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An Assessment of the Earthquakes of Ancient Troy, NW Anatolia, Turkey

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Additional information is available at the end of the chapter

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1. Introduction

Many destructive earthquakes occurred in Northwestern Anatolia during historical and instrumental periods and as a result of these earthquakes civilities were damaged. Approximately 30 km southwest of Çanakkale the ancient city of Troy is located, containing remains belonging to the period between B.C. 3000 and A.D. 400 (Figure 1).

According to the intermittent archeological excavations, carried out from 1871 up to the present, there exist nine different layers of settlements in Troy. Although there is some archeological evidence which indicates that some of these layers, especially Troy III (B.C. 2200-2050) and Troy VI (B.C. 1800-1275) have been damaged by one or more earthquakes, no multidisciplinary geoscientific research has been carried out so far on the active faults which could have caused these earthquakes.

Troy which once controlled the commercial crossing point between Asia and Europe over Dardanos (the Dardanelles) used to be one of the most important trade centers of that era. Because of this fact Troy, besides being one of the hundreds of ancient cities situated in Anatolia, was a city that played an important role in the development of Western Anatolian and Aegean cultures. As a result of Troy's dominant position, several European countries believe that their roots lie in Troy and Trojans. When the architecture of Troy, represented by 9 layers of settlements spanning the period between B.C. 3000 and A.D. 400, is examined, it is observed that passages between civilizations are not gradual; instead, there are radical changes in building styles and materials. This observation can lead to the assumption that the events causing passages between civilizations are natural phenomena such as earthquakes rather than wars, fires or epidemics. On the other hand, Professor Manfred Korfman, who meticulously presided over Troy excavations between 1968 and 2005, talks

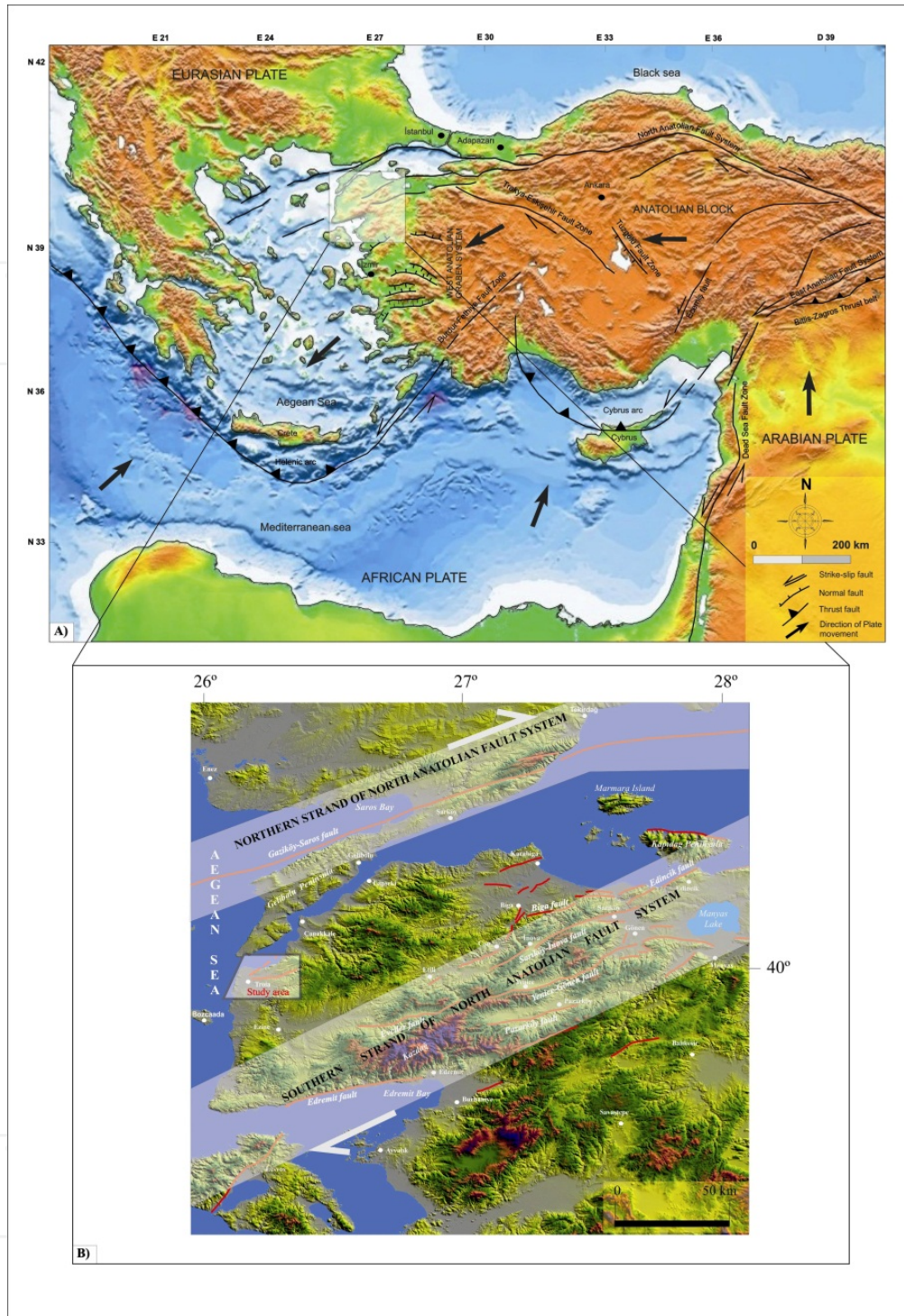


Figure 1. A. The major active tectonic structures of Eastern Mediterranean Region (Modified from Şengör et al., 1985), B. The locational relationship of Troy with the northern and southern branches of NAFS and the major active faults in the region (Modified from Şaroğlu et al., 1992).

about archaeological findings indicating that especially Troy VI Layer (B.C. 1800-1275) was damaged by one or more earthquakes. In the light of this information, some deformation structures thought to be of seismic origin have been observed, especially on the walls of Troy VI Layer. These deformation structures can be classified as systematic cracks, rotations

and blocks tilting (Figure 2). In this article, the results of the research related to the earthquakes that caused the deformation structures observed in the remains of ancient Troy city are presented.



Figure 2. Deformation structures of seismic origin within Troy VI Layer a) clockwise rotation b) Tilting c) systematic cracks in the walls of Troy VI Layer that Prof. Manfred Korfman showed the project team

2. Regional geology and tectonic framework

In the study area, rock units having ages from Lower Cretaceous to present-day outcrop (Figure 3). The basement of the study area is constituted by Lower Cretaceous aged Denizgören ophiolites (Okay, 1987). Denizgören ophiolites are unconformably overlain by Çanakkale formation (Şentürk and Karaköse, 1987). Çanakkale formation, which outcrops at relatively high plateaus over a large part of the study area, is composed of a succession of pebblestones, sandstones, sandy limestones and limestones deposited in lagoonal, coastal and offshore environments. The age of the unit is Upper Miocene-Pliocene according to ostracoda and pelecypoda fossils contained in it (Şentürk and Karaköse, 1987). All units outcropping in the study area are unconformably covered by Quaternary deposits. Quaternary deposits are represented by paleoterrace deposits of Dümrek river, flood plain deposits

of Dümrek and Karamenderes rivers and alluvial fan deposits developed at the front of the Troy Fault.

The study area is located in the peninsula in the NW corner of Anatolia. This area, known as Biga Peninsula, is being deformed under the effect of the roughly N-S oriented Western Anatolian Extension System and the western extensions of the North Anatolian Fault System (NAFS). The study area, situated at the NW part of Biga Peninsula, is mostly under the influence of NAFS. NAFS, which is one of the most important active tectonic structures of the eastern Mediterranean Region, is divided into two branches as the north and south branches, starting from the east of Adapazarı. The northern branch that reaches the Sea of Marmara from Hersek delta, after traversing the Marmara Sea in approximately E-W direction is connected to the Ganos-Saroz Fault (GSF) on which Şarköy-Mürefte Earthquake (Mw=7.2) of 1912 occurred. GSF is oriented N70°E and cutting through Gallipoli Peninsula in this orientation from Saroz Gulf, reaches North Aegean Sea. The fault segments constituting the south branch of NAFS, by traversing Biga Peninsula in NE-SW direction reach North Aegean Sea. The most important ones of these NE-SW oriented faults are, from north to south, Edincik fault, Biga fault, Sarıköy-İnova fault, Yenice-Gönen fault, Evciler fault, Pazarköy fault and Edremit fault.

The ancient city of Troy is situated within a right lateral deformation zone bordered by the northern and southern branches of the North Anatolian Fault System (NAFS). The northern border of this deformation zone is formed by Gaziköy-Saroz Fault. And the southern border of the deformation zone is represented by the south branch of NAFS composed of faults which are parallel or subparallel to each other and extend between Kapıdağ Peninsula and Edremit Bay (Figure 1b). Troy Fault System, which is represented by E-W oriented normal faults, NE-SW oriented right lateral and NW- SE oriented left lateral strike slip faults, exists in the area within this deformation zone. When taken into account its geologic fault length and morphotectonic characteristics, 12-km long Troy Fault is the most important one of the E-W oriented faults within the Troy Fault System (Tutkun and Pavlides, 2005). And the most important of the NE-SW oriented right lateral faults is Kumkale Fault which possesses a total length of 15 km including its continuation in the sea.

Destructive earthquakes occurred on the active faults in Biga Peninsula (Troy is also located here) and in its vicinity, during historical and instrumental eras (Figure 4 and 5).

3. Material and method

This study is a multidisciplinary research in which geomorphological, geological and geophysical methods were applied in a specific order.

Within the framework of the geomorphological studies, a 1/25 000 scale digital elevation model of the study area was constructed and on this model, geomorphological features such as stream/valley drainage areas, mountain front sinuosity ratio and ratio of valley floor width to valley height were investigated.

