ANALYSIS OF THE SEISMIC ACTIVITY IN TUZ GÖLÜ FAULT ZONE AND SURROUNDING AREAS FOLLOWING THE 2023 EAST ANATOLIAN EARTHQUAKES

by

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ABSTRACT

ANALYSIS OF THE SEISMIC ACTIVITY IN TUZ GÖLÜ FAULT ZONE AND SURROUNDING AREAS FOLLOWING THE 2023 EAST ANATOLIAN EARTHQUAKES

The aim of this study is to examine whether the major earthquakes that occurred in the East Anatolia in 2023 had an impact on the Tuz Gölü Fault Zone and its surroundings and to carry out earthquake analysis of the region since the earthquakes. During the study, the seismic activity of the region in the 9-month period starting from the February 6 earthquakes was examined using Kandilli Observatory and AFAD data. Focal mechanism solutions and relocation studies were also carried out to obtain detailed results. Following the 2023 Eastern Anatolia earthquakes, significant seismic activity was detected in the south of the Tuz Gölü Fault Zone in Central Anatolia. In this study, earthquake relocations and focal mechanisms related to this activity are discussed.

The relocation and focal mechanism solutions of the seismic activity of the region in the two-month period starting from the February 6 earthquakes shows that the activity occurred on two almost N-S structures that are to the west of Hasandağı Volcano. The mechanisms and epicenter locations are consistent with a right-lateral N-S fault for the eastern activity with some normal component. The activity might be related to the volcanism considering that they are on the proximity of fissures to the west of Hasandağı.

ÖZET

2023 Doğu Anadolu Depremleri Sonrası Tuz Gölü ve Çevresindeki Deprem Aktivitesinin İncelenmesi

Bu çalışmadaki amaç, 2023'te Doğu Anadolu'da meydana gelen büyük depremlerin Tuz Gölü Fay Zonu ve çevresinde bir etki yaratıp yaratmadığı hakkında incelemeler yapmak ve bölgenin büyük depremlerden bu yana deprem analizini gerçekleştirmektir. Çalışma sırasında Kandilli Rasathanesi ve AFAD verileri kullanılarak bölgenin 6 Şubat depremlerinden itibaren 9 aylık süreçteki sismik aktivitesi incelenmiştir. Yapılan incelemelerde 2023 Doğu Anadolu depremlerinin ardından Orta Anadolu'da Tuz Gölü Fay Zonu'nun güneyinde önemli sismik hareketlilik saptanmıştır. Bu saptama üzerine bölgedeki depremlerin yeniden mevki tayini ve odak mekanizmalarının çözümlemelerine çalışılmıştır.

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LIST OF SYMBOLS

s	Second
t	Time
m_b	Body wave magnitude
M_L	Local magnitude
M_0	Seismic moment magnitude
M_w	Moment magnitude

LIST OF ACRONYMS/ABBREVIATIONS

AFAD	General Directorate of Disaster and Emergency Management
E	East
JMO	Jeoloji Mühendisleri Odası
KOERI	Kandilli Observatory and Earthquake Research Institute
MTA	Maden Tetkik ve Arama Enstitüsü
N	North
S	South
SAC	Seismic Analysis Code
TDVMS	Türkiye Deprem Veri Merkezi Sistemi
TGFZ	Tuz Gölü Fault Zone
TMMOB	Türkiye Mühendis ve Mimar Odaları Birliği
W	West

1. INTRODUCTION

The goal of this study is to examine activity that initiated three days after the February 6 2023 Mw7.8 and Mw7.6 East Anatolia Earthquakes. East Anatolian doublet of 2023 led to significant seismic activity along the Anatolian block. A noticeable activity also occurred near Hasandağı which is located to the southwest of the Tuz Gölü Fault Zone.

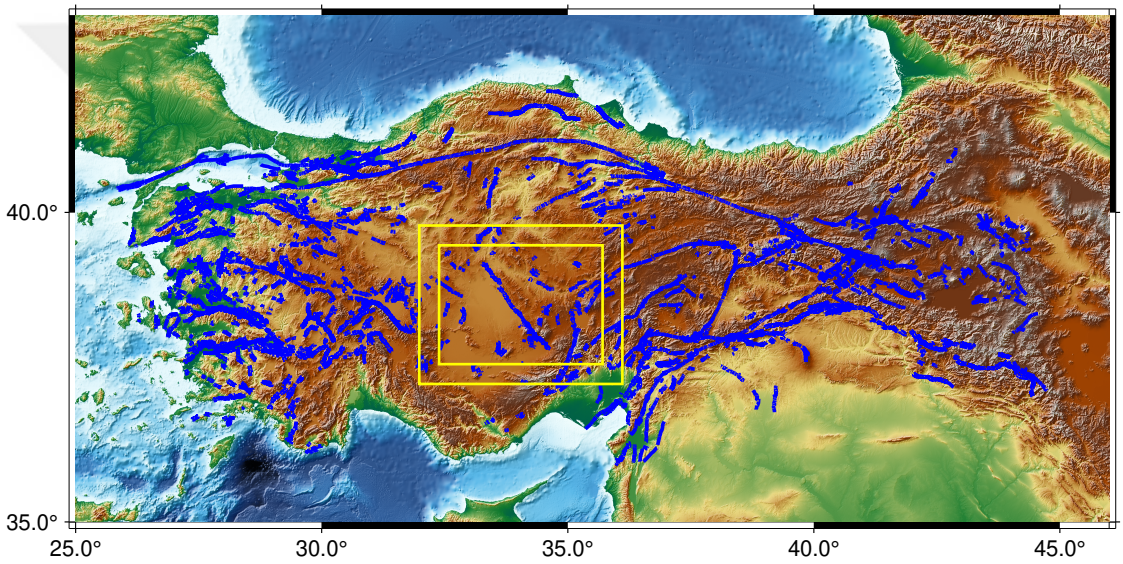


Figure 1.1. MTA active fault map of Türkiye (Emre et al., 2013).

In this study, we relocated the earthquake activity in this zone by combining AFAD and KOERI catalogs and relocating the earthquakes that occurred during a two-month period February-March 2023. In addition to earthquake relocations, we model the source mechanisms of earthquakes that are M>3.5 in order to understand the type of faulting, since the location of activity cannot be associated with the active fault map of Directorate of Mining and Exploration of Türkiye (MTA).

2. STUDY REGION

Central Anatolia forms part of the Anatolian block. Anatolian block is bounded by two major strike-slip fault zones, North Anatolian Fault Zone to the north and East Anatolian Fault Zone to the east. Due to rollback of along the Hellenic arc, Anatolia has a counterclockwise motion. In addition to motion along the boundaries there is significant internal deformation especially along the Aegean where N-S extension leads to crustal stretching and thinning (Le Pichon and Angelier 1981; Reilinger et al., 2006; Reilinger et al., 2010).

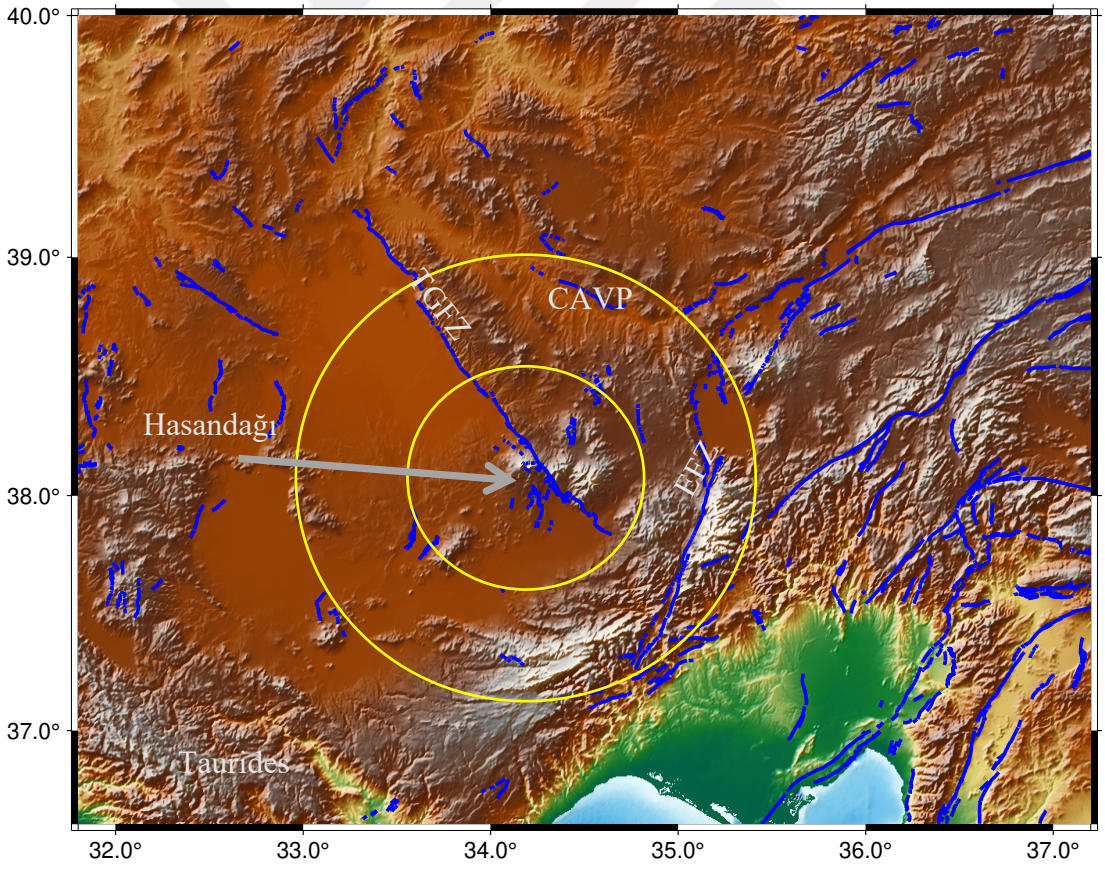


Figure 2.1. The study area with active faults and topography around Hasandağı. TGFZ: Tuz Gölü Fault Zone, EFZ: Ecemiş Fault Zone, CAVP: Central Anatolian Volcanic Province. Fault map is active fault map of MTA (Emre et al., 2013).

Central Anatolia is bounded by Tauride Mountains to the South, Pontite Mountains to the north. Although not as active as the other parts of Türkiye, there are active faults in the Central Anatolia. Tuz Gölü Fault Zone (TGFZ) is the most significant intra-continental active fault zone in Central Anatolia (Figure 2.1.). Tuz Gölü Fault forms the western boundary of the Central Anatolian Volcanic Province (CAVP). On the east the CAVP is cut by N-E striking left-lateral Ecemiş Fault Zone.

