroba	1.495	346	19	1.030	112	60	0.498	247	23	1.440	0.583	341
Balkar	1.439	200	8	0.981	20	82	0.480	290	0	1.430	0.480	20
Ozan	1.495	163	20	1.030	37	59	0.498	263	24	1.436	0.587	348
Ozan Tunnel	1.455	70	3	1.002	190	85	0.485	340	4	1.454	0.488	70

THE INFERRED STRESS STATE FOR SURFACE RUPTURES OF THE 2023 EKINÖZÜ EARTHQUAKE

Major surface ruptures of Sürgü-Çardak fault zone took place in Nurhak fault complexity, which was designated by Duman and Emre (2013), Çardak Fault and Göksun bend, on the basis of segmentation suggested by Duman and Emre (2013). The striation of the surface ruptures in Kullar, Çiftlikkale, Karadut, Ericek and Fındık villages were analysed in this study.The fault observed at Çiftlikkale was spectacular in terms of fault orientation, the fault gouge and the fracturing within fault zone near ground surface. Table 4 gives the computed stress state parameters for the striations of the fault scarps of Nurhak fault complexity, Çardak Fault at several localities mentioned above.

FOCAL MECHANISM SOLUTIONS OF THE 2023 PAZARCIK AND EKİNÖZÜ EARTHQUAKES AND DISCUSSIONS

Focal Mechanism Solutions of the 2023 Pazarcık Earthquake

The focal mechanism of the Pazarcık earthquake was estimated by several seismological institutes and results are given in Table 5. The estimations imply that the earthquake occurred along a NE-SW trending fault with sinistral slip. Among all focal plane solutions, focal plane by KOERI is much more closer to the actual situations of faulting throughout the region investigated by the author and his group and the stress state for this solution is given in Table 6. As noted from Figure 6, the maximum horizontal stress is orientated in the direction of N18E. It should be also noted that this study is concerned with fresh fault ruptures that appeared during the earthquakes. However, the author measured striations on the old fault surfaces and they may be also important to explain the correlations among the new fault striations and old fault striations observed during the reconnaissance as well as those reported in the literature (e.g. Chorowicz et al. 1984; Yürür and Chorowicz, 1988).

Table 4. Computed results for Çardak Segment

Tablo 4. *Çardak segmenti için elde edilen sonuçlar*

Location	σ_1			σ_2			σ_3					
	$\frac{\sigma_1}{\sigma_v}$	d_1	p_1	$\frac{\sigma_2}{\sigma_v}$	d_2	p_2	$\frac{\sigma_3}{\sigma_v}$	d_3	p_3	$\frac{\sigma_h}{\sigma_v}$	$\frac{\sigma_H}{\sigma_v}$	d_{σ_H}
Kullar	1.473	68	22	1.015	197	57	0.491	328	23	1.400	0.578	62
Çiftlikkale	1.462	63	23	1.007	193	57	0.487	323	23	1.385	0.571	58
Karadut	1.509	60	2	1.040	158	74	0.503	327	16	1.500	0.544	59
Ericek	1.443	252	13	0.994	32	74	0.481	160	10	1.422	0.497	71
Fındık	1.599	256	25	1.102	14	45	0.533	148	35	1.491	0.742	67

Table 5. Focal plane solutions by different seismological institutes for the Pazarcık Earthquake

Tablo 5. *Pazarcık depremi için değişik deprem kurumların elde ettiği faylanma mekanizması parametreleri*

Institute	Mw	LAT	LON	Depth (km)	Fault Plane			Auxiliary Plane		
					Strike	Dip	Rake	Strike	Dip	Rake
GCMT	7.8	37.6	37.5	15	54	70	11	320	80	160
USGS	7.9	37.4	37.8	33	234	79	14	142	76	169
KOERI	7.7	37.1	37.1	10	222	64	-27	324	65	-152
ERD	7.8	37.2	37.1	18	233	74	18	140	77	168
IPGP	8.0	37.2	37.0	13	230	81	-18	323	72	-171

Table 6. Computed results for Pazarcık earthquake (KOERI Solution)

Tablo 6. *Pazarcık depremi (KOERI çözümü) için elde edilen sonuçlar*

σ_1			σ_2			σ_3			$\frac{\sigma_h}{\sigma_v}$	$\frac{\sigma_H}{\sigma_v}$	d_{σ_H}
$\frac{\sigma_1}{\sigma_v}$	d_1	p_1	$\frac{\sigma_2}{\sigma_v}$	d_2	p_2	$\frac{\sigma_3}{\sigma_v}$	d_3	p_3			
1.282	22	35	0.883	181	53	0.427	285	10	1.149	0.444	18