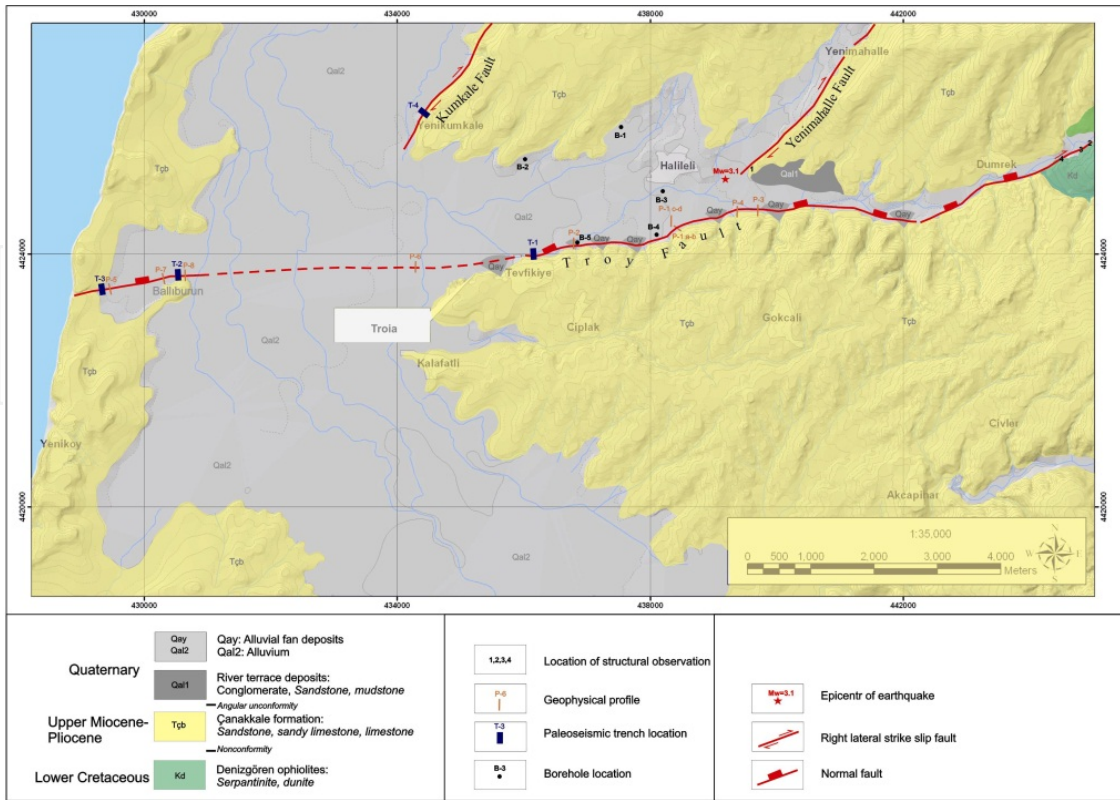


Figure 3. Geological map of Troy and its vicinity.

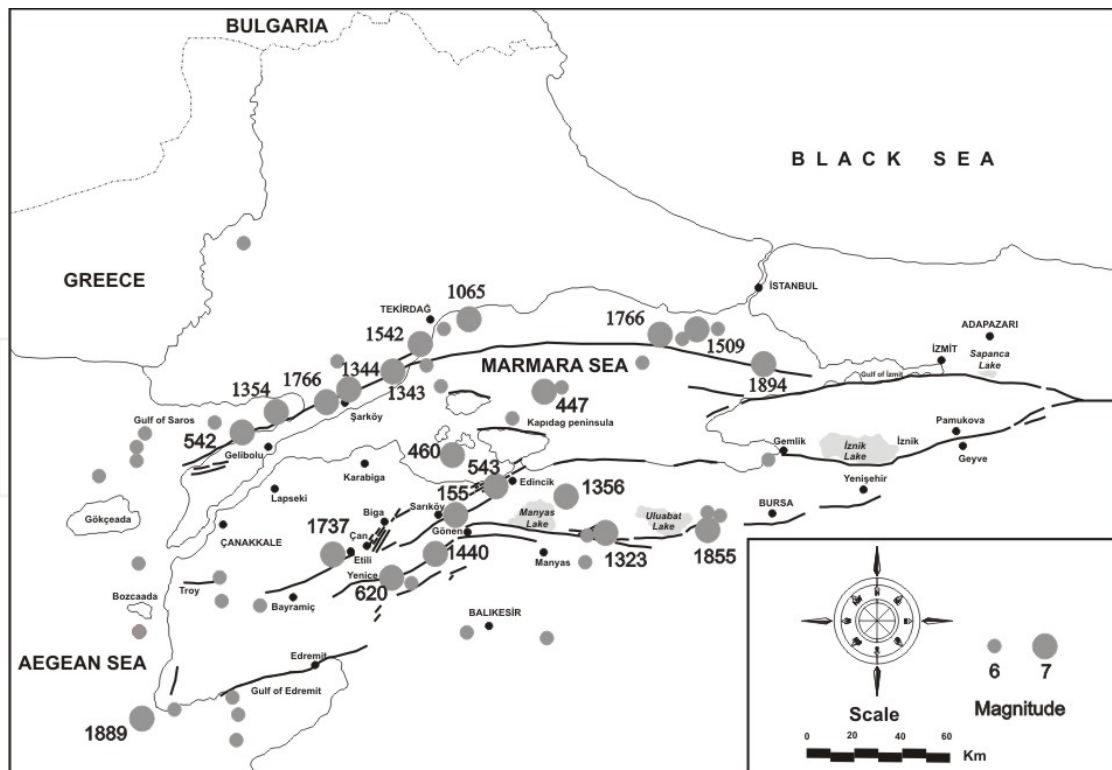


Figure 4. Western segments of NAFS in the study area and in its near vicinity (modified after Şaroğlu et al., 1992) and the historical earthquakes that occurred on these faults between A.D. 32 and A.D. 1900 (modified after Ambraseys and Finkel, 1991)

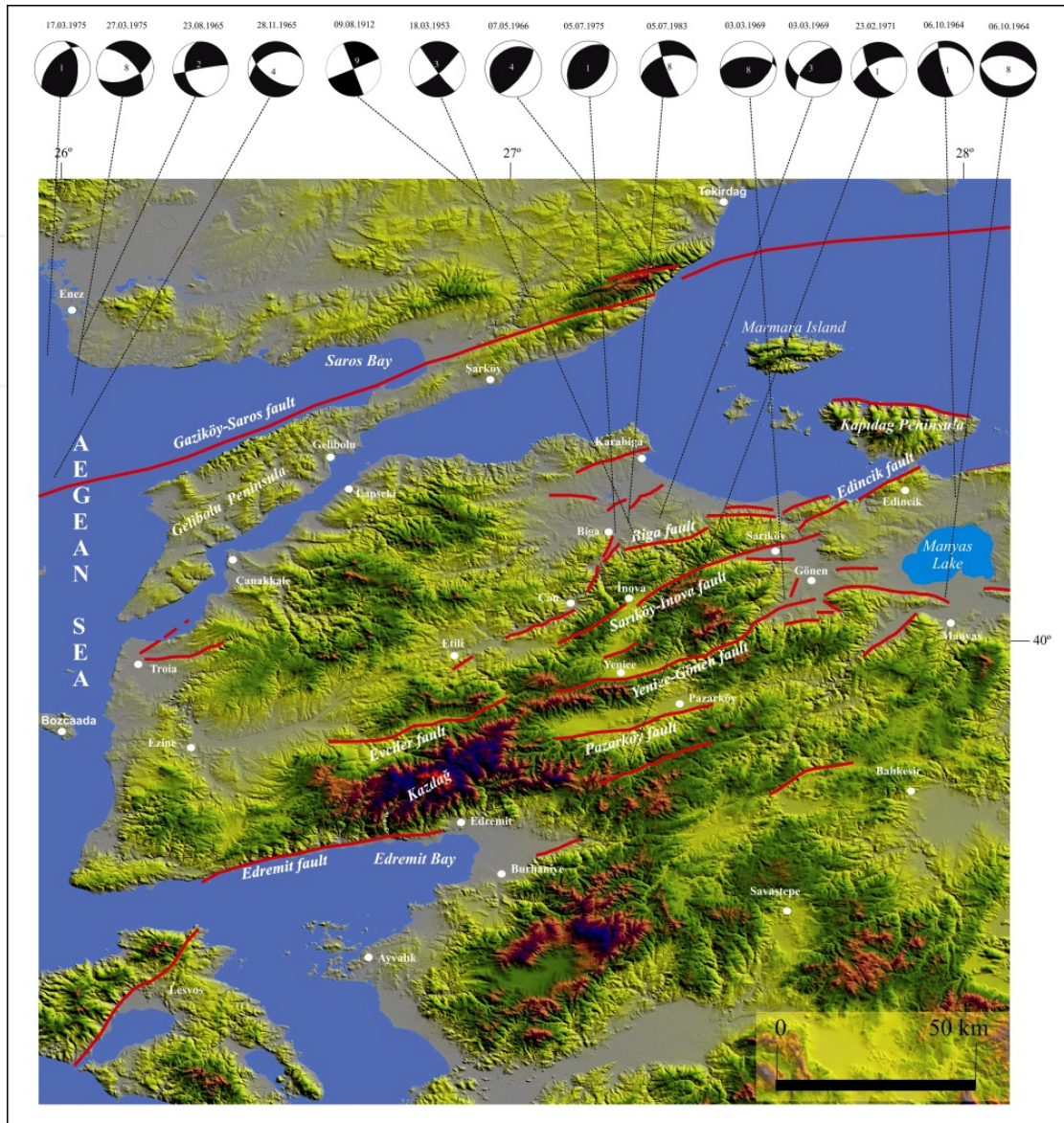


Figure 5. Extensions of North Anatolian Fault System (NAFS) in Biga Peninsula, instrumental period earthquakes related to these faults and focal mechanism analyses (Focal mechanism analyses were taken from 1: Kıyak, 1986; 2: Canitez and Tokgöz, 1971; 3: McKenzie, 1972; 4: Kalafat, 1978; 5: Kalafat, 1988; 6: Jackson and McKenzie, 1984; 7: McKenzie, 1978; 8: Taymaz, 2001; 9: Aksoy et al., 2010)

Within the framework of the geological studies, a 1/25 000 scale geologic map of the region was prepared. Afterwards, structural observations were made on the faults within the Troy Fault System. The data obtained from these observations were evaluated in the kinematical analysis program developed by Carey (1979) and the stress regimes effective in the region at the present time were determined. In active tectonic researches, shallow (0-15meter) drilling works can be conducted in order to determine and document basin asymmetry originating from active faults. With the help of shallow core drillings, lateral and vertical variations of the Quaternary deposits in the basin can be determined. In this study, a total of 5 shallow drillholes with depths varying between 3 and 9 meters were opened in the area north of the Troy fault and where Quaternary deposits outcrop. The core samples compiled from the

drillings were logged and interpreted. In this study, along the Troy fault, using Direct Current Resistivity method measurements were made along 8 profiles with an average length of 200 meters and perpendicular to the fault. And applying two-dimensional inverse solution, geoelectric cross-sections for the shallow depths (0-15 meters) of the earth were obtained. And lastly, in the study paleoseismological trench works were conducted in the areas determined according to geological observations and geophysical data. Within the scope of this work, a total of 4 trench works were carried out, 3 trenches on Troy fault and 1 on Kumkale fault. All of the trenches were excavated perpendicular to the fault, with an average length of 10-15 meters, 3-4m wide and 4-6m deep. A total of 20 carbon-containing soil samples were compiled from the trenches for C-14 dating. These samples were analyzed at Beta Analytical Laboratory in the United States of America.

4. Findings

4.1. Morphotectonic analysis of Troy Fault

The geomorphology of a region can be described based on specific measurements of its morphological characteristics. This method, defined as morphometry, is realized by digitally deriving information about geomorphological elements from the elevation values (DEM - Digital Elevation Model) belonging to the region and analyzing them. These values, obtained with the help of morphometry, can provide consistent and fast information both on the evolution of the drainage in the study area and on the degree, distribution and character of the structural/lithological control on this evolution (Keller and Pinter, 1996).

For this purpose, through the digitization of the 1/25 000 scale sheets of Ayvalık I 16 a2 and Ayvalık I 16 b1 belonging to the study area, the digital elevation model of the region was created (Figure 6). The geomorphological characteristics of the region were investigated on this model. The geologic map of the region was draped over the digital elevation model as a separate layer and a relief geologic map was obtained (Figure 3).