2.1 Tectonics

Tuz Gölü Fault Zone (TGZF) marks the western boundary of the Central Anatolian Volcanic Province (CAVP) and Hasandağı is at the southwestern corner of the CAVP. CAVP formed during various stages of closure of the Neo-Tethys Ocean (Figure 2.1., Gençalioğlu et al., 2008). The older volcanic units indicate a subduction related volcanism while younger eruptions are more post-collisional obduction related.

TGFZ is a right-lateral strike slip fault zone with a significant normal component, approximately 200-220 km long and 15-25 km wide, extending between Paşadağ in the northwest and Bor district in the southeast. While some geological studies indicate that TGFZ is a normal fault (Yıldırım, C., 2014), it is indicated as transtensional right-lateral fault (Toprak and Göncüoğlu, 1993). The section between Paşadağ and Bor is quite linear and consists of many parallel and semi-parallel faults with a length of 5-80 km. It borders the northeastern edge of the Tuz Gölü basin. TGFZ consists of eleven parallel or semi-parallel geometric fault segments with lengths varying between 9 and 30 km. It is assumed that TGFZ segments can produce earthquakes with a maximum magnitude of M=6.11–6.80 (Kürçer, A., 2014), (TMMOB, JMO, Konya Earthquake Report, 2020).

On the northern end of the fault zone, earthquakes are predominantly right-lateral as observed during the Bala and Afşar Earthquake sequence during 2005 and 2007 (Kalafat and Görgün 2019).

In terms of active tectonics, the seismicity and the function of the major faults in Central Anatolia are not well understood. The strain rate on these faults is too low to infer the motion from geodetic data (Weiss J. R., 2020).

3. EARTHQUAKE ACTIVITIES AROUND TUZ GÖLÜ FAULT ZONE

There have been 28 earthquakes with M ≥ 4.0 in this region since 1900, the largest being Mw5.7 (AFAD, 2020).

There are 732 earthquakes in the KOERI catalog within the ten-year period before February 6, 2023 in the vicinity of Tuz Gölü Fault Zone (Figure 3.1.). In the same time-period, there are 564 earthquakes in AFAD catalog. The epicenter distribution of these events show that these events are located along the Tuz Gölü Fault Zone, to the south of Tuz Gölü and to the west of Hasandağı. Especially the activity to the west of Hasandağı in 2020 is quite noticeable (Figure 3.3.).

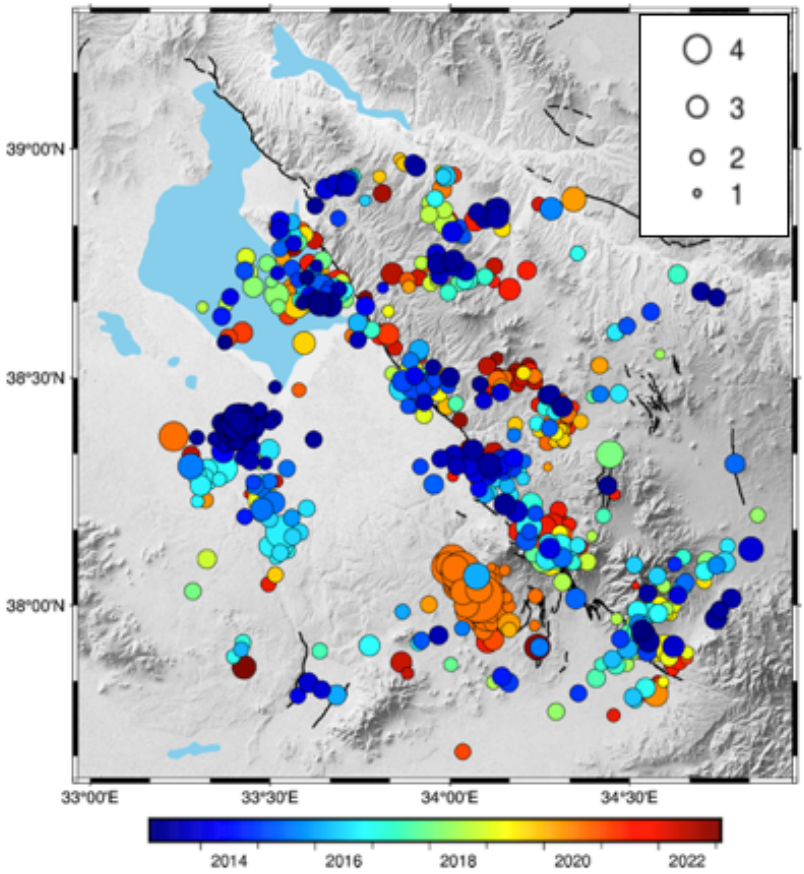


Figure 3.1. Epicenters of earthquakes in KOERI earthquake catalog during the last ten years preceding the February 6th 2023 earthquakes. The colors are scaled with the time of the earthquake.

In the nine-month period following February 6, 2023, 83 earthquakes were listed in the AFAD catalog. 119 were recorded in the region in the nine months following the February 6, 2023 sequence according to the data of Kandilli Observatory (Figure 3.2.). The majority of this activity is on the southwestern end of the TGFZ where no active or inactive fault is mapped by the General Directorate of Mineral Research and Exploration (MTA).

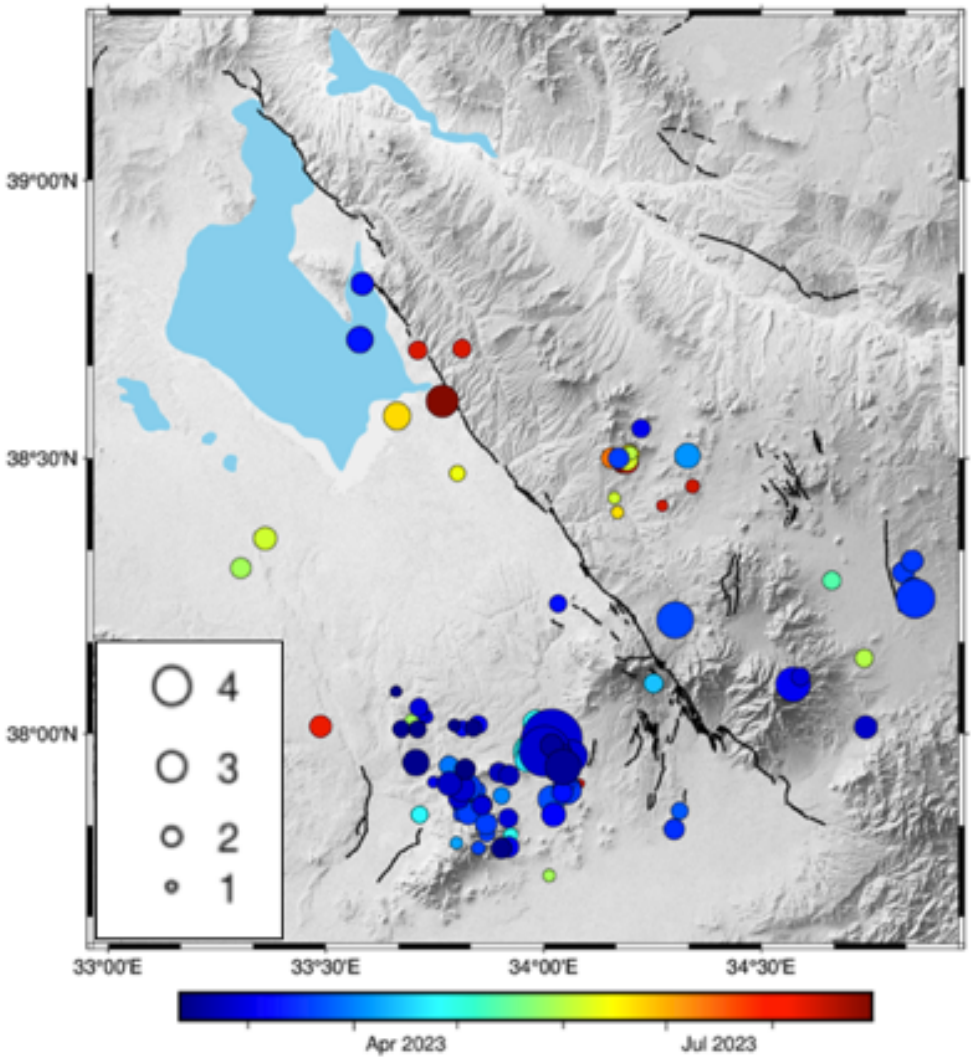


Figure 3.2. Epicenters of earthquakes in KOERI earthquake catalog during the first nine months following the February 6th 2023 earthquakes.

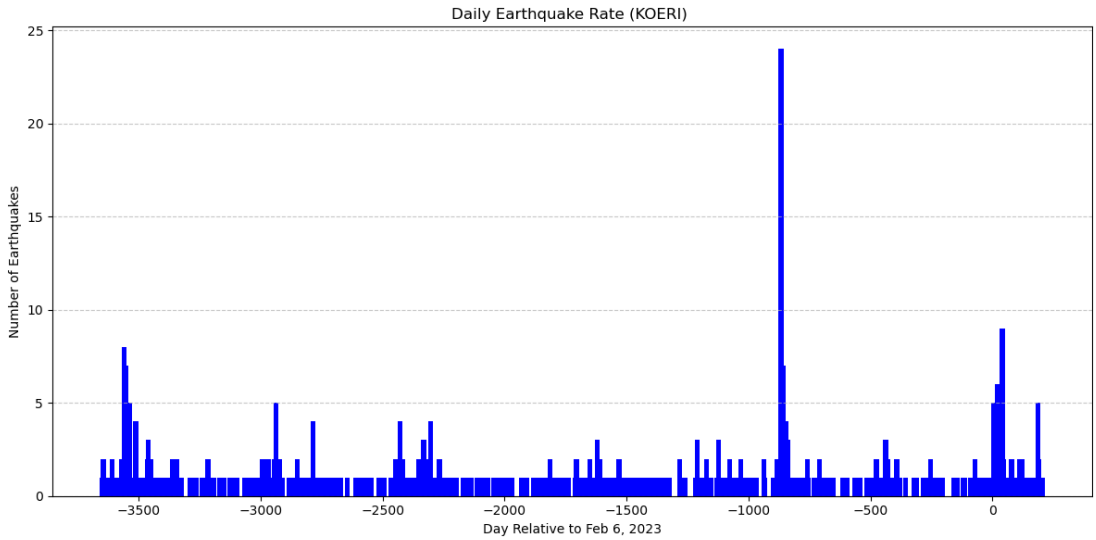


Figure 3.3. Daily Earthquake Rate of the Kandilli catalog around Tuz Gölü Fault Zone in last ten years. The region is the same as Figure 3.1. and Figure 3.2.

Our primary interest was to look at structures triggered by the 2023 earthquakes. In this study we focused on the activity following February 6, 2023 Mw7.8 and Mw7.6 earthquakes to the west of Hasandağı.