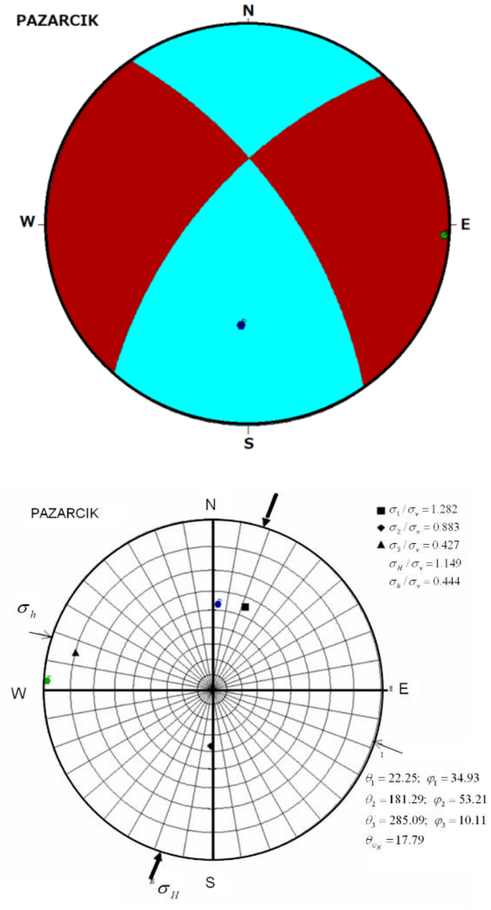

Figure 6. Focal mechanism by KOERI (2023) (re-drawn by the author) and its associated stress state for Pazarcık earthquake

Şekil 6. *Pazarcık depremi için KOERI (2023)'nin faylanma çözümü (yazar tarafından yeniden çizilmiştir) ve ilişkili gerilme ortamı*

Focal Mechanism Solutions for Ekinözü Earthquake

The focal mechanism of the Ekinözü earthquake was estimated by several seismological institutes and results are given in Table 7. The estimations imply that the earthquake occurred along a NE-SW trending fault with sinistral slip. Among all focal plane solutions, the focal plane computed by KOERI is close to the actual situations in view of rupture observations during the reconnaissance and the stress state for this solution is given in Table 8. As noted from Figure 7, the maximum horizontal stress is orientated in the direction of N65E. This implies that the stress state of the Pazarcık earthquake caused a great disturbance in the overall stress state of the region.

Discussions

Aydan (2016, 2020) evaluated the stress state of Türkiye using different techniques as shown in Figure 8 together with new additional data as well as those reported in the previous sections. The results plotted in Figure 8 obtained from various direct stress measurement techniques such as Acoustic Emisson (AE) method, stress relief method, flat jack method and indirect stress inference techniques such as GPS method, fault striation method, focal plane solution method (e.g. Aydan (2000a,b, 2020); Aydan and Paşamehmetoğlu, 1994; Tuncay et

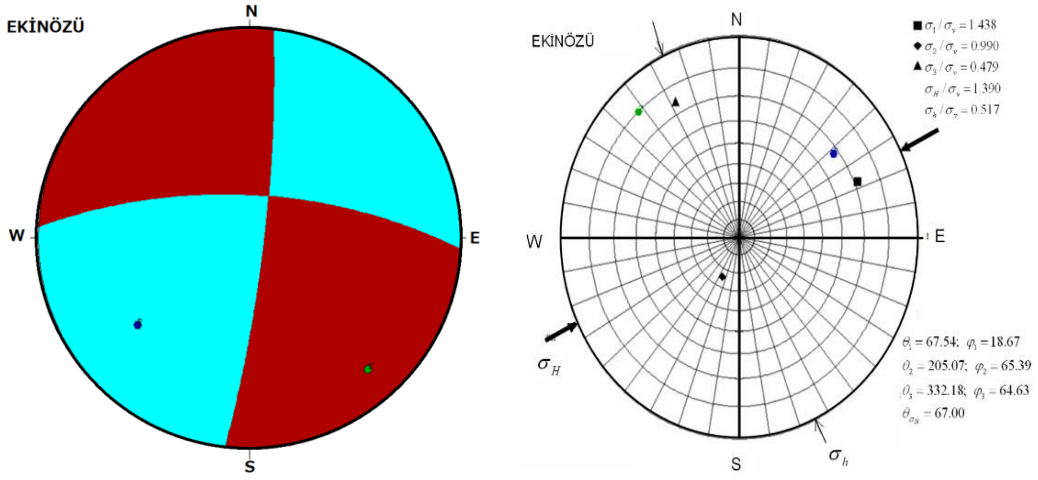

Figure 7. Focal mechanism by KOERI (2023) (re-drawn by the author) and its associated stress state for Ekinözü earthquake.