The purpose of the morphotectonic analysis is to digitally reveal the degree of influence of the erosional and tectonic processes effective in the morphological shaping of a region. In this study, such geomorphological indices as mountain front sinuosity ratio (Smf index), stream/valley drainage areas and profiles, and valley floor width to valley height ratio (Vf index) were calculated.

Mountain front sinuosity ratio (Smf) is an index that reflects the balance between erosional forces that tend to cut embayments into a mountain front and the tectonic forces that tend to produce a straight mountain front. Mountain fronts uplifted by active tectonism are straight and have low Smf values. And mountain fronts that move slowly or have lost their activity display irregular forms and high values because they are destroyed by erosional forces (for further information, see Keller and Pinter, 1996). If Smf values are between 1 and 2, the fault in question has high activity. If this value is greater than 2, the activity of the fault should be considered as doubtful. However, one must bear in mind that Smf index can also be affected by the strength properties of the rocks forming the mounting front involved in faulting and by erosional activities.

In the evaluation made by taking into account mountain front sinuosity ratios, Troy Fault is subdivided into three geometric segments (Figure 6). These are, from east to west, Dümrek, Halileli and Tevfikiye segments, respectively. According to their mountain front sinuosity ratios, Tevfikiye and Halileli segments in the west have similar properties and are more active ($S_{mf}=1.15$ and 1.48 , respectively), while Dümrek segment in the east has relatively lower activity ($S_{mf}=2.52$).

Morphological cross-sections were prepared in five areas along Troy fault (Figure 7). While there is disharmony between Dümrek and Halileli segments with regard to normal fault scarp elevation, an agreement is observed between Halileli and Tevfikiye segments. Normal fault scarp values also indicate that Halileli and Tevfikiye geometric segments should be evaluated together.

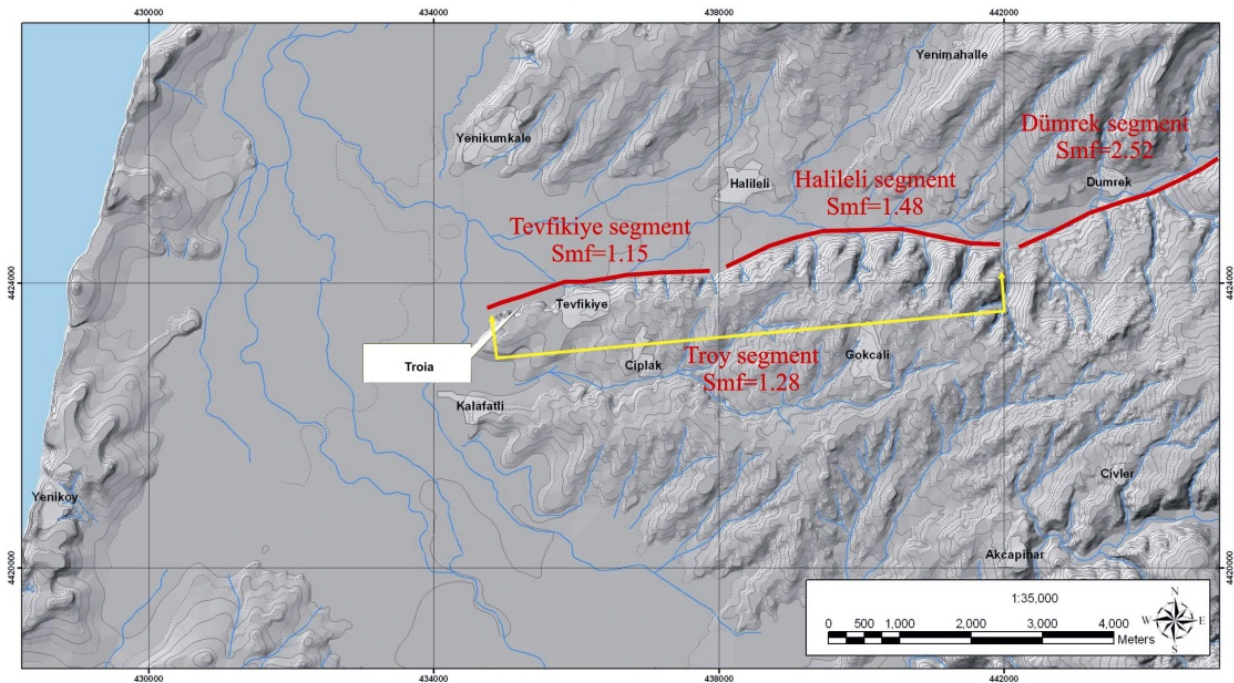


Figure 6. Digital elevation model of the study area and on this model, the segments of Troy fault according to mountain front sinuosity ratio.

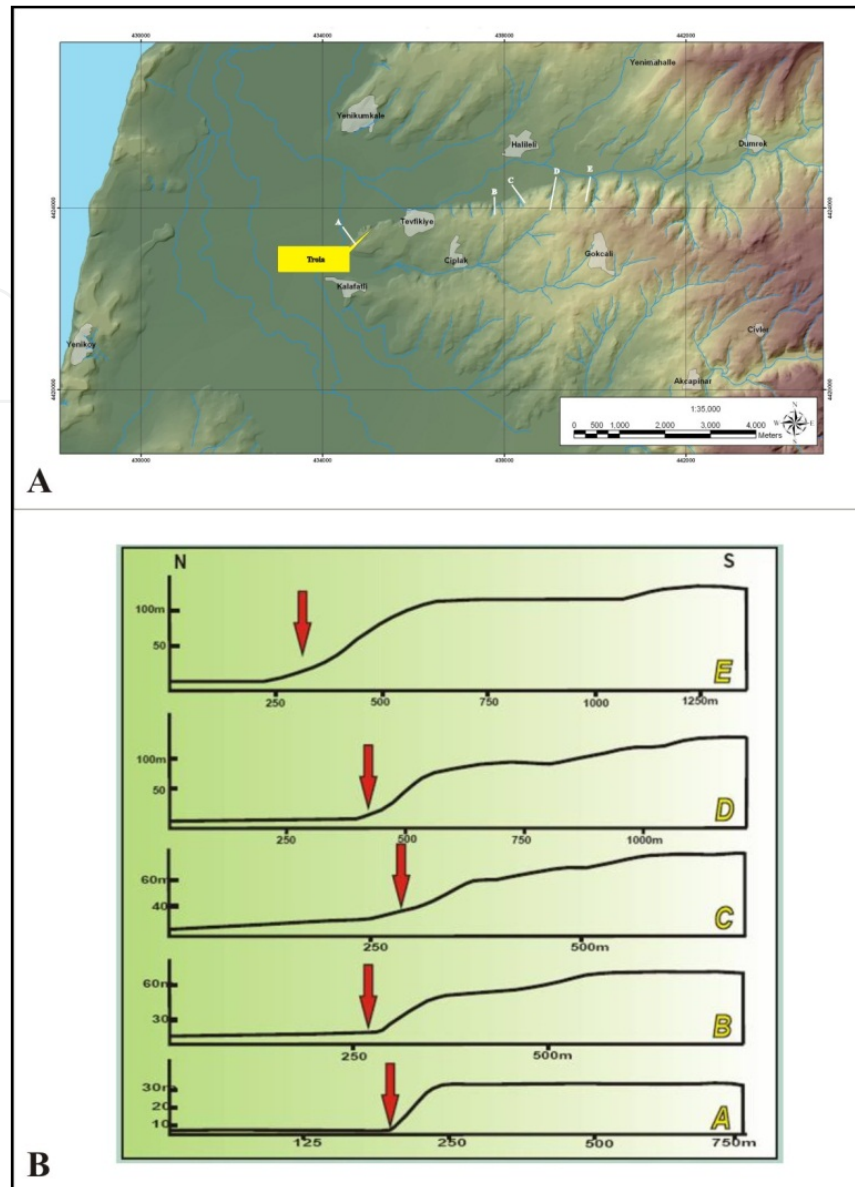


Figure 7. Locations of cross-sections along Troy fault

When the ratio of valley floor width to valley height (V_f) is calculated, the parameters in the formula are calculated at a certain distance from the mountain front for each valley. Higher V_f values show lower uplift speed and lower V_f values indicates actively uplifted areas.

V_f values showed that Tevfikiye and Halileli segments show similar properties and are more active; on the other hand, Dümrek segment has higher V_f values and hence is less active.

As a result of the morphotectonic analysis studies, since Tevfikiye and Halileli segments display similar morphotectonic characteristics, they were evaluated together and named the Troy segment. Since Troy segment is more active compared to Dümrek segment, the shallow geophysical and paleoseismological investigations related to the Troy fault were mostly conducted on this segment.

On the other hand, the expected maximum earthquake magnitude for Troy fault was calculated using the empirical equations proposed by Pavlides and Caputo (2004). The total length of the Troy fault is about 11-12km, hence, the expected maximum earthquake magnitude for the Troy fault was computed from the formula

$$M_s = 0.9 \cdot \log(\text{SRL}) + 5.48 \quad (\text{Pavlides and Caputo, 2004})$$

as $M_s = 6.2-6.5$

4.2. Kinematic analysis studies along the Troy fault

Troy fault system, located within the right lateral deformation zone between the northern and southern branches of NAFS, is represented by approximately E-W oriented normal faults, NE-SW oriented right lateral and NW- SE oriented left lateral strike slip faults. When taken into account its geologic fault length and morphotectonic characteristics, the Troy fault is the most important one of the approximately E-W oriented normal faults within the Troy Fault System.

Troy fault was defined for the first time by Tutkun and Pavlides (2005). It is a normal fault which is 11-12 km long, approximately E-W oriented, dipping 60° to the north (see Figure 3). Troy fault has highly pronounced normal fault morphology and is composed of two segments: Troy and Dümrek segments (See Figure 6). The Troy fault cuts Lower Cretaceous aged Denizgören ophiolites in the NE parts of the study area. To the east of Dümrek village, the fault makes a bend towards the west and continues in E-W direction, and it brings Neogene aged Çanakkale Formation and Quaternary deposits face to face in this area (Kürçer et al., 2006).

The fault enters the alluviums of Karamenderes Stream starting from the area where ancient Troy settlement is located, but its continuation from here towards the west is not clear. However, when its direction is followed, it can be seen that the fault trace again becomes evident between Ballıburun and Kesiktepe (See Figure 3). That's why, the sector of the Troy fault between ancient Troy settlement and Ballıburun was interpreted as probable active fault. In the drilling works we conducted in the Quaternary sediments in the hanging wall of the Troy fault, the top of the Çanakkale Formation was cut at 7-8 meter depth in the drillings B-4 and B-5 (See Figure 3) just north of the Troy fault. In the morphological cross-section (See Profile B in Figure 7) taken from an area between B-4 and B-5 drill locations, a normal dip slip of about 50 meter was measured. When the top of Çanakkale formation is taken as reference plane, cumulative dip slip in the Troy fault is around 60 meters including 7-8 meters obtained from the drillings.

In the study area, apart from the Troy fault, strike slip reverse and normal faults are observed, as well. In this context, within the Troy fault system, from 4 sites (for site locations, see Figure 3, Table 1) where outcrop conditions permit, a total of 67 fault planes were measured and calculated using numerical analysis method (Table 2). Site 1 was measured in Neogene aged Çanakkale formation. Thanks to this site, the kinematic condition of the final tectonic regime in the Troy region was determined.