3.1. Focal Mechanisms

Four earthquakes larger than magnitude 4 were recorded in the region in the last decade before February 6, 2023 according to AFAD (Figure 3.4.). These earthquakes have almost pure strike-slip, with either left lateral east-west striking or right lateral north-south striking mechanisms (Table 3.1.).

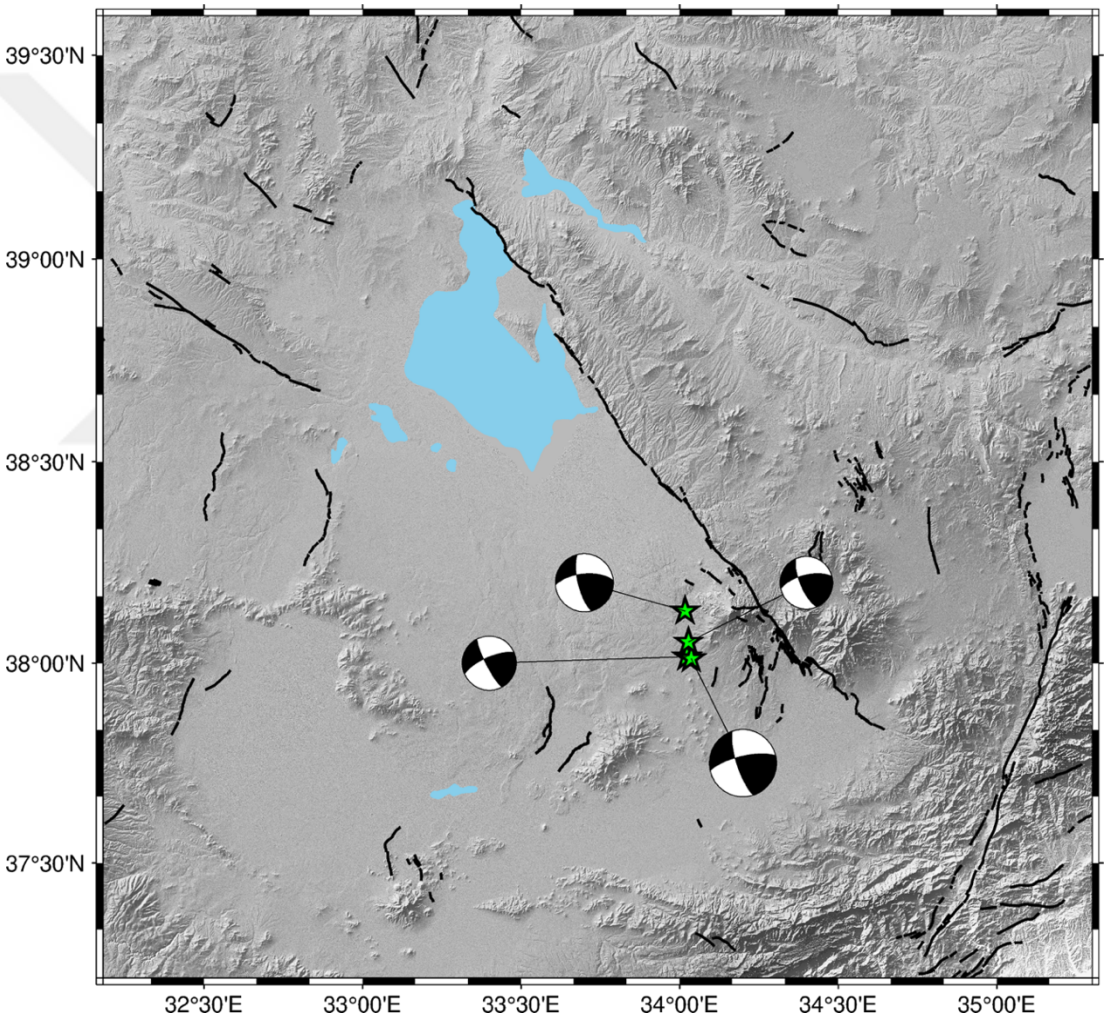


Figure 3.4. AFAD focal mechanism solutions last ten years before 6th February 2023.

Table 3.1. AFAD Focal Mechanism Solutions

Date	Mw	Latitude	Longitude	Depth	Strike	Dip	Rake
2020.09.20	5.1	34.0370	38.0110	6.20	162	75	-162
2020.09.21	4.1	34.0233	38.0156	7.03	153	80	-162
2020.09.24	4.4	34.0175	38.1298	2.67	166	72	-153
2020.09.30	4.0	34.0281	38.0525	6.98	157	71	-154
2023.02.24	4.5	34.0040	37.9580	3.41	18	50	-107
2023.02.25	5.3	33.9930	37.9870	2.28	267	88	-4

Table 3.1. AFAD Focal Mechanism Solutions around Hasandağı.

Two earthquakes larger than magnitude 4 were recorded in the region in the last nine months after February 6, 2023 according to AFAD (Figure 3.5.). One of the earthquakes have a similar mechanism to those before however the other focal mechanism is given as a pure normal fault (Table 3.1.).

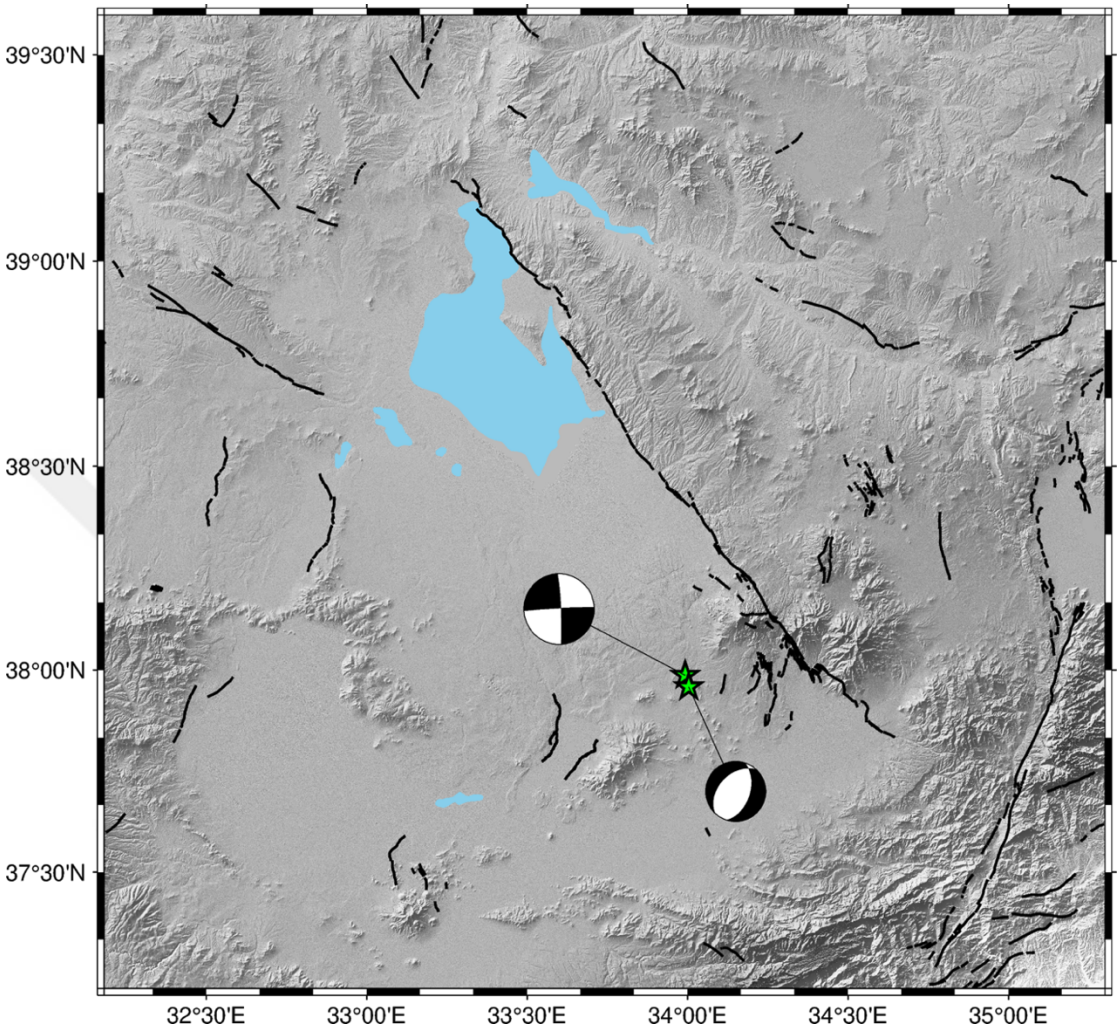


Figure 3.5. AFAD focal mechanism solutions first nine months after 6th February 2023.

In this study, we focus on this region that is west of Hasandağı Volcano, and try to understand the faulting that is related to this unusual activity. Volcanic regions are sensitive to stress perturbations because of the presence of highly pressurized fluids in volcanic fissures (Manga, M., 2012).

4. DATA & METHODS

4.1. Earthquake Relocation

In order to obtain the relocations of the activity following the 2023 East Anatolian Earthquakes, we compiled the data from KOERI and AFAD. Total of thirty-nine stations were used, fourteen of which were from Kandilli Observatory and twenty-five from AFAD. The seismometers consist of broadband, accelerometer, and short period instruments. The stations were selected within an approximately 250 km width of the examined area. The data of the selected stations covers a two-month period, starting from midnight on 6 February 2023 at 00:00 until 00:00 on 31 March 2023, in order to examine the earthquake activity of the Tuz Gölü Fault Zone and its surroundings after the 6 February 2023 Kahramanmaraş earthquakes. Data were downloaded from KOERI and TDVMS websites in miniseed format.

Then, the catalogs from AFAD and KOERI were merged for the region south west of Hasandağı between latitudes 37.8037, 38.9572 and longitudes range of 33.2114, 34.7247. The merged catalog has seventy-three events in February and March 2023.

Afterwards, we used a python script by utilizing the ObsPy package (Kircher et al., 2015) to cut event-based waveforms from the continuous data and to convert them into SAC format (Goldstein et al., 2003; Goldstein & Snoke, 2005) format files (Kircher. et al., 2015). The SAC files have the initial picks from the phase catalog.

Finally, we manually picked P and S arrival times and generated new phase arrival catalogs in NORDIC format and relocated the earthquakes using HYPOCENTER algorithm which is part of the SEISAN package (Haskov and Ottermuller 1999; Haskov et al., 2020). For the calculated travel times, we used the velocity model from Yolsal Çevikbilen et al., (2012) as tabulated in Table 4.1.