Şekil 7. *Ekinözü depremi için KOERI (2023)'nin faylanma çözümü (yazar tarafından yeniden çizilmiştir) ve ilişkili gerilme ortamı*

Table 7. Focal plane solutions by different seismological institutes for the Ekinözü Earthquake

Tablo 7. *Ekinözü depremi için değişik deprem kurumların elde ettiği faylanma mekanizması parametreleri*

Institute	Mw	LAT	LON	Depth (km)	Fault Plane			Auxiliary Plane		
					Strike	Dip	Rake	Strike	Dip	Rake
GCMT	7.7	38.1	37.2	12	261	42	-8	358	84	-132
USGS	7.6	38.0	37.2	19	276	82	-6	6	85	-172
KOERI	7.6	38.0	37.3	10	273	67	-9	6	81	-157
ERD	7.6	38.0	37.2	16	174	90	13	358	73	174
IPGP	7.7	38.0	37.2	13	270	60	-9	5	82	-150

Table 8. Computed results for Ekinözü earthquake (KOERI Solution)

Tablo 8. *Ekinözü depremi (KOERI çözümü) için elde edilen sonuçlar*

σ_1			σ_2			σ_3			$\frac{\sigma_h}{\sigma_v}$	$\frac{\sigma_H}{\sigma_v}$	d_{σ_H}
$\frac{\sigma_1}{\sigma_v}$	d_1	p_1	$\frac{\sigma_2}{\sigma_v}$	d_2	p_2	$\frac{\sigma_3}{\sigma_v}$	d_3	p_3			
1.438	68	19	0.990	205	65	0.479	332	65	1.390	0.517	65

al. (2002, 2003)). As noted from the figure, maximum horizontal stress directions tend to be aligned in the directions of N-S, NE or NW. However, the stress state in the Arabian, which subduct beneath Anadolu platelet, orientated mainly in NE direction. The domain shown in Figure 8 is expanded and the results shown in the previous sections are re-plotted in Figure 9 together with available data previously. The data obtained from the analyses of striations on fault scarps caused by the doublet earthquakes are denoted with different colours in the respective figures. The direction of the maximum horizontal stresses obtained for Pazarcık earthquake are quite similar to those of the previous evaluations. On the other hand, the stress state within the Anadolu platelet is mainly NW-SE in the north of latitude 38 degrees. The stress state south of latitude 38 degrees is N-S or similar to that inferred for Ekinözü earthquake. It seems that the stress state within the earthquake affected area is rather complex and there is no doubt that the confirmation of the true stress state through in-situ stress measurement techniques is desirable despite such measurements are quite scarce in Türkiye.

Some stress directions for striations observed in this region are reported by Chorowicz et al. (1994) and Yürür and Chorowicz (1998), they utilized a method proposed by Angellier (1984), which actually violates the principles of rock and fault mechanics together with an arbitrary assumption on the first principle stress invariant and it fails to evaluate the stress state for a single fault plane and striation in view of the fundamental definition of stress tensor (e.g. Aydan 2021, Eringen 1980). While the maximum horizontal stress orientations might be similar to those obtained in this study, the least horizontal stress will never be the same in terms of magnitude, orientation and sense of compression.