Site	Longitude (N)	Latitude (E)	Age	Lithology
1	35 s 0435107	4423466	Neogene	Sandstone
2	35 s 0446204	4426875	Lower Cretaceous	Serpantinite
3	35 s 0446695	4427003	Lower Cretaceous	Serpantinite
4	35 s 0445035	4426292	Lower Cretaceous	Serpantinite

Table 1. Coordinates of the sites where fault planes or fault assemblages outcropping in the vicinity of Troy were measured; lithology and age of the measured geological units.

Site	N	σ_1 Az / dip	σ_2 Az / dip	σ_3 Az / dip	R	M.D.	S. D.
1	11	80 / 26	256 / 64	349 / 1	0.29	9.4	13.1
2	27	127 / 59	287 / 29	22 / 9	0.25	7.7	12.0
3	11	279 / 18	100 / 72	9 / 0	0.43	10.4	9.4
4	18	85 / 11	213 / 73	352 / 13	0.69	8.9	11.0
$S_1 = 285 \pm 22^\circ / 4^\circ$ $S_3 = 15 \pm 21^\circ / 6^\circ$ $R_m = 0.37$							

Table 2. The conditions of the principal stress axes [(σ_1) , (σ_2) , (σ_3)] computed as a result of the evaluation of fault assemblages measured in the vicinity of Troy using Carey (1979) numerical analysis method; R ratio, number of measurements (N), fault measurement sites, mean (M.D.) and standard deviation (S.D.) values

The results of the faults (measured in the vicinity of Troy), obtained employing the method developed by Carey (1979) for kinematical analysis of fault assemblages are as follows: Although the sites where fault assemblages were measured (Figure 8) are composed of geological units of various ages, one site (Site 1) was measured in Neogene aged units. Accordingly, the tectonic regime effective at the present time implies transtensional strike slip faulting. In harmony with this strike slip faulting (compression) normal faulting (tension) regime developed, which represent the Troy fault as well.

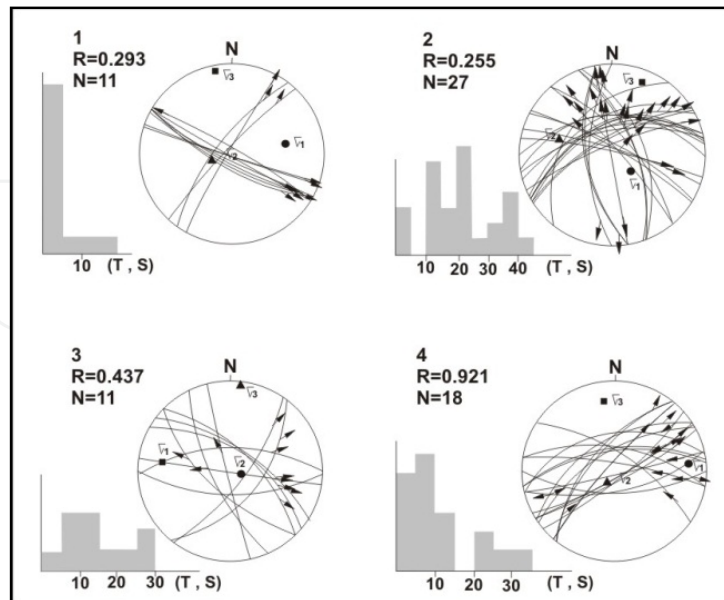


Figure 8. Presentation of the kinematical analyses carried out at locations belonging to faultings given in Table 2 on equal angle lower hemisphere (Wulf) (the distribution of the angle of deviation between the predicted slip vector (τ) and computed slip vector (s) is given in histograms).

For the purpose of correlating the results of the kinematical analyses of the fault assemblages with the focal mechanism inverse solutions of the recent earthquakes, focal mechanism inverse solution of the earthquake (Figure 3, Table 3) with a magnitude of 3.1 that occurred on 03.02.2008 was carried out (Figure 9). Focal mechanism inverse solution presents a faulting with strike slip normal component, developed under transtensional stress regime that is characterized by WNW-ESE oriented compression (P) and NNE-SSW oriented tension (T). This data is compatible with the stress conditions obtained from the kinematical analyses of the fault assemblages (Figure 10).

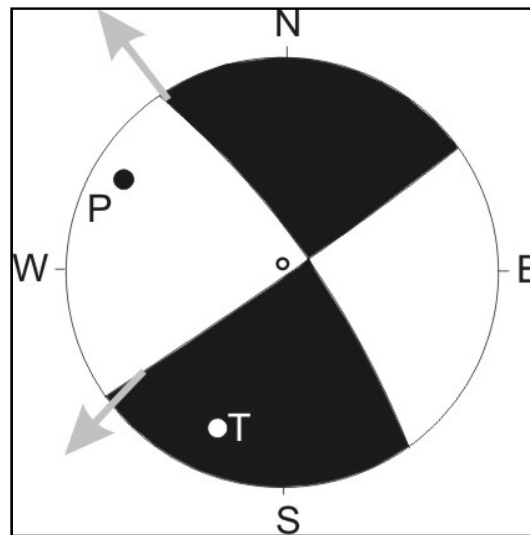


Figure 9. Focal mechanism inverse solution of the earthquake that occurred on 03.02.2008 (Özden et al., 2008)

Explanations	Values
Date	03.02.2008
Time	15 09
Latitude	39.94 N
Longitude	26.22 E
Magnitude (Mw)	3.1
Depth (km)	12
Plane 1	55°/88°/-165°
Plane 2	325°/75°/-3°
P axis	302°/10°
T axis	210°/10°
Source	BOUN-KOERI
Focal solution and reference	Özden et al., 2008

Table 3. Numerical values of the earthquake that occurred on 03.02.2008 (Özden et al., 2008)

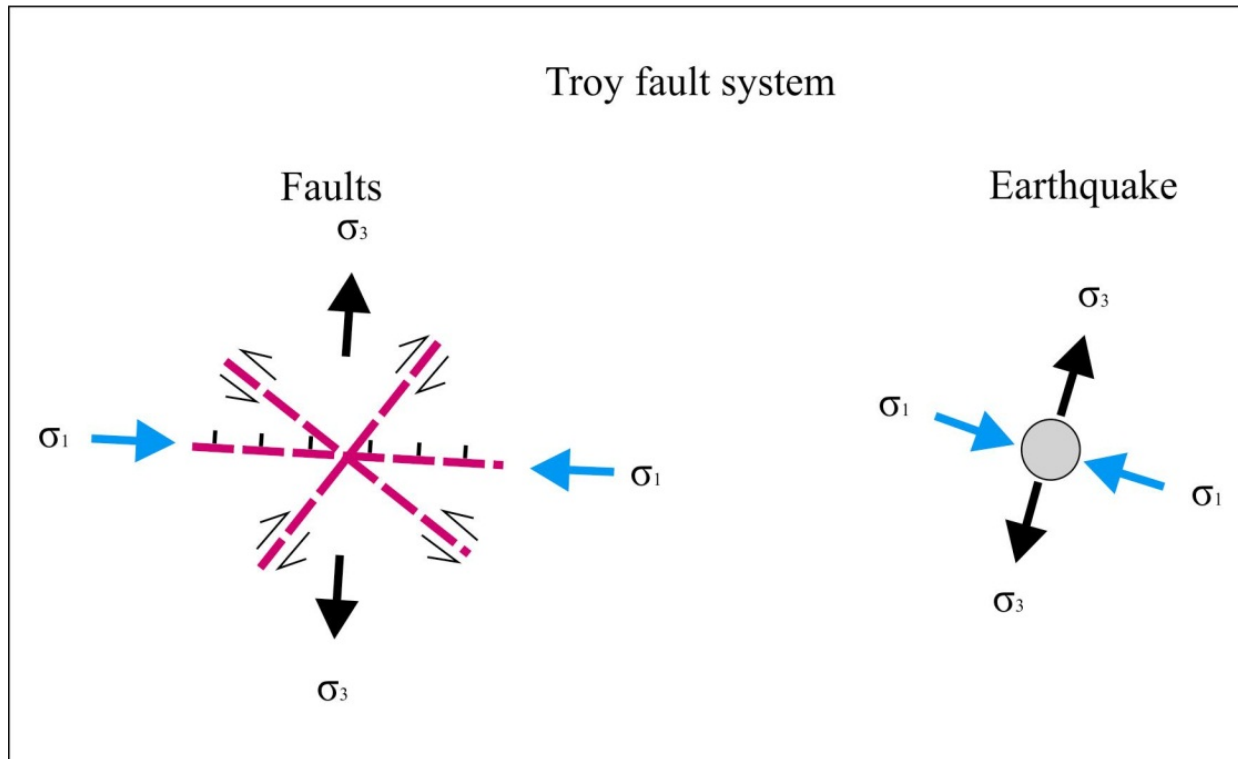


Figure 10. Comparative presentation of the regional stress conditions obtained from the kinematical analyses of the fault assemblages outcropping in the vicinity of Troy and the earthquake (black arrows represent effective regimes and blue ones represent non-effective regimes)

As a result; the Troy Fault System and stress regimes effective at the present time in the Troy region show that a NNW-SSE trending compression and a NNE-SSW oriented tension is effective in this region and as a result of it, strike slip and normal faults developed under transtensional tectonic regime.

4.3. Shallow geophysical surveys along the Troy fault

Structural geology studies conducted along Troy fault aroused the suspicion that the fault scarp might have been degraded in the course of time. In order to determine the fault trace within Quaternary sediments, shallow geophysical researches employing direct current resistivity method were carried out. Within this context, shallow depths (0-20m) were investigated along a total of 8 profiles determined perpendicular to the fault trace along the Troy fault (for profile locations, see Figure 3). Two-dimensional inverse solutions of the obtained profiles were made and geoelectric cross-sections were constructed (Figure 11). According to the geoelectric cross-sections obtained by means of shallow geophysical studies, some discontinuities were encountered (Figure 11).

According to the Direct Current Resistivity studies conducted on the profiles perpendicular to the fault trace along Troy fault, it passes 30-100 meters north of morphologic escarpment bordering the Troy rise. This condition can be explained by the degradation of the Troy fault scarp in the course of time.