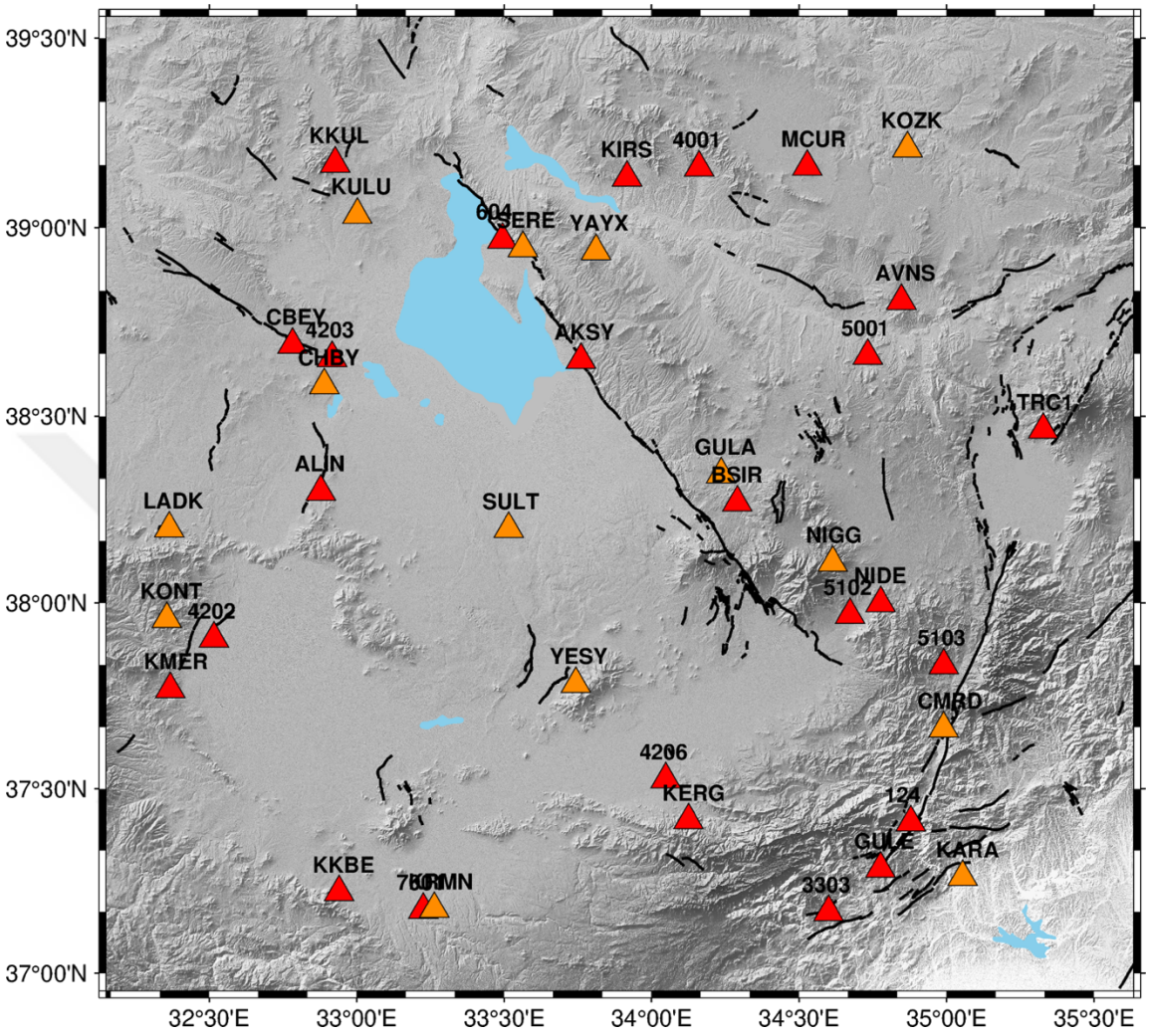


Figure 4.1. Station map used for earthquake relocation. Red triangles show the AFAD stations and orange triangles show the Kandilli Observatory stations.

Table 4.1. shows that the velocity model which is used in the study region adopted from Yolsal-Çevikbilen et al., 2012.

Table 4.1. The 1-D *P*-wave velocity model used for the study area.

Layer Depth (km)	Layer Thickness (km)	Vp (km s^{-1})
-2.0	-2.0	2.15
0.0	5.0	3.86
5.0	2.0	5.66
7.0	2.0	5.99
9.0	2.0	6.09
11.0	4.0	6.10
15.0	5.0	6.18
20.0	10.0	6.20
30.0	10.0	6.62
40.0*	10.0	7.67
50.0*	-	8.10

*Denotes an undetermined layer velocity by the 1-D inversion.

Table 4.1. Velocity model which is used in the study region (Seda Yolsal Çevikbilen, et al., 2012).

4.2 Focal Mechanism Solutions

Our initial goal was to use first motion polarities to constrain the focal mechanisms of earthquakes. However, our preliminary attempts showed us that the constraint from first motion polarities is quite limited. In order to remedy this situation, we used a regional waveform inversion scheme.

In that regard, we utilized the GROND package (Heimann et al., 2018) which is part of the Pyrocko package (Heimann et al., 2017) which is a Python package used in seismology and geodesy. In this package, the regional Rayleigh and Love waves are modeled using a 1-D Green's functions. A Bayesian bootstrap is applied to determine the station weights and model parameter uncertainty. The period range of the filter for the events larger than M4 are 30 to 50 s. For the events that are M4 and smaller events, the data and model predictions are 15 to 33 s. A time shift of 4 s is allowed to account for Green's function errors, but there is also a penalty term in the inversion for shift in the inversion scheme.

5. RESULTS

Two-month period earthquake relocations have been carried out since February 6, 2023. Total of seventy-three earthquakes were examined and the arrival times of P and S waves to the stations were peaked manually, and fifty-three of them could be relocated. Due to the low data quality of the remaining twenty earthquakes, relocation of those earthquakes could not be performed.

The P and S travel time residuals from all stations are shown in Figure 5.1. Most of the P arrival time residuals are between ±0.5 seconds. The S travel time residuals are higher as expected. Figure 5.2-5.6 show the travel time residuals for each station. For most of the stations, 1-σ residual for P wave arrivals is 0.2 to 0.3 s. 1-σ S-wave arrival residuals for stations with statistically significant number of phase picks are between 0.34 and 0.75 s. In some stations there is also some mean residual, which implies that the residuals are not centered around zero. This could be corrected using a station correction term, but since we used a velocity model from another study, we did not add any station corrections.

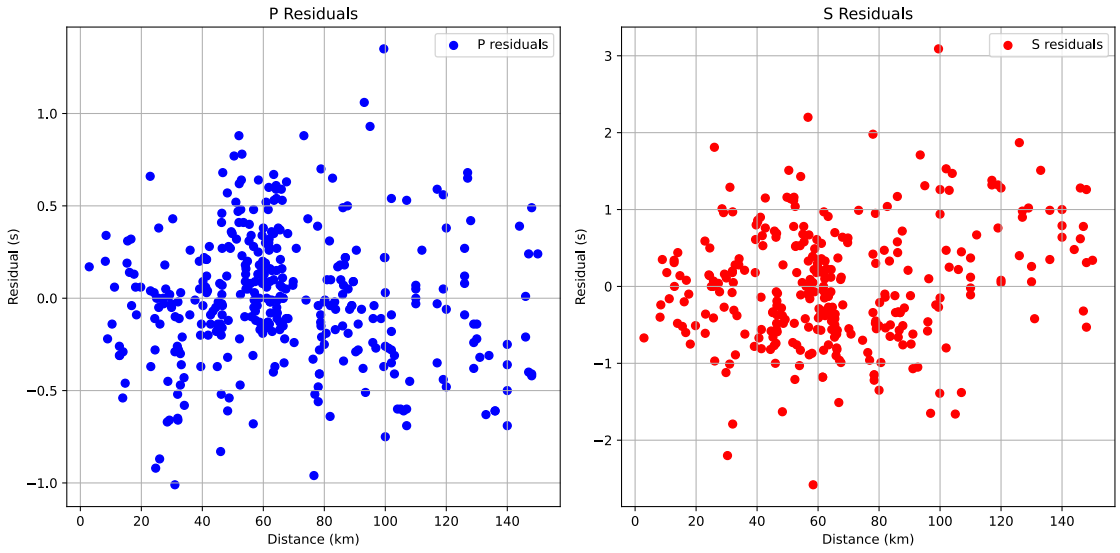


Figure 5.1. Distance from the earthquake vs P and S travel time residuals (travel time pick minus the model predicted travel time) of the Kandilli catalog around Hasandağı.

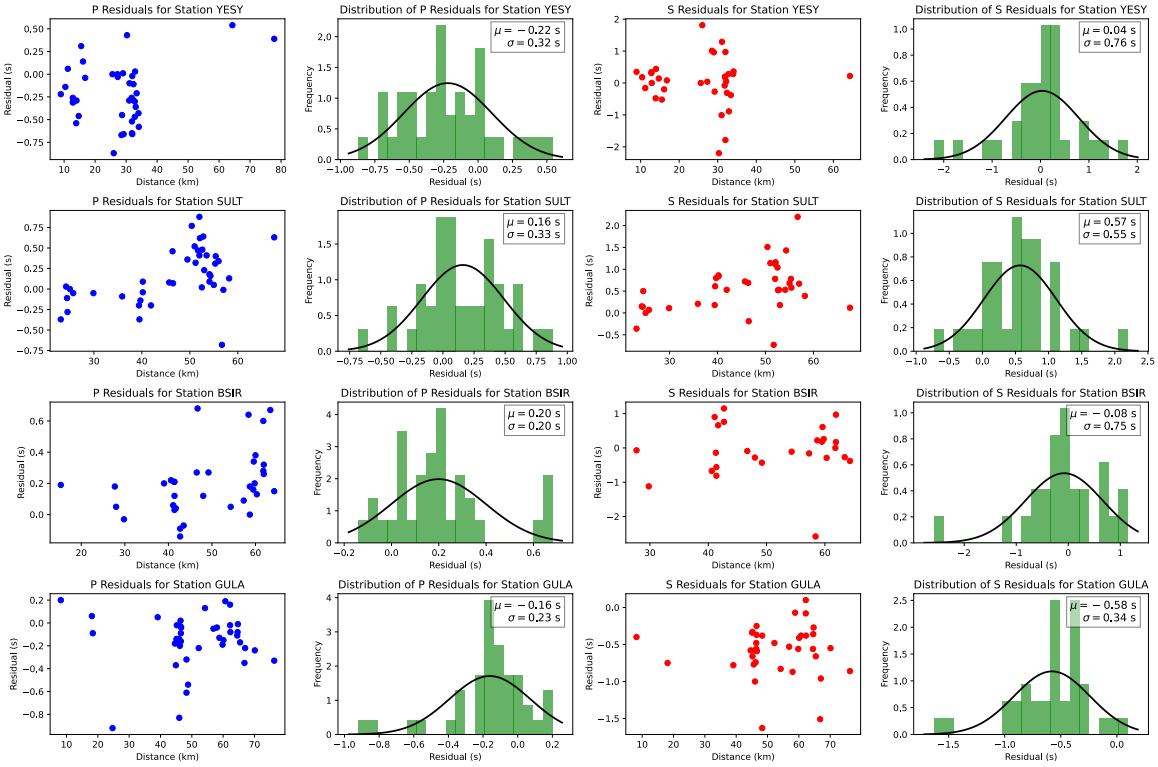


Figure 5.2. Travel time residuals for stations YESY, SULT, BSIR and GULA.

