International Journal of Earth Sciences Knowledge and Applications
www.ijeska.com

Research Article

e-ISSN: 2687-5993

Geological Structure and Geothermal Potential of the Southeastern Alaşehir, Gediz Graben (Western Anatolia, Turkey)

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INFORMATION

Article history
Received 18 March 2021
Revised 10 April 2021
Accepted 15 April 2021
Available 15 July 2021

Keywords
Detachment fault
Transfer fault
High-temperature geothermal field
Geothermal potential
Gediz Graben

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ABSTRACT

In this study, the observations at different locations were made to explain the structural features of the region where the study area is located and to reveal its faulting type, geometric properties, and faulting mechanism in detail. Fault and layer planes were measured at the observation points to obtain information about the faulting properties, fault geometry, faulting environments that will carry the geothermal fluid up, and bring out the geothermal potential of the area. Within the scope of field studies, alteration zones were mapped in the study area. The alterations areas were generally observed at the intersection of the strike-slip faults that tear high-angle normal faults in the north, which intersect the stepping faults. The intersection zones of the bounding detachment faults which limit the study area from the southwest with the NW-SE trending high-angle normal faults with southern-to-north steps and the NE-SW trending transfer faults in the subsurface were identified as the areas with high potential for the existence of a high-temperature geothermal field.

1. Introduction

The Aegean extensional province, where the study area is located, occurs by the north-dipping Hellenic subduction zone in Africa-Eurasia convergent boundary in the Eastern Mediterranean region (Fig. 1). There are two sets of Cenozoic extensional grabens and sedimentary basins in and around the Menderes Massif: those with NNE-SSW-trending and filled with Lower Miocene and younger siliciclastic, volcaniclastic, volcanic rocks, and those ~E-W-trending and filled mainly with siliciclastic rocks (Yilmaz et al., 2000; Purvis and Robertson, 2005; Ersoy and Helvaci, 2007; Ersoy et al., 2010). Most of these grabens are bounded by high-angle normal faults with strike-slip components (Yilmaz et al., 2000; Bozkurt, 2003; Ersoy et al., 2010). These E-W-trending grabens and basins are bounded by normal faults dipping with high to moderate-angles, some of which are seismically active (Arpat and Bingöl, 1969; Eyidogan and Jackson, 1985; Çiftçi and Bozkurt, 2009; Çiftçi and Bozkurt, 2010), and destroying and cross-cutting NNE-SSW-trending grabens and basins.

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Yilmaz et al. (2000) reported that NNE-trending grabens locally occur as 'hanging grabens' in the footwalls of the E-W trending ones and that the trapped structures and sedimentary units of these older NNE-trending grabens are distinguishable in the seismic profiles. 2D gravity and magnetotelluric modeling of the structure of the Gediz-Alasehir Graben has revealed the existence of a series of these NE-SW-trending grabens and sub-basins at deeper depths (Gürer et al., 2001) and indicated that the regional structural fabric seen at the surface continues beneath the Quaternary sedimentary fill of the E-W-trending modern graben system.