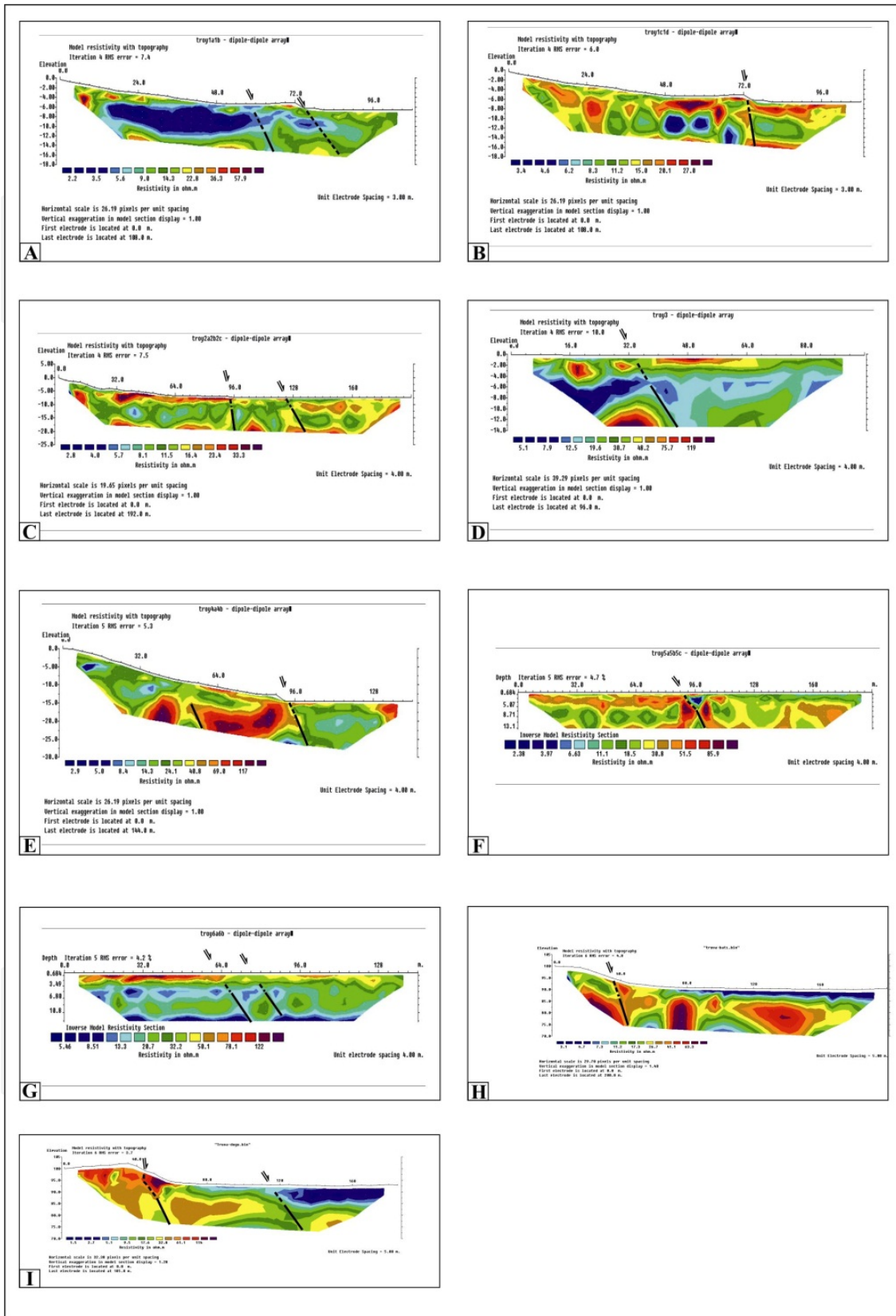


Figure 11. Geoelectric cross-sections measured by Direct Current Resistivity method along Troy fault and obtained employing two-dimensional inverse solutions. A: Profile 1a-b, B: Profile 1c-d, C: Profile 2, D: Profile 3, E: Profile 4, F: Profile 5, G: Profile 7, I: Profile 8 (for profile locations, see Figure 3).

4.4. Shallow drilling works on the hanging wall of the Troy fault

In active tectonic research, in order to determine and corroborate basin asymmetry, shallow (0-15 m.) drilling works can be carried out. Lateral and vertical variations of the Quaternary sediments within the basin can be determined with the help of shallow drillings. In this study, a total of 5 shallow drillholes having depths of 3-9m were opened in the area where Quaternary sediments outcrop, north of the Troy fault (for drill locations, see Figure 3).

The phases of the shallow drilling works are presented in Figure 12. In the drilling works, "Percussion drilling set for soils with gasoline powered percussion hammer-Cobra MK1" core drill machines were used. In the first phase, Quaternary sediments were drilled with the core drill machine (Figure 12A). Then with the help of a simple lever of the drill machine, the drill set was hoisted (Figure 12B). After labeling of the hoisted drill cores (Figure 12C), the drill cores were split into two along their long axes (Figure 12D). After these split cores were photographed (Figure 12E) and defined, the drill work was completed (Figure 12F). The well logs of the drillholes are given in Figure 13. According these well logs, Quaternary sediments become thicker towards the Troy fault.

When the information obtained from the shallow drillings were transferred onto the three-dimensional geologic cross-section of the region, it was observed that the plane constituting the boundary between Quaternary deposits and Neogene aged units are tilted towards south (towards the Troy fault) and consequently Quaternary sediments became thicker (Figure 14). In other words, the area north of the Troy fault is tilted back. This corroborates basin asymmetry and points to Quaternary activity of the Troy fault as well.

4.5. Paleoseismological trench works on Troy fault system

The tectonic regime type effective in Troy region at the present time is strike slip faulting with normal component (transtensional) developed under WNW-ESE oriented compression regime. The geological and geophysical investigations we conducted in Troy region showed that a NNE-SSW oriented tensional regime depended on this compression was effective in this region. The products of the transtensional tectonic regime effective in the region are E-W oriented normal faults, NE-SW oriented right lateral and NW-SE oriented left lateral strike slip conjugate faults. In this study, paleoseismological trench studies were conducted on the Troy normal fault, which is prominent by its geological fault length and morphotectonic properties, and on the right lateral strike slip Kumkale fault.

Within the scope of this work, a total of 4 trench works were carried out, 3 trenches along the Troy fault and 1 along Kumkale fault (for trench locations, see Figure 3). The trenches were excavated 15 meters long, 4 meters wide and 4 meters deep.

The existence of a fault, E-W oriented and dipping to the north, just north of the Troy rise was stated by various researchers (for example; Kayan, 2000; Tutkun and Pavlides, 2005; Kürçer et al., 2006). The fault named the Troy Fault (Tutkun and Pavlides, 2005) brings in contact the Neogene Çanakkale formation and Quaternary deposits outcropping in Dümrek plain (see Figure 3). There is an elevation difference of 50 meters on average between the



Figure 12. Phases of shallow drill works A: Drilling, B: Hoisting of drill set, C: Numeration, D: Splitting of drill cores, E: Photographing, F: Logging

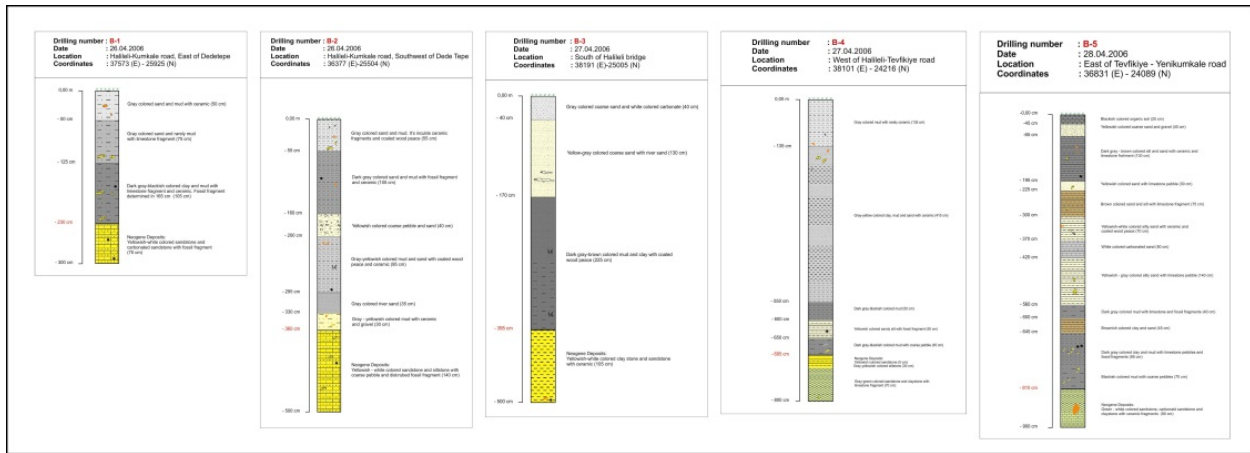


Figure 13. Well logs of shallow drillings conducted on the hanging wall of Troy fault

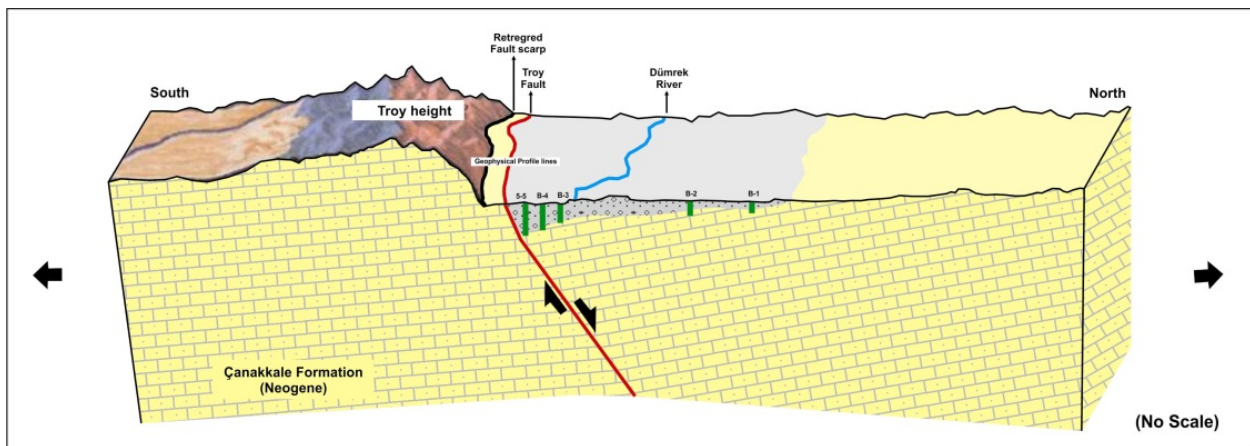


Figure 14. Three-dimensional schematic geologic cross-section of the Troy region constructed making use of surface geology and drilling data

floor of the plain and the Troy rise. In the shallow drilling works conducted by us, it was determined that Quaternary-Neogene boundary in sectors near the fault was at 8 meters. In the light of this information the cumulative dip slip on the Troy fault is thought to be approximately 60 meters.

When all the information about Troy fault, known and obtained by this study, is evaluated altogether, it is assumed that Troy fault was initially an E-W oriented normal fault developed within Western Anatolia Stress System (WASS). It gained some right lateral strike slip character owing to the western extensions of NAFS that affected the region as of Late Pliocene. The Troy fault that bears the traces of both WASS and NAFS has become one of the most significant morphologic elements in the region at the present time.

On the Troy fault, paleoseismological trench studies were conducted in three locations. These locations are: Tevfikiye (Figure 3, T1), Ballıburun (Figure 3, T2) and Kesiktepe (Figure 3, T3).

Tevfikiye Trench (T1)

Tevfikiye trench is located in an area east of the village road that connects Tevfikiye and Yenikumkale villages, very near to the drillhole B-5 and on the geophysical profile line

number 2 (P-2) (see Figure 3, T-1). In this area, an excavation work was conducted that is 5-5.5 meters deep, 8 meters wide, 48 meters long and multibenched (Figure 15).