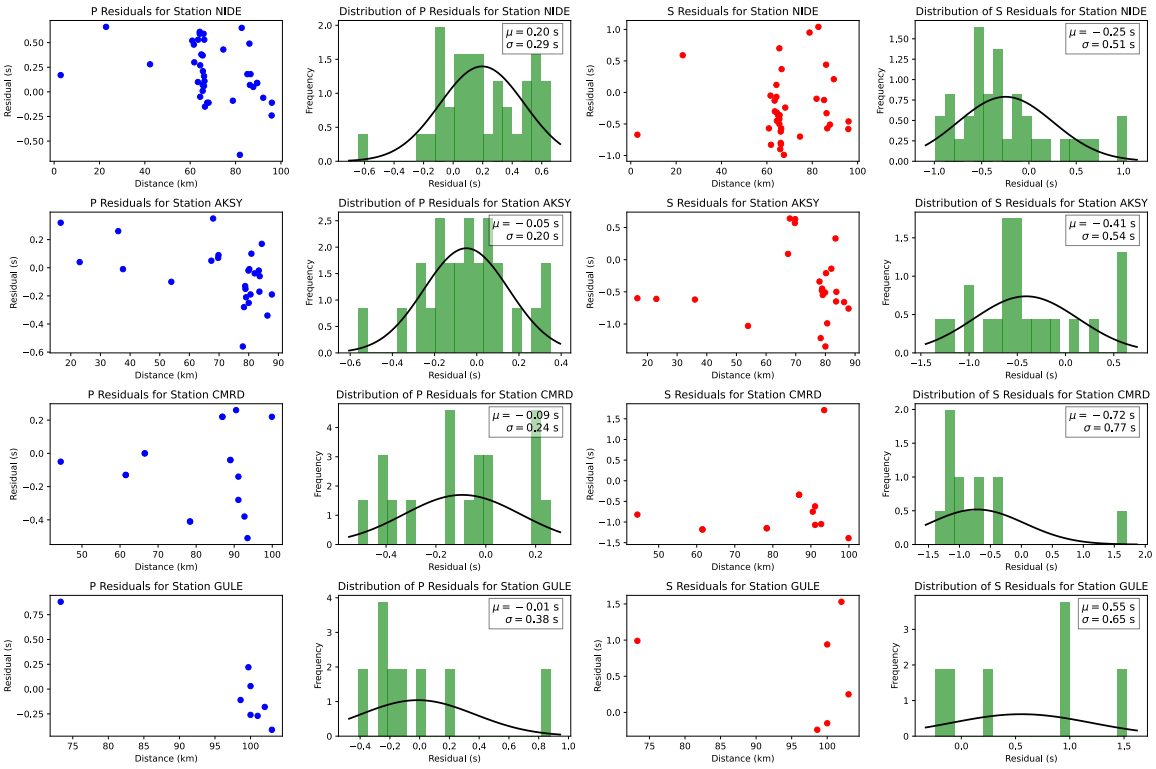
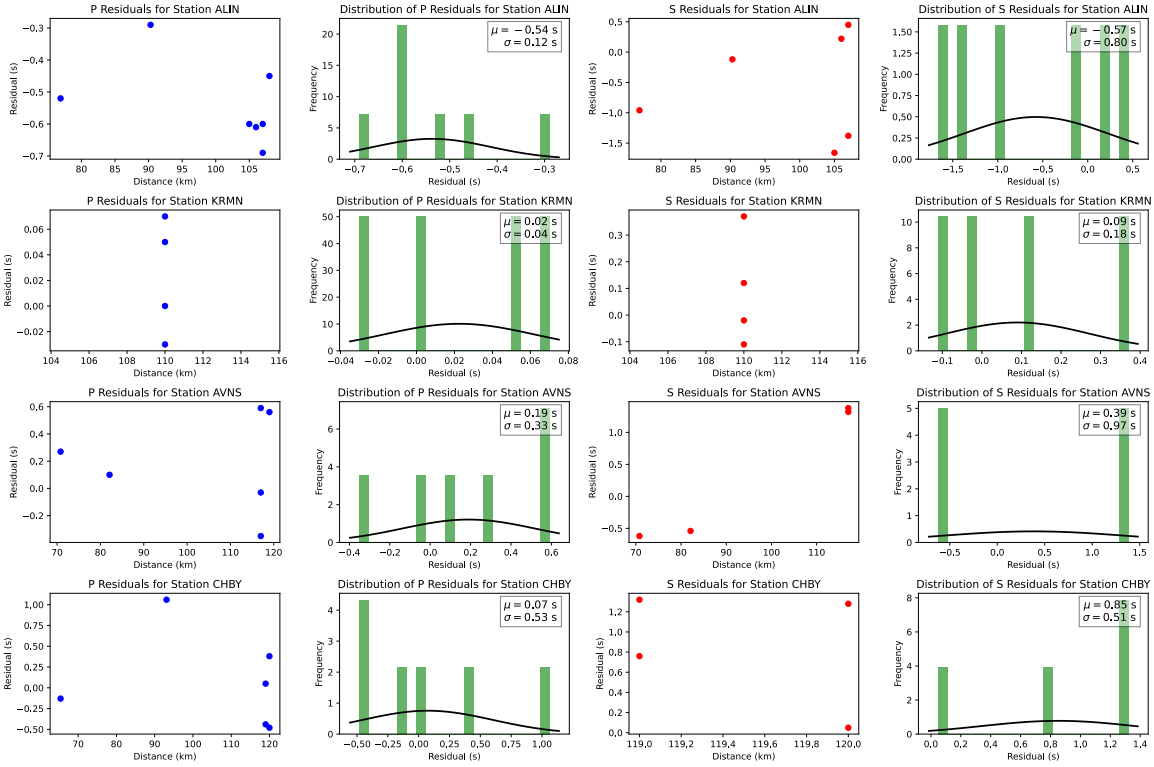


Figure 5.3. Travel time residuals for stations NIDE, AKSY, CMRD and GULE.



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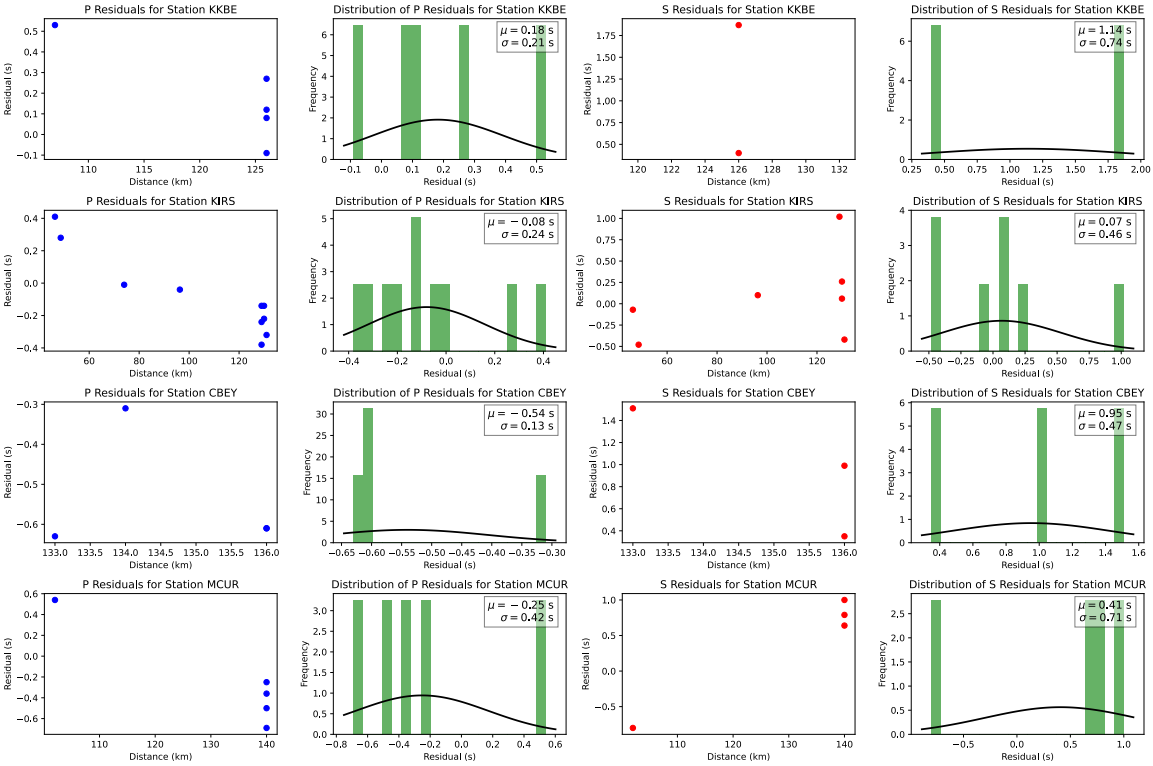

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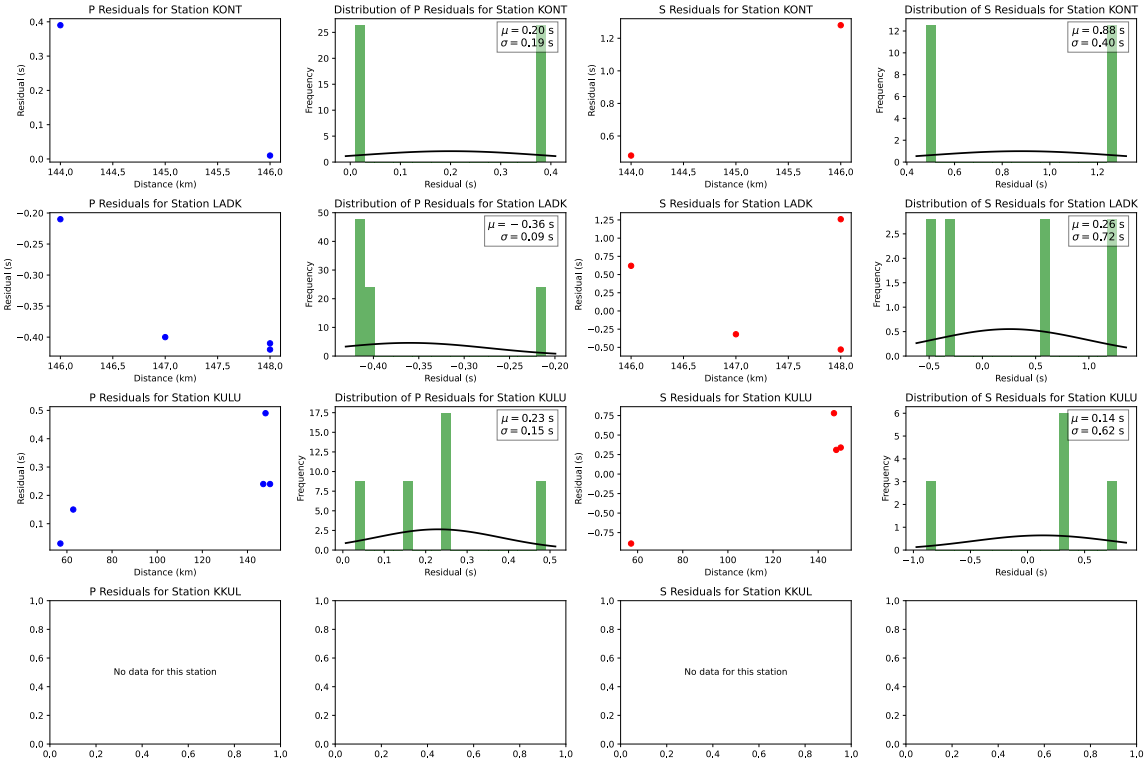

Figure 5.6. Travel time residuals for stations KONT, LADK, KULU and KKUL.