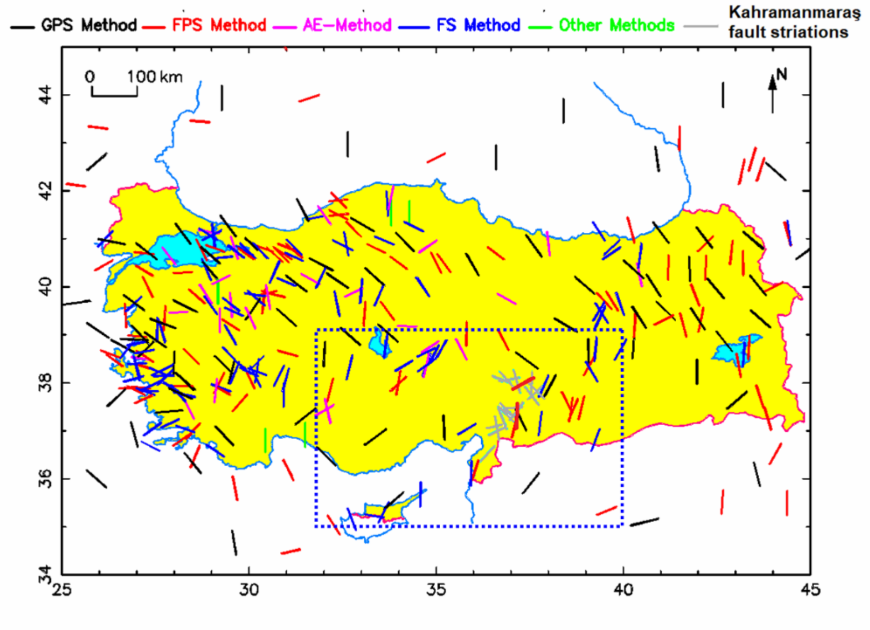

Figure 8. Distributions of maximum horizontal stress directions in Türkiye (from Aydan 2016, 2020) together with new additional data as well as those reported in the previous sections.

Şekil 8. *Aydan (2016, 2020) yayınladığı sonuçlar ve bu çalışmada elde edilen sonuçlar kullanılarak elde edilen Türkiye'de etkin en büyük yatay gerilme yönlerinin dağılımı*

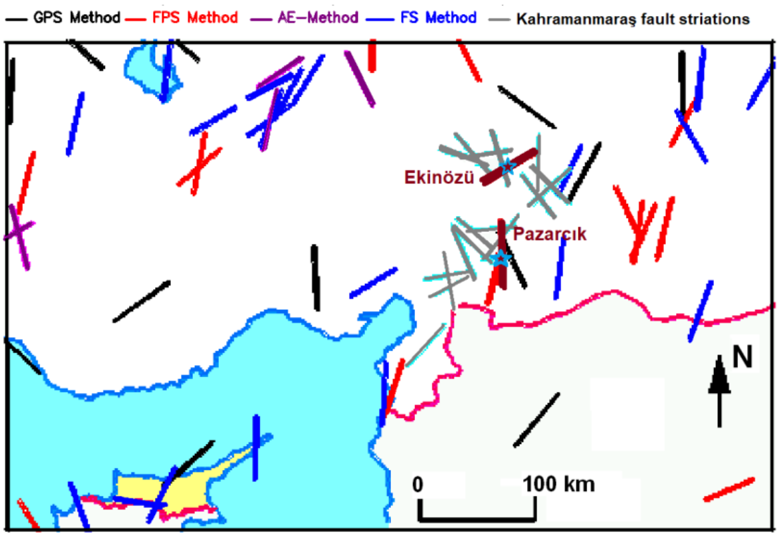

Figure 9. An expanded re-plot of the domain depicted in Figure 8

Şekil 9.*Şekil 8'de işaret edilen bölgenin büyütülmüş yeniden çizimi*

Following the Pazarcık and Ekinözü earthquakes or briefly Kahramanaraş earthquakes, some studies (e.g. Toda et al. 2023) were done on the stress changes using the Coulomb stress transfer method, which is based on static dislocation theory utilising the closed form solutions proposed by Okada (1992) for elastic isotropic half-space. However, this method can only evaluate static changes for a given prescribed displacement/traction distribution and it does not consider the total stress state acting in the earth's crust and the elasto-visco-plastic dissipation of stored energy during faulting. Therefore, the method can not evaluate the true stress state presented in this study. As also shown by Aydan (2015), it is possible to evaluate the changes of orientation and stress components due to earthquakes if peak and residual friction angles of the earthquake fault are available. In addition, better computational methods considering the three-dimensional crustal structure, stress state prior to earthquakes an elasto-visco-plastic dissipation of the stored energy are recently summarized and discussed in a text book by Aydan (2023) on Earthquake Science And Engineering.

CONCLUSIONS

The stress state obtained from the striation of the fault surface ruptures in this study can be usefull to infer the stress state of the earthquake region. The stress state along the fault segments of Dead Sea Fault Zone may be similar that of the Amanos segment. On the other hand, the stress state of the Pazarcık segment is slightly different than that of the Amanos segment. Furthermore, the orientation of the stress state of the Ekinözü earthquake differs by more than 40-50 degrees. This may imply that the stress states in the subducting Arabian plate and Anadolu platelet differ from each other, which is quite similar to the situation of Tokai Region in Japan (Aydan 2003, 2013). This difference is likely to be the main driving forces for earthquakes along the Çardak-Sürgü Fault. However, it is quite desirable to validate the estimations presented in this study through in-situ stress measurements available in the field of Rock Mechanics and Rock Enineering (Amadei and Stephanson, 1997; Aydan 2016, 2020). The borehole breakout method for deep oil and gas borings may also be used for assessing the stress field of this region.

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