Tevfikiye trench was planned in S15E-N15W direction starting from Neogene aged deposits as to include the discontinuity indications on the geophysical profile line number 2 (see Figure 11-C). In figure 16, the composite trench cross-section belonging to the Tevfikiye trench location is presented. The composite trench cross-section was constructed making use of the excavation site belonging to Tevfikiye trench, the drilling information of drillhole B-5 and the observation of the small Tevfikiye trench excavated in this region.

As it can be seen from the trench section, Tevfikiye trench was excavated, at first, 48 meters long towards the north starting from the Neogene deposits. In the excavated 48- meter section, it was observed that Quaternary deposits unconformably overlie Neogene units with an erosional contact. The contact between Quaternary and Neogene can be distinctly traced over the 48-meter section. No trace of deformation that can be attributed to active tectonism was encountered in this section. However, numerous normal faults having dips not exceeding several centimeters and some paleoliquefaction structures in the type of fire structure were observed within the Neogene aged deposits at the basement, between 14th and 15th meters of the trench (Figure 17).

It was impossible to continue at the targeted depth towards north after 48th meter due to conditions of groundwater level. Thereupon, an additional trench with an average depth of 6 meters was excavated between 55th and 58th meters. No trace of deformation within Quaternary deposits at the upper parts of this trench was encountered, either. The Quaternary-Neogene contact was encountered at the depth of -6 meters (see Figure 16).

B-5 drillhole is located at the 74th meter of Tevfikiye excavation area (see Figure 16). In B-5 hole, Quaternary- Neogene contact was encountered at the depth of -8.10 meters (see Figures 13 and 16). When additional trench information and B-5 drilling data were transferred onto the trench cross-section belonging to Tevfikiye excavation area, it was seen that, at the 66th meter of the trench, Quaternary-Neogene contact is at different depths. This point corresponds to the discontinuity sign encountered at the 96th meter of the geophysical profile number 2 (see Figure 11-C). Geological observations in the Tevfikiye excavation area and shallow geophysical data point to the presence of a fault the south block of which was up-thrown at the 66th meter of the excavation area. As can be seen from the composite trench cross-section prepared according to geological information, if a comparison is made taking Quaternary-Neogene contact as a basis, it is seen that the south block is uplifted about 2 meters compared to the north block. When evaluated under the regional tectonic framework, this fault is thought to be a normal fault dipping to the north (the Troy fault). No data, related to the continuation of the fault in the Quaternary deposits, was obtained from Tevfikiye trench. The age B.C.1190-1140 was obtained from the sample numbered TEV-E-04 compiled from Tevfikiye trench. TEV-E-04 sample was taken from the greenish yellow colored silty clay number 2. No trace of deformation was encountered within the unit number 2 in the Tevfikiye excavation area. This indicates that no earthquake occurred resulting from the Troy fault during the period from the deposition of the unit number 2 up to the present (B.C. 1190-Present-day), at least in Tevfikiye trench area.



Figure 15. Look at Tevfikiye Trench from the North

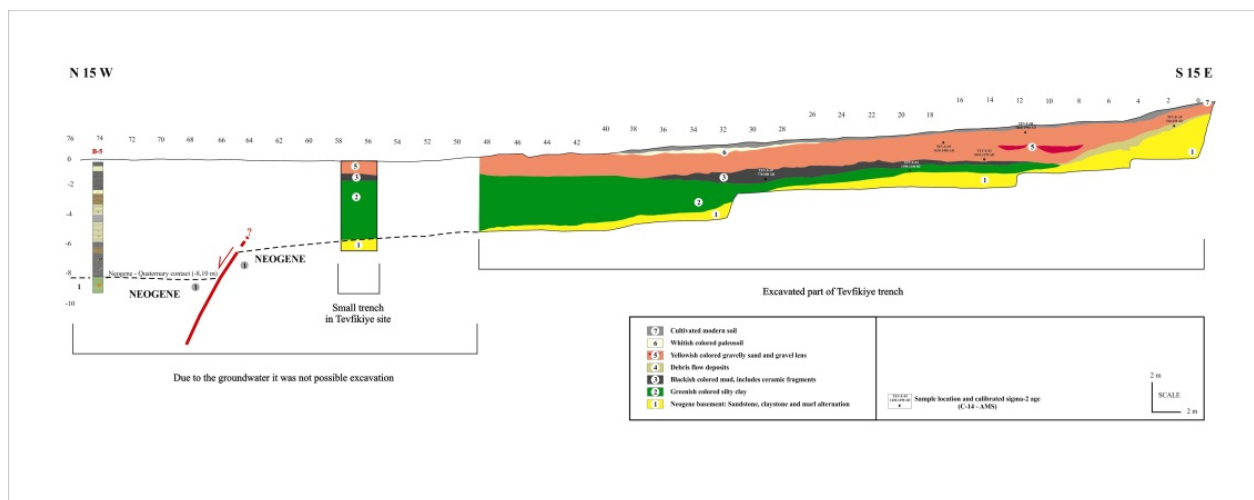


Figure 16. Composite section of the East Wall of Tevfikiye Trench (T1)



Figure 17. Small scale normal faults and paleoliquefaction structures observed between 14th and 15th meters of Tevfikiye Trench (Look from West to East)

Balliburun Trench (T-2)

Balliburun Trench is located between the electric resistivity profiles P-7 and P-8 at the Balliburun location west of Tevfikiye (see Figure 3, T-2). The trench was excavated 22 meters long, 3 meters wide and 4 meters deep on average. Balliburun trench was planned, starting from Neogene sediments, in S10W-N10E direction as to involve the discontinuity signs on the geophysical profile line number 8 (see Figure 11-I). In Figure 18, the trench cross section and the photograph belonging to the west wall of Balliburun Trench are presented. As can be understood from the trench section, no sign of faulting was observed in Balliburun trench. However, some paleoliquefaction structures that can be secondary proof of an earthquake were observed within the mud which is black colored and rich in organic matter, at a depth of -2 meters from the surface, between 12th and 14th meters of the trench (Figure 18B).

Three samples were collected and dated from Balliburun trench. Two of these samples were collected from Unit 1 and the third one was taken from Unit 3 in which paleoliquefaction structures were observed. Since the age of the sample taken from Unit 3 is greater than the other two samples, it was considered as an allochthonous sample and was not counted in the interpretation. The ages of the remaining two samples support each other. As there is no

usable age information from Unit 3, in which paleoliquefaction structures were observed, it can be said that the age of the earthquake, that might have caused these paleoliquefaction structures, is younger than the ages obtained from the samples BAL-5-13C and BAL-5-4C. Since the youngest age obtained from Unit 1 in the Ballıburun Trench is B.C. 760, the age of the earthquake that might have caused these paleoliquefaction structures is the time interval B.C. 760-Present-day.

Kesiktepe Trench (T-3)

The Troy fault enters the alluvium deposits of Karamenderes brook starting from the west of Tevfikiye village and loses its morphologic trace. It becomes again morphologically distinct in the sector between Ballıburun and the Aegean Sea (see Figure 3). In the highland that is located west of Ballıburun and composed of Neogene aged Çanakkale formation is known as “Kesik Tepe” (Truncated Hill) and this area is characterized by its “V” shaped morphology. It is thought that this morphologic anomaly was initially shaped by Troy fault and later modified by human activity. For the purpose of checking the anomaly, electrical resistivity measurements were carried out along P-5 profile from Kesiktepe location and geoelectric cross-section was obtained (see Figure 11-F). In the geoelectric cross-section, a discontinuity was determined in the region where Kesik Tepe is located and for the purpose of testing this discontinuity, Kesiktepe Trench was excavated, which is 6 meters long, 2 meters wide and 4.5 meters deep on average (Figure 3, T-3). The trench cross section of Kesiktepe trench is presented in Figure 19.

No sign of faulting was encountered in Kesiktepe trench. However, Kayan (2000) mentions that Neogene deposits were cut at different depths in two drillholes very near to each other, drilled in the south and north of Kesiktepe. According to the researcher, while the Neogene deposits were cut at -2 meter in the south, they were cut at -8meter just in the north. This indicates that the north block was relatively downthrown. As to support this, some signs of discontinuity were encountered at the 96th meter on the geophysical profile number 5 (see Figure 11-F). On the other hand, it is known that, during Troy era, in Kumkale plain some drainage canals were excavated in order to dry the swamp that caused malaria (personal communication with Dr. Rüstem Aslan. 2005; Figure 20). And one of these drainage canals is situated just on the Troy fault trace in Kesiktepe location. By means of the discontinuity in the geoelectric cross-section, archeological information and geomorphological approach, it is thought that the Troy fault reaches the Aegean Sea over Kesiktepe. However, since the canal, excavated as drying canal, was filled with recent sediments during the period from its last activity to the present time, no trace of active faulting was encountered at the first 4 meters from the surface (from B.C. 1500 up to the present).

Kumkale Trench (T-4)

In the Troy region, there are also NE-SW oriented, right lateral strike slip faults that were developed within NAFS. The best examples for these faults are Kumkale and Yenimahalle faults (see figure 3). Kumkale fault is a N25°E oriented, dipping 75° to NW right lateral strike slip fault that borders from the north the ridge on which Kumkale village is situated. Yaltrak et al. (2000), in their shallow sea seismic studies conducted in Dardanelles and its