Figure 5.7. shows the earthquake distribution after relocation. In this figure, that black circles represent the relocated locations with the given scale on the left bottom. The red line segments show the original location of the same earthquake in the Kandilli catalog. While some of the earthquake epicenters have significantly shifted most of them are at similar locations to the original locations.

The distribution of epicentral locations show that these earthquakes occurred along two almost N-S lineation and are not located on any known fault of the active fault map of Türkiye (Emre et al.,2013).

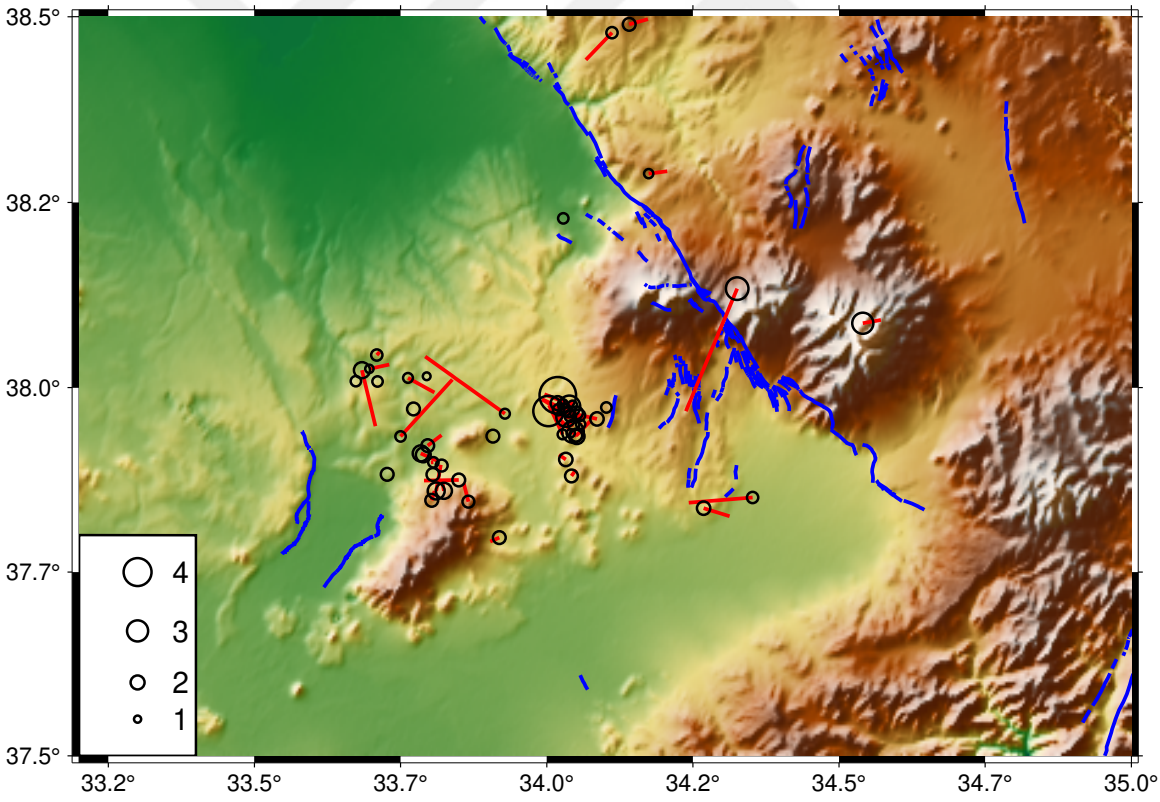

Figure 5.7. Black circles represent the relocated locations while the red line segments show the epicenter location in the Kandilli catalog. The circles scale with the earthquake magnitudes based on the scale given on the bottom-left.

In order to understand the faulting related to these earthquakes we employed a regional waveform based CMT solution of the 2023 sequence. Since the distribution of the earthquakes is quite limited, we also added earthquakes that occurred during the 2020 cluster (Figure 3.1., Figure 3.3.).

Figure 5.8 shows an example of station distribution and weighting for one of the earthquakes. We only consider the stations that are less than 300 km apart from the earthquake source. In most cases the azimuthal coverage is quite sufficient.

The earthquake is an Mw5.2 earthquake which occurred on September 20, 2020. Figures 5.9., 5.10. and 5.11. show the data and model fits for the September 20, 2020 earthquake. The quality of the fits shows that the velocity model from Yolsal-Çevikbilen et al., 2012 is adequate for waveform modeling.

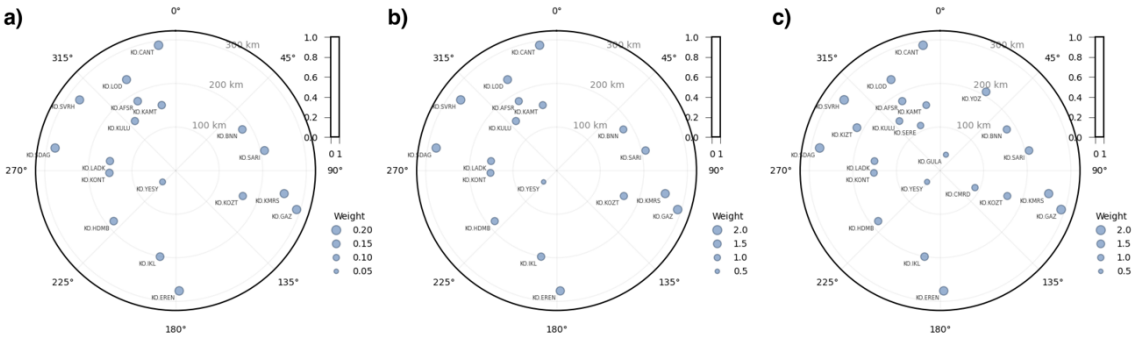

Figure 5.8. Station distribution and weights for Mw5.2 2020/09/20 earthquake for a) Tangential b) Radial c) Vertical component. Each station is represented by a circle based on its distance and azimuth with respect to the source location. The circle sizes scale with weight.

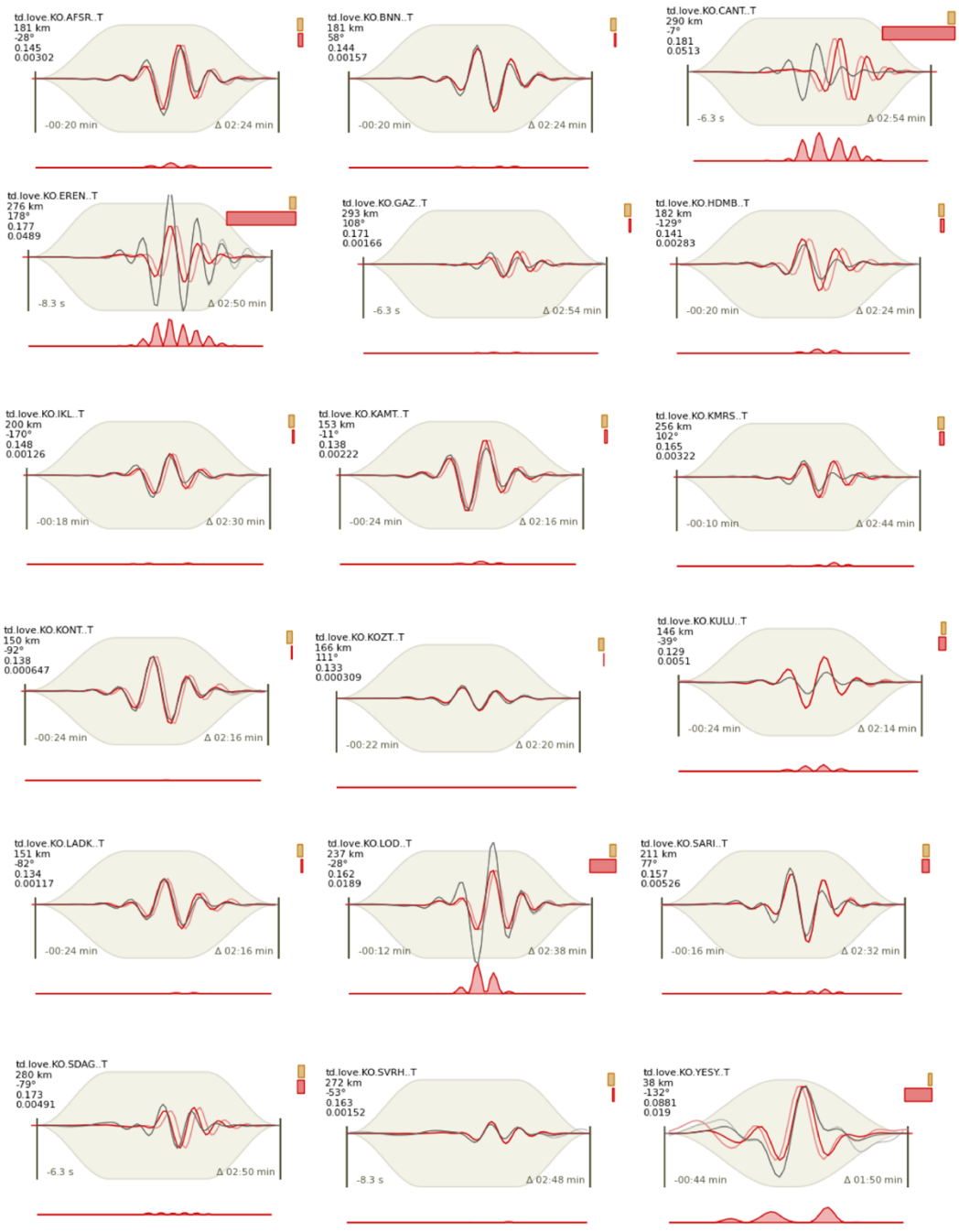

Figure 5.9. Tangential data (black) and synthetics (red) traces for the for Mw5.2 2020/09/20 earthquake. The original model traces are shown in light red while filtered and shifted model predicted waveforms are shown in red. The gray background shows the taper window. The station information is given on top left of each trace. The red curve below each trace show the difference between the data and model predictions that contribute to the total misfit. The red bars at top right indicate the relative contribution to the total misfit.