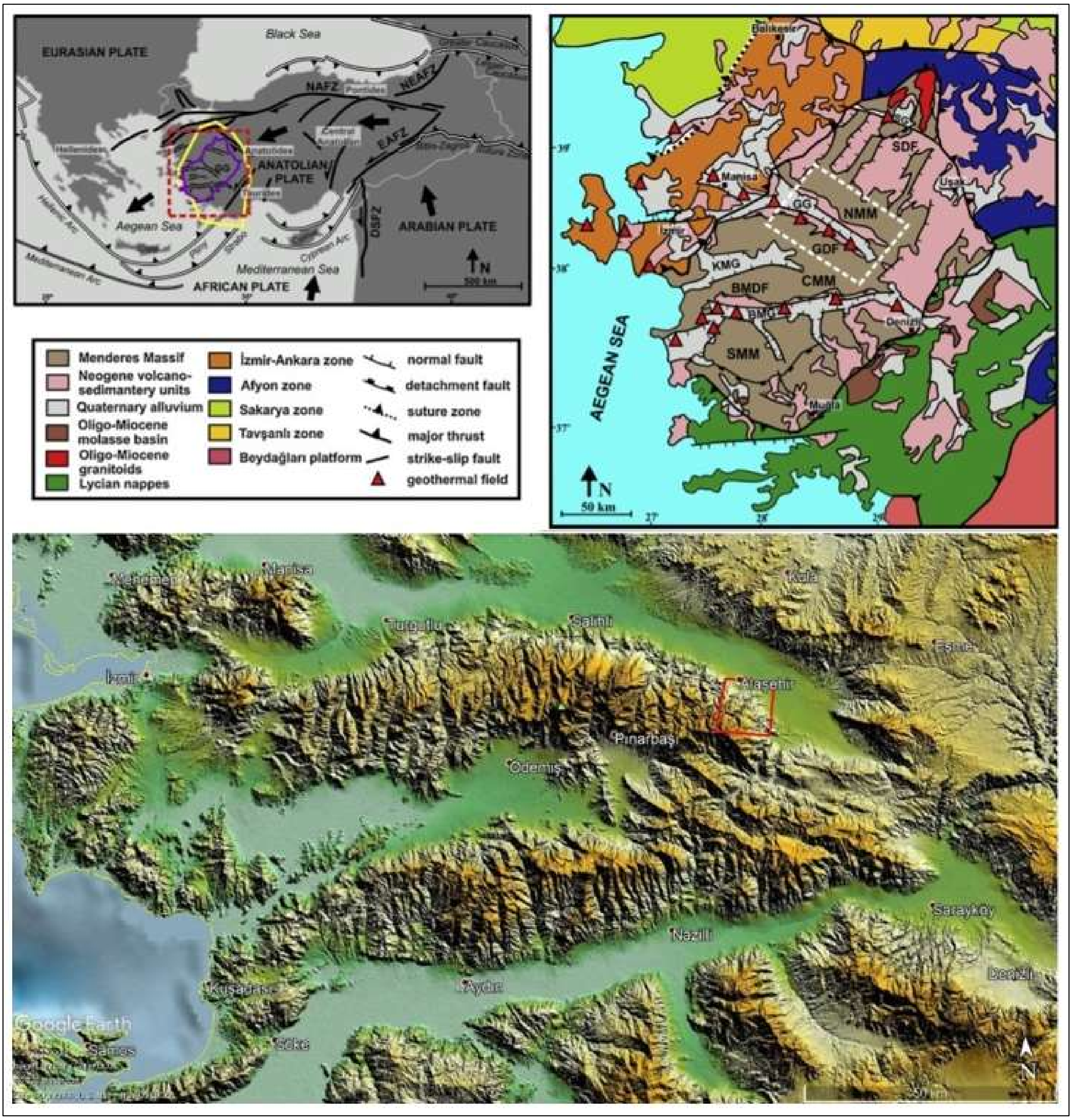

Fig. 1. Location map of the study area (red polygon). Main structures and grabens: NMM: Northern Menderes Massif, CMM: Central Menderes Massif, SMM: Southern Menderes Massif, BMG: Büyük Menderes Graben, GG: Gediz Graben, KMG: Küçük Menderes Graben, GDF: Gediz Detachment Fault, BMDF: Büyük Menderes Detachment Fault (modified from Hacıoğlu et al., 2020).

The initial geothermal studies in Gediz Graben in Western Anatolia started in the 1960s because of the presence of numerous high-temperature hot springs located in the region. Temperatures in the Gediz Graben range from 188 to 287 °C. Geothermal resources are utilized for the purposes of district and greenhouse heating, production of chemical substances, tourism and health facilities, and mainly in the generation of electricity (Ozdemir et al., 2017; Ozdemir and Palabiyik, 2019a; Ozdemir and Palabiyik, 2019b; Palabiyik and Ozdemir, 2019; Ozdemir et al., 2021). There are more than 200 deep geothermal wells in the Graben. 6 geothermal power stations are currently being operating and approximately electricity of 160 MW is generated from these power stations (Ulgen at al., 2018). In this study, the geological features and structural elements of the study area in the Gediz Graben, where high-temperature fields are located (Fig. 1), have been examined and the high-temperature geothermal field potential has been tried to be determined.

2. Geological Setting

In the region covering the study area and its surroundings, there are eight different units: (1) schists of the Precambrian - Middle Triassic Menderes Massif, (2) metagranites of the Precambrian-Middle Triassic Menderes Massif, (3) metaophiolites of the Precambrian-Middle Triassic Menderes Massif, (4) marbles belonging to the Precambrian-Middle Triassic aged Menderes Massif, (5) conglomerates and sandstones of the Upper Miocene-Lower Pliocene Alaşehir-Gediz Formation, (6) volcanic units of the Upper Miocene-Lower Pliocene Gediz Formation, (7) claystones and sandstones of the Upper Pliocene-Quaternary Kaletepe formation, and (8) Quaternary alluvial deposits (Fig. 2).

There are some differences in the geological units outcropping in the southeast half and northwest half of the Asar Stream flowing through the middle of the study area. In the southeastern half of the study area, close to the southwestern border, south of Söpüce, while schists and metaophiolites of the Menderes Massif are brought to contact by the detachment fault; on the southwestern border, around Söpüce, schists and marbles are juxtaposed. Metagranites are exposed in the area between Elmacık, Türkmen, and Küçükbahçe in front of the detachment fault. In the north of the Kepez, around the Küçükbahçe-Narlıdere-Belenyaka, Quaternary units consisting of tuffites and red pebbles of Upper Miocene-Lower Pliocene volcanic units are exposed.