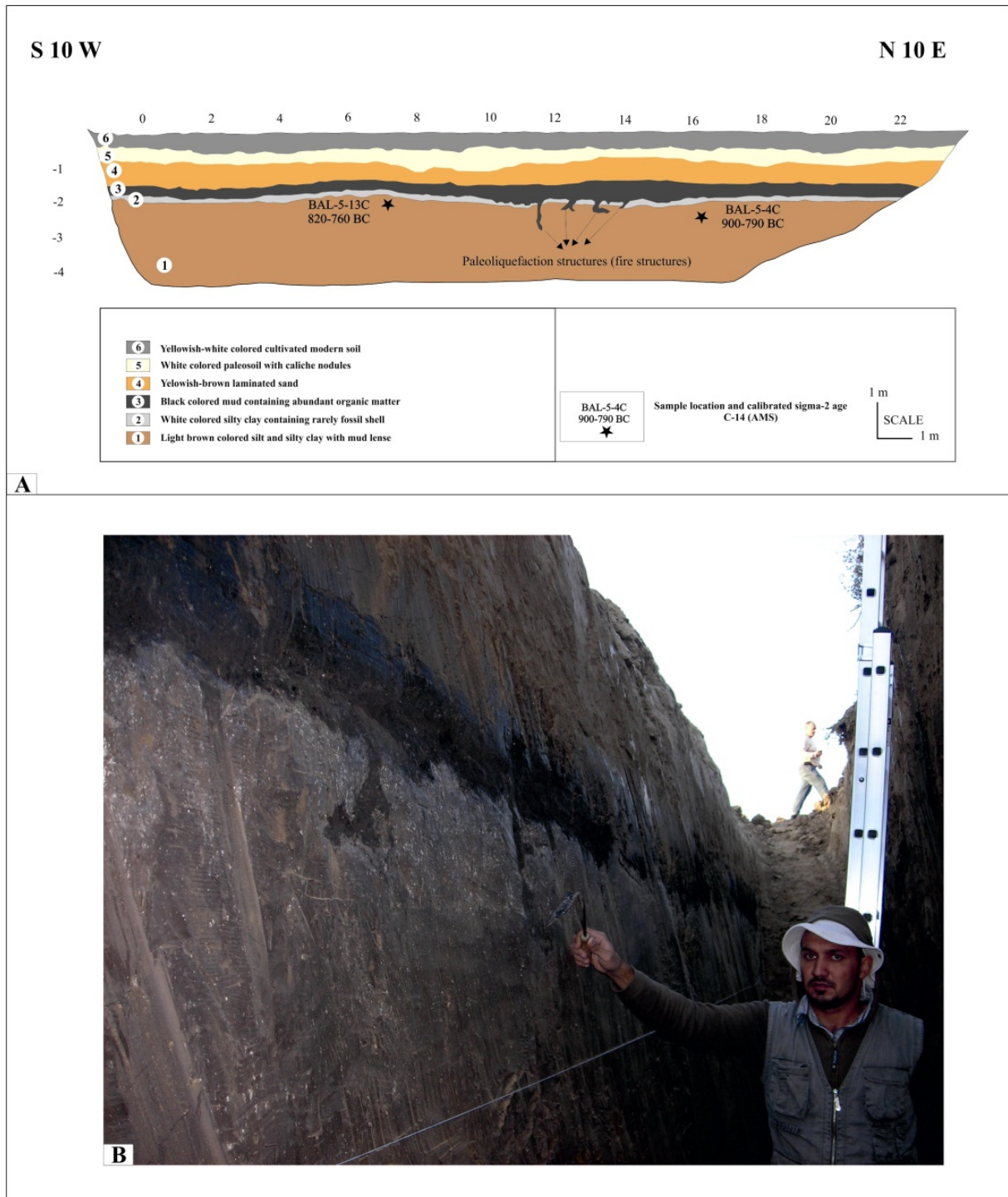


Figure 18. A: West wall cross-section of Balliburun trench (T-2) B: Paleoliquefaction structures

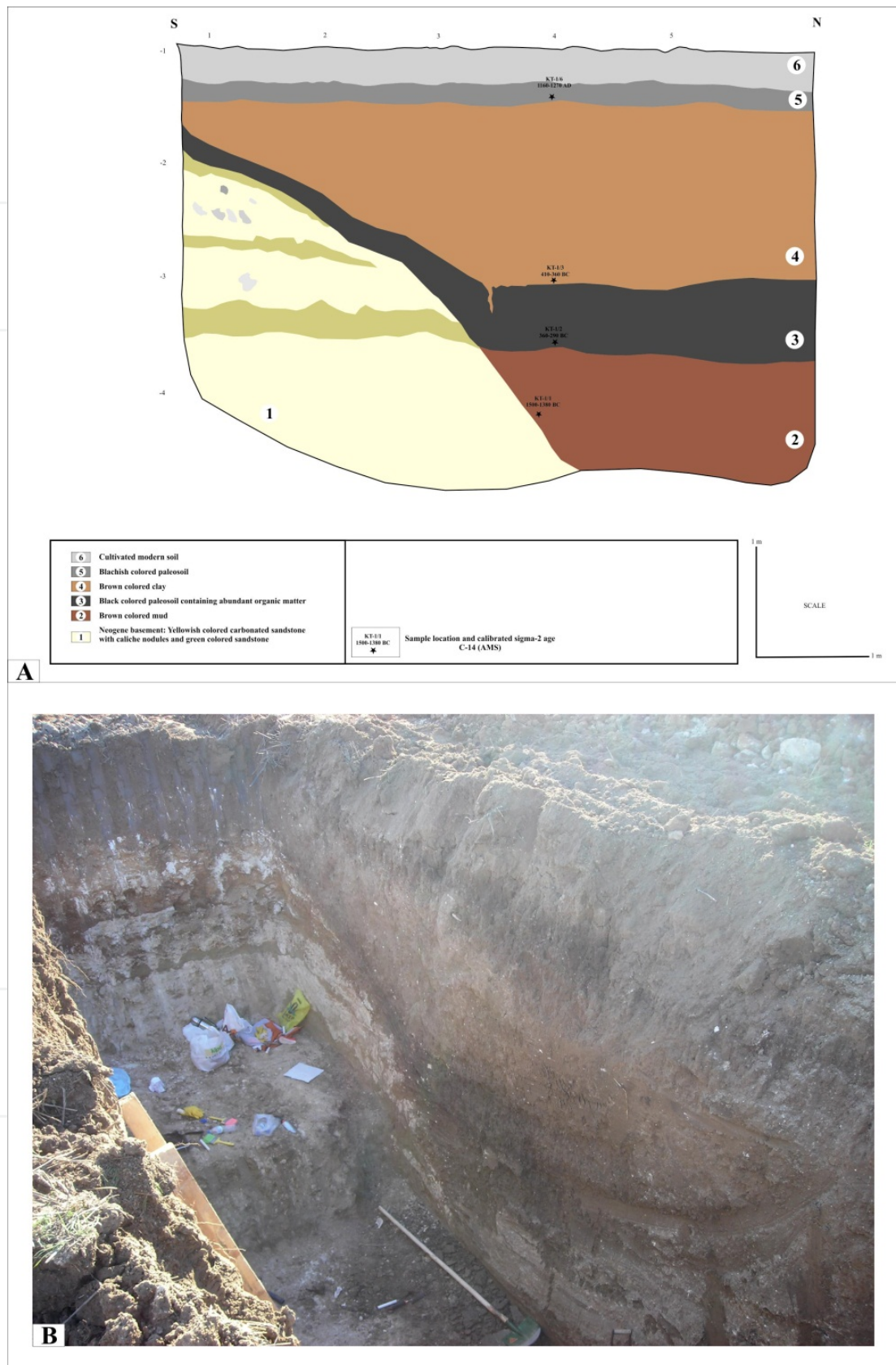


Figure 19. A: West wall cross section of Kesiktepe Trench (T-3), B: Photograph of West Wall of Kesiktepe Trench



Figure 20. Relief geomorphological map of Troy region (Forchammer, 1850) Red lines show drainage canals opened in order to dry the swamp

vicinity, documented NW-dipping faults as the continuation of Kumkale fault. These faults are the continuation of Kumkale fault in the sea. The total length of Kumkale fault is 15 km including its continuation in the sea. Kumkale fault is thought to be one of the primary synthetic strike slip faults developed within NAFS.

Kumkale fault brings Neogene units and Quaternary deposits face to face (Figure 21). This relationship could be observed in the open outcrop in Figure 21 B. Afterwards; this observation point was leveled with the help of a working machine and transformed into a

trench (see Figure 3, T-5). In Figure 22, the photomosaic and trench cross section are presented.

Four samples were taken from T-5 Trench and ages could be obtained from three of them.

Through the evaluation of trench microstratigraphy and C-14 age data together, two earthquakes were defined in T-5 Trench. The first of them is associated with the faulting that cuts Unit C and is covered by Unit B. Consequently, the event horizon for this fault (Event II) is between Units C and B. The age obtained from Unit C is between B.C. 40 and A.D. 130, and the age obtained from Unit B is between A.D. 780 and 1000 (see Figure 24). According to these age data, the first earthquake occurred between A.D. 130 and 780. The second fault (Event I) is associated with the faulting that cuts Unit B and is covered by Unit A. The event horizon for this earthquake is between Units B and A. The age obtained from Unit B is A.D. 780-1000. And the age obtained from Unit A is between A.D. 1300 and 1430 (see Figure 22). According to these age data, the second fault (Event I) occurred between A.D. 1000 and 1300.

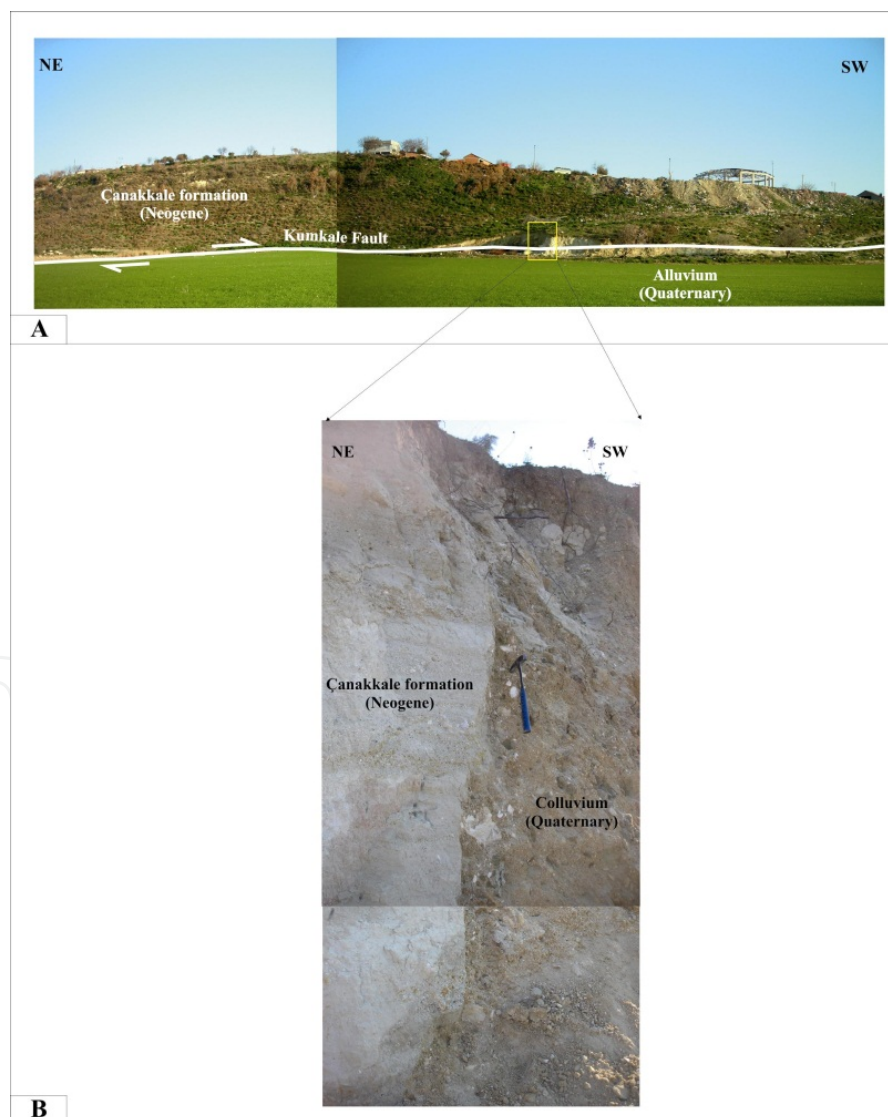


Figure 21. A: Panoramic sight of Kumkale fault, B: Sight of Kumkale fault in the outcrop