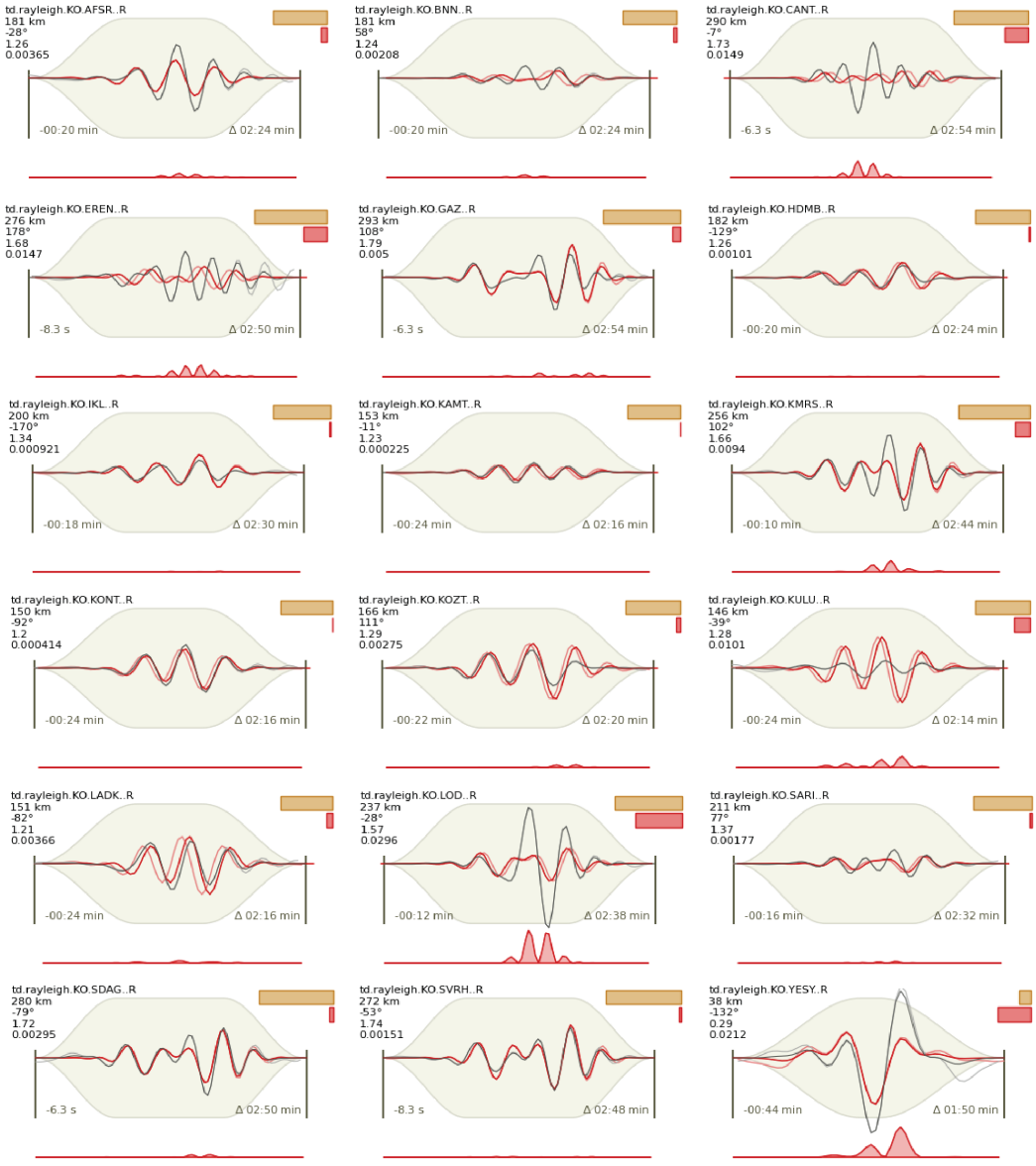

Figure 5.10. Radial data (black) and synthetics (red) traces for the for Mw5.2 2020/09/20 earthquake. The original model traces are shown in light red while filtered and shifted model predicted waveforms are shown in red. The gray background shows the taper window. The station information is given on top left of each trace. The red curve below each trace show the difference between the data and model predictions that contribute to the total misfit. The red bars at top right indicate the relative contribution to the total misfit.

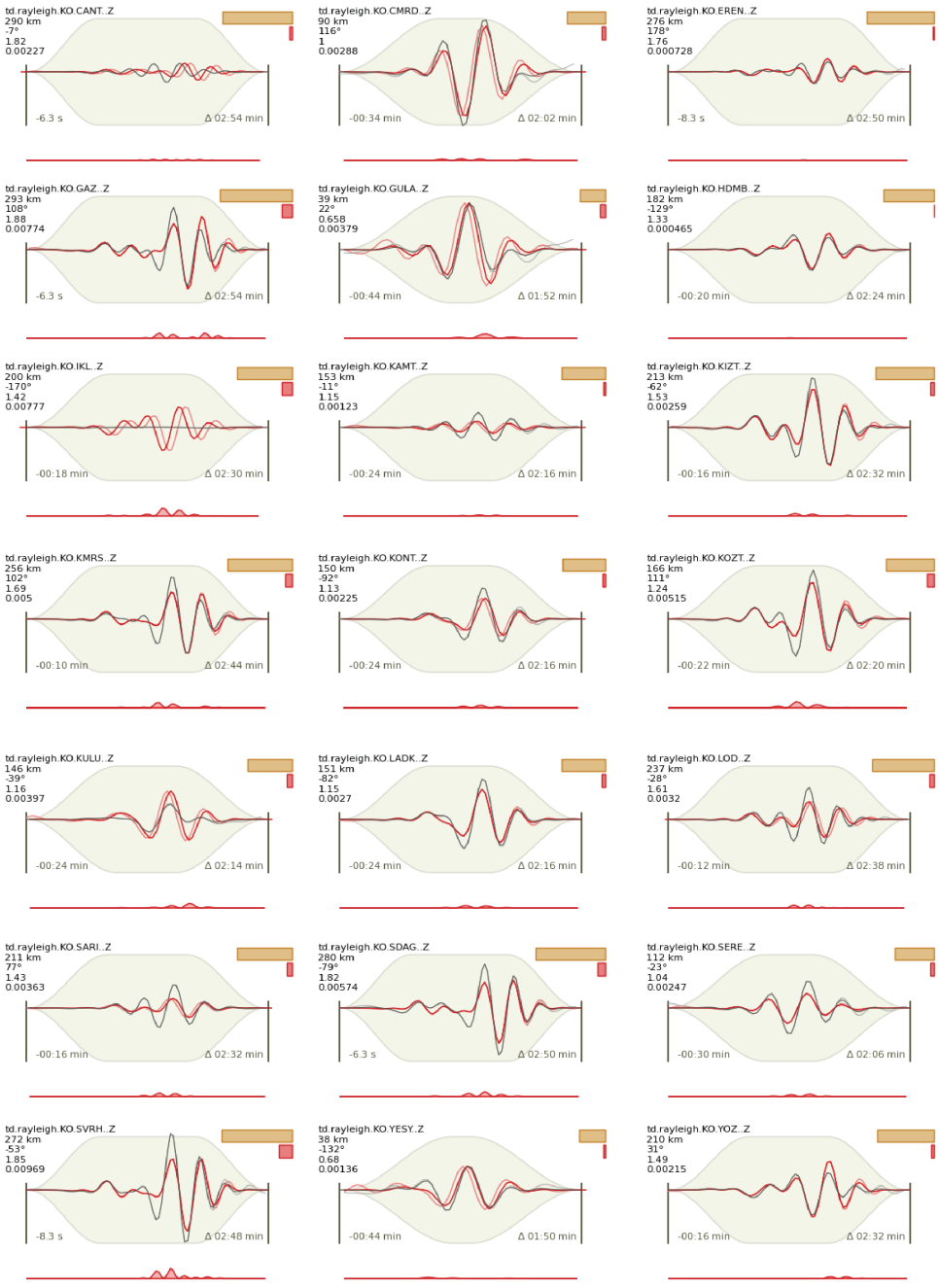

Figure 5.11. Vertical data (black) and synthetics (red) traces for the for Mw5.2 2020/09/20 earthquake. The original model traces are shown in light red while filtered and shifted model predicted waveforms are shown in red. The gray background shows the taper window. The station information is given on top left of each trace. The red curve below each trace show the difference between the data and model predictions that contribute to the total misfit. The red bars at top right indicate the relative contribution to the total misfit.

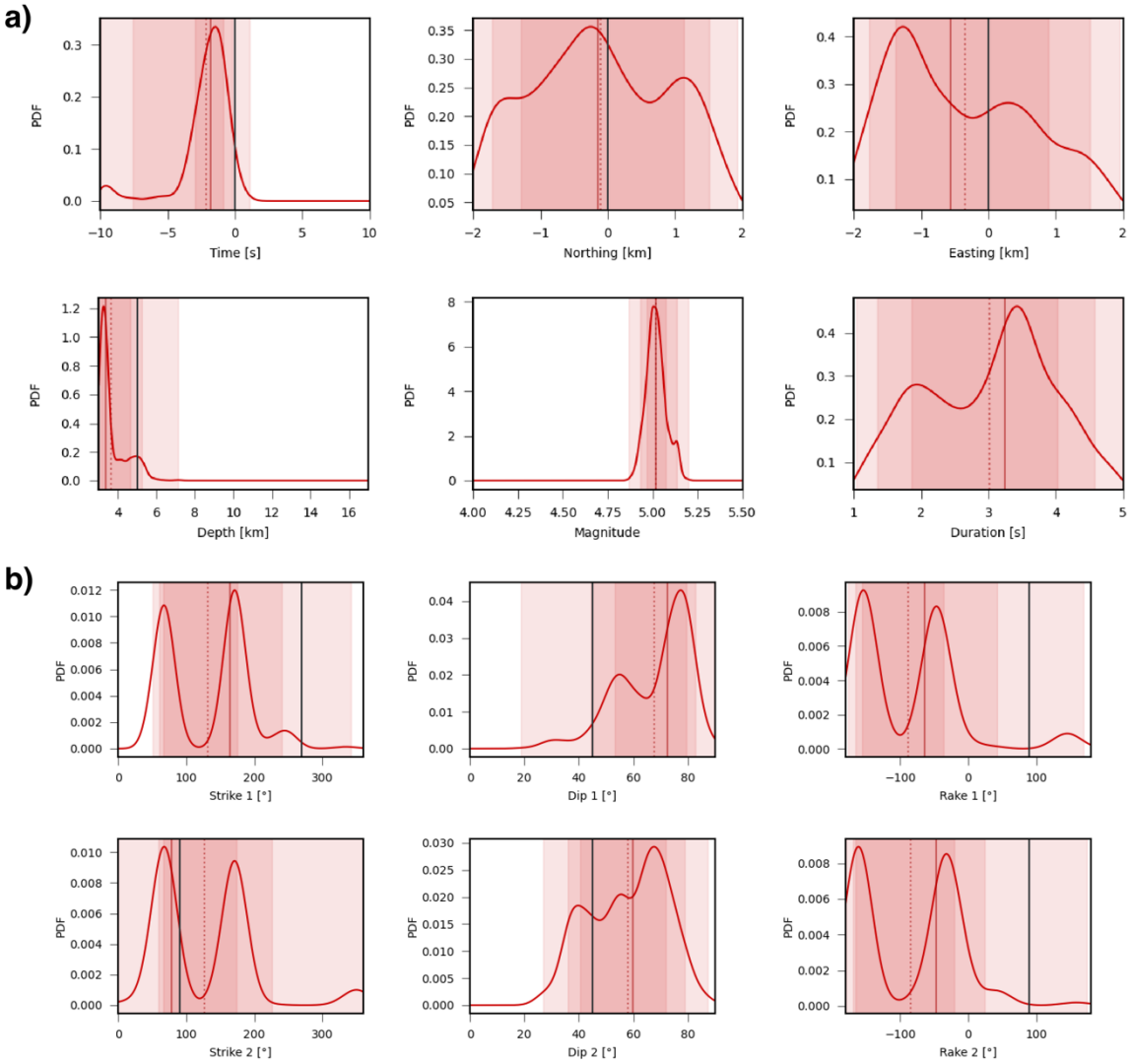

Figure 5.12. The probability distribution of model parameters obtained by Bayesian bootstrapping. The double peaks in strike, dip and rake is the result of the double couple radiation pattern.

Figure 5.12. shows the probability distribution of parameters. We constrain the earthquake depth to be between 3 and 18 km. The Mw5.2 event turns out to be very shallow, close to the upper limit allowed in the inversion. The source parameters are generally well resolved as shown in Figure 5.12.

We were able to obtain focal mechanism solutions for three earthquakes for the earthquakes triggered by the February 6, 2023 earthquake. In order to better understand the faulting, six earthquake focal mechanism solutions for 2020 and one more solution for 2016 were made in the same region. A total of ten earthquake focal mechanism solutions were added to the focal mechanism catalog. Figure 5.13. shows the 3 solutions from the 2023 cluster and 7 earthquakes from the previous activity. The mechanisms are listed in Table 5.1.

All of the earthquake CMT locations in Table 5.1. are very shallow with maximum depth of 8 km while most of them have depths of 5 km or less. Figure 5.13. shows the 2023 cluster and mechanisms of the previous activity on a map view.

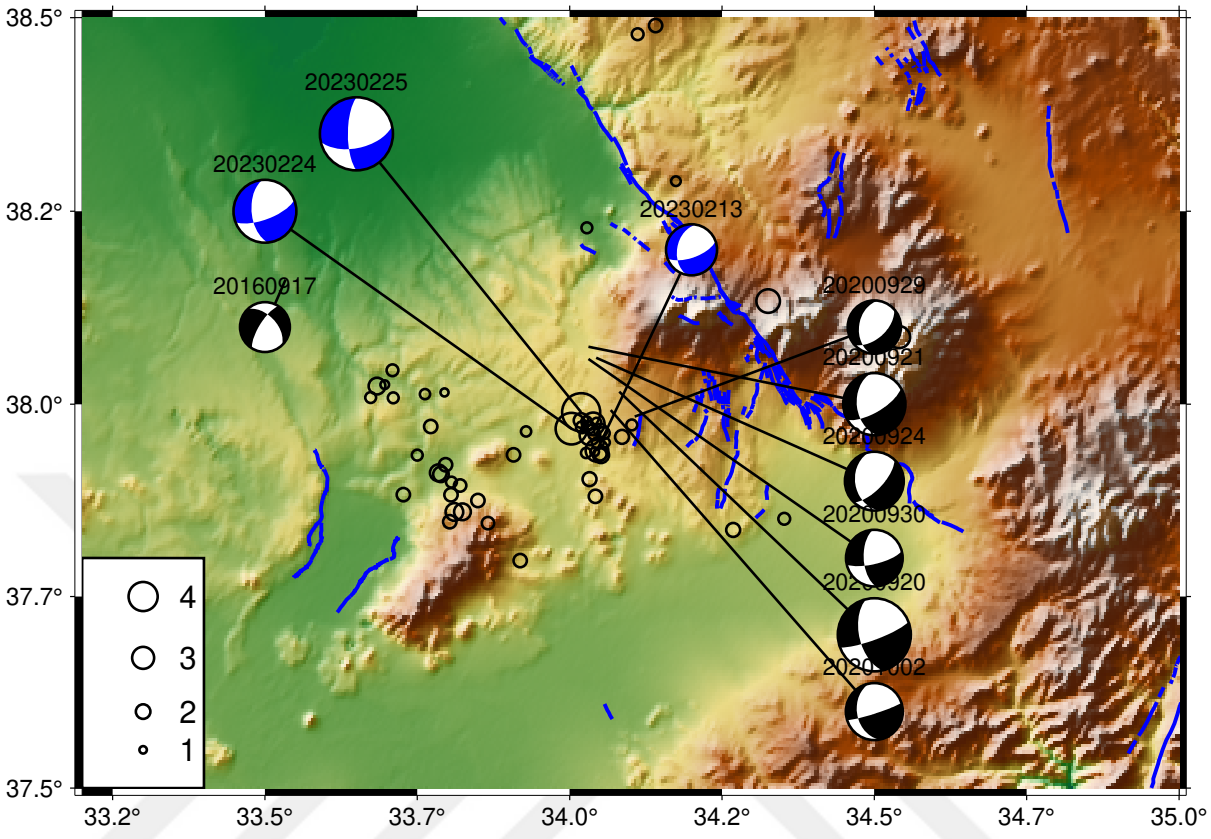

Figure 5.13. Focal mechanism solutions of earthquakes in the study area around Hasandağı. The blue beachballs show the mechanisms during the 2023 activity while the black beach balls are the mechanisms of prior earthquakes.

Most of the earthquakes have oblique mechanisms. Considering the distribution of epicenters and mechanisms it is very likely that the activity around 34° longitude show oblique right-lateral faulting with some normal component. The lineation of the epicenters of the 2020 sequence and the 2023 cluster show a possible faulting of ~30 km striking along N-S direction.

The second activity further west does not have large enough events during the 2023 activity to resolve the source mechanisms. We did find an event that occurred in 2016 further north, in which the mechanism might indicate the same strike direction as the activity. However, this activity requires further study to understand the exact pattern of behavior.

Table 5.1. Focal Mechanism Solutions

Date	Mw	Latitude	Longitude	Depth	Strike	Dip	Rake
2016.09.17	3.4	33.5338	38.1613	6.1	212	72	-40
2020.09.20	5.0	34.0815	38.0163	3.4	167	56	-167
2020.09.21	4.3	34.0308	38.0745	4.5	174	43	-148
2020.09.24	4.0	34.1068	38.0603	5.7	171	35	-137
2020.09.29	3.6	34.0435	37.9838	3.2	188	42	-122
2020.09.30	3.9	34.0308	38.0587	3.3	177	59	-160
2020.10.02	3.9	34.0673	37.9923	6.1	170	39	-170
2023.02.13	3.5	34.0447	37.9400	5.0	190	43	-142
2023.02.24	4.3	34.0028	37.9682	7.8	175	55	-154
2023.02.25	5.0	34.0188	37.9895	5.0	180	71	-146

Table 5.1. Focal Mechanism Solutions obtained in this study for earthquakes around Hasandağı.

6. DISCUSSION

In this study or goal was to examine a cluster of seismicity triggered by the 2023 East Anatolian Earthquakes. The cluster was located to the west of Hasandağı Volcano. The activity was relocated using manual phase picks from stations nearby.

The relocated activity can be identified as occurring on two subparallel orientations. The western cluster show an NNW-SSE lineation while the activity on the east is shows a N-S elongation. We also note that in the AFAD catalog the two mechanisms are listed for the activity following 2023 earthquake (Table 3.1., earthquakes on 2023.02.24 and 2023.02.25). One of the earthquakes is pure strike slip while the other is pure normal although their locations are very similar. In this study, through waveform modeling we show that actually these two mechanisms are quite similar and indicate earthquakes on the same fault zone.

The focal mechanisms of the eastern cluster and a previous activity on September 2020 show an oblique right-lateral and normal faulting with a N-S strike and dipping toward the west at about 40° to 50°.

Considering that two Mw~5 earthquakes, it is likely that the causative fault is a significant tectonic feature. The total length of the 2020 and 2023 activity is about 30 km. The shallow character of the activity and its sensitivity to the stress perturbations suggest that it might be related to volcanism.

Toprak & Göncüoğlu (1993) indicates that there are N-S oriented tensional fractures to the west of Hasandağı and TGFZ (see Figure 2 of Toprak & Göncüoğlu 1993). In this study, relocated earthquakes on the Tuz Gölü Fault Zone is compatible with what Toprak & Göncüoğlu (1993) mentioned and shows in their study.

Thus, we can infer that the 2023 activity following the East Anatolian Earthquakes likely occurred on the fissures of Hasandağı volcano. The mechanism of most of these events are consistent with a N-S right lateral faulting with normal component. The fault is dipping toward east. The uncertainty of the dip angle is higher than strike and rake, so there is some variance. However, overall most of the events indicate same fault structure rupturing for a length of 30 km.

7. CONCLUSION

This study examines the activity triggered by the 2023 East Anatolian events in Central Anatolia to the south of Tuz Gölü Fault Zone. The relocation and focal mechanism solutions of the seismic activity of the region in the two-month period starting from the February 6 earthquakes shows that the activity occurred on two almost N-S structures that are to the west of Hasandağı Volcano. The mechanisms and epicenter locations are consistent with a right-lateral N-S fault for the eastern activity with some normal component. The suggested fault dips toward the east. For the western activity there are not large enough magnitude events to decipher the faulting. However, a prior earthquake further north might indicate a normal fault with NNW strike. The activity might be related to the volcanism considering that they are on the proximity of fissures to the west of Hasandağı.

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