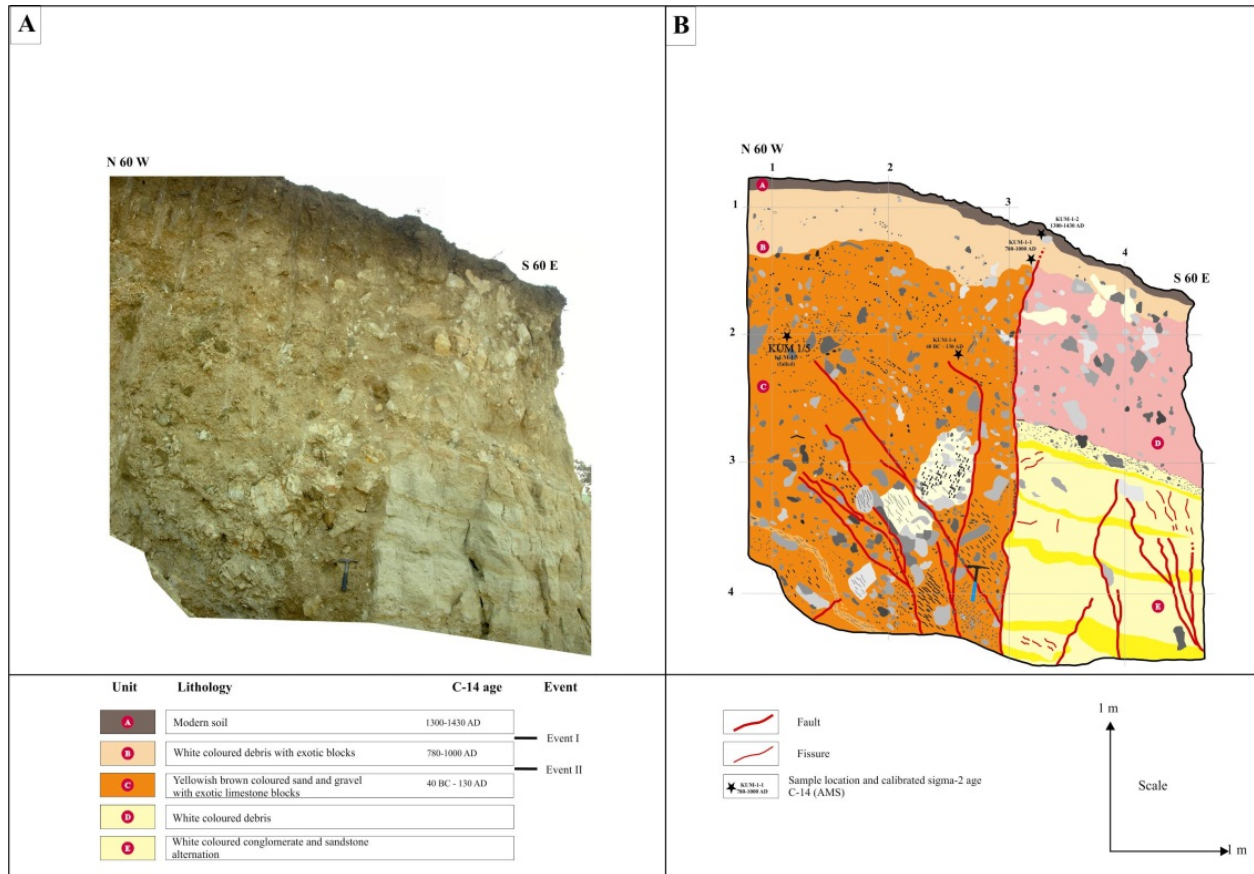


Figure 22. Photomosaic (A) and cross-section (B) of the south wall of Kumkale Trench (T-5)

5. Results and discussion

As a result of this study;

According to the morphotectonic studies conducted on the Troy fault, the Troy fault is divided into three segments, from west to east, as Tevfikiye, Halileli and Dümrek segments. Since their mountain front sinuosity ratio (S_{mf}) and valley floor width to valley height ratio (V_f) are similar, Tevfikiye and Halileli segments were evaluated together and given the name “the Troy segment”.

The mountain front sinuosity ratio of the Troy segment was computed as $S_{mf}= 1.28$ and that of Dümrek segment was computed as $S_{mf}=2.52$. Taking into account these values, the Troy segment was determined to be more active and therefore, subsequent geological and geophysical studies were concentrated on the Troy segment.

In the calculations carried out using the empirical equations suggested in the studies that investigate the relation between the geological fault length and the greatest earthquake (for example, Pavlides and Caputo, 2004), the greatest earthquake magnitude that can result from 11-12 km long Troy fault was computed as $M= 6.2-6.5$.

Both the results of the kinematic analysis studies of the fault assemblages and the focal mechanism inverse solution of the earthquake having the magnitude of 3.1 that occurred on

the Troy fault on 03.02.2008, indicate a strike slip with normal component faulting developed under transtensional stress regime characterized by WNW-ESE oriented compression (P) and NNE-SSW oriented tension (T) in the Troy region at the present time. The fault systems in the Troy region and the stress regimes which are effective at the present time show that strike-slip faults and concordant normal faulting in active in the Troy region.

According to the Direct Current Resistivity profile studies conducted on profile lines perpendicular to the fault trace along the Troy fault, it was understood that the Troy fault passes 30-100 meters north of the morphological escarpment which borders the Troy rise from the north. This situation can be explained by means of the degradation of the Troy fault scarp in the course of time. According to the geoelectric cross-sections obtained from the shallow geophysical studies, some discontinuity signs were encountered. However, it was observed that these discontinuities do not reach the surface but come to an end at the depth of about -10 meters from the surface.

In the Quaternary deposition area north of the Troy fault, in order to examine the lateral thickness variation of the Quaternary deposits towards the fault, 5 shallow drilling works with depths varying between 3 and 9 meters were conducted at 5 points along a direction perpendicular to the Troy fault. When the information obtained from these drilling works were transformed onto the three dimensional schematic geological cross-section, it was seen that the plane which constitutes the boundary between the Quaternary deposits and the Neogene aged units gets thicker towards the south (towards the Troy fault). In other words, this boundary is tilted towards the Troy fault. This corroborates the asymmetry of the basin and at the same time points to the Quaternary activity of the Troy fault. From the paleoseismological trench studies it was understood that no earthquake resulting from the Troy fault occurred in the last 3000 years from B.C. 1190 up to the present, in Tevfikiye trench. Since the thickness of the sediments accumulated on the fault during the period from the last earthquake which resulted from the Troy fault up to the present was greater than the depth that can be reached in paleoseismological trench works, it was not possible to reach traces of faulting in the trench excavations.

In Ballıburun trench, some paleoliquefaction structures, developed during the time from B.C. 760 up to the present as a result of an earthquake that was originated from the nearby faults, were observed.

Two earthquakes were dated in the paleoseismological studies conducted on the Kumkale fault. The first of these faults occurred between A.D. 130 and 780 and the second one occurred between A.D. 1000 and 1300.

The paleoliquefaction structures observed in Ballıburun trench might have resulted from the Kumkale fault.

In this study, it was understood that the earthquakes which destroyed Troy III and Troy VI layers had not developed depending on the Troy fault system. Although their source is not clearly known, these earthquakes might have originated from the active faults in Biga Peninsula or from Gaziköy-Saroz fault which represents the north branch of NAFS. The

isoseist maps of the large earthquakes that caused surface faulting on Gaziköy-Saroz, Yenice-Gönen and Biga faults in this region, in the last century are presented in Figure 23.

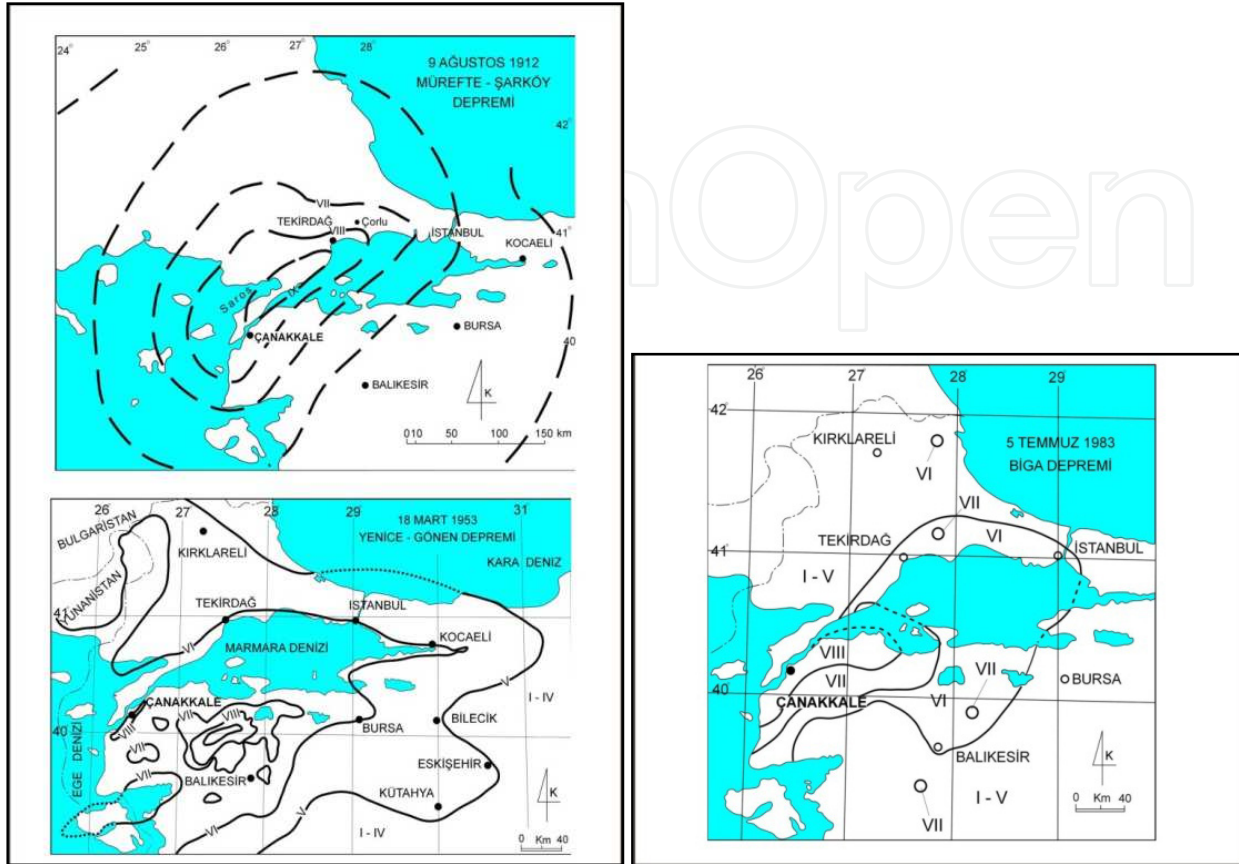


Figure 23. Isoseist maps of Mürefte-Şarköy (1912, Yenice-Gönen (1953), and Biga earthquakes (1983) (Kalafat et al., 2007)

As can be clearly seen in Figure 24, the region where Troy is located was affected at an intensity of VIII-IX by all three earthquakes. When such properties as local soil conditions and building style are taken into account, it is possible to state that historical earthquakes resulted from these faults affected Troy region. Rockwell et al., (2001) conducted paleoseismological studies on Gaziköy-Saroz segment of NAF in the vicinity of Kavakköy and documented 5 earthquakes from the present-day backwards. Kürçer et al., (2008), in their paleoseismological studies carried out on Yenice-Gönen fault, documented two earthquakes that they dated to A.D. 620 and A.D. 1440. In the light of all this information, it is the possible that the earthquakes that affected the Troy region might have resulted from the other active faults in the region.

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