However, in the SE half of the study area, there is no unit with the Upper Miocene-Quaternary age range (Fig. 2). Between the Söpüce and Alakıraç, very thin slope debris are observed on the slopes.

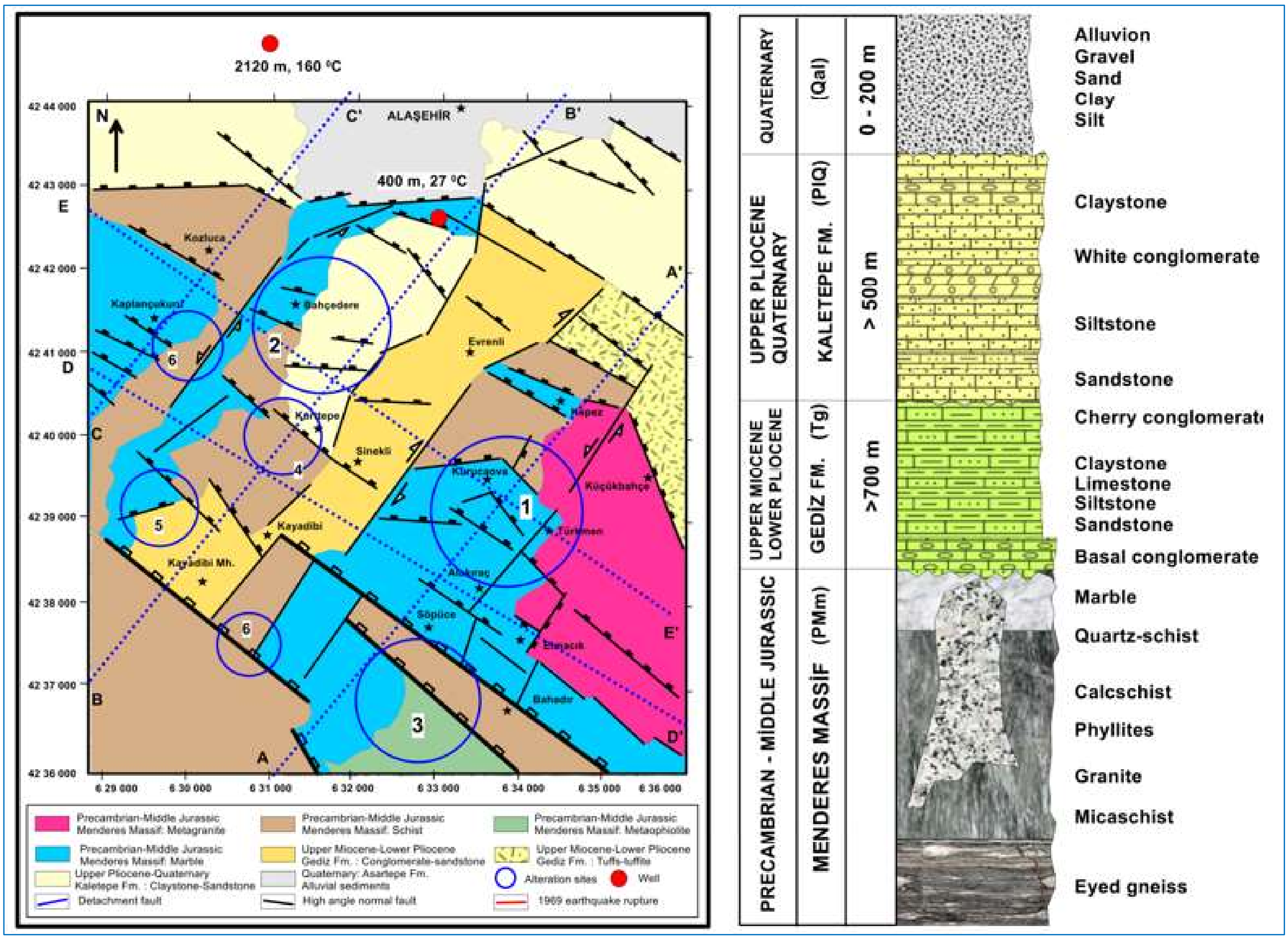

Fig. 2. Simplified geological map, generalized stratigraphic section, and geological cross-section lines of the study area (also see Section 3.2)

In the northwestern half of the study area between Asar Stream and Dokuzpınar Stream, around Kayadibi, the schists of Menderes Massif are juxtaposed with the conglomerates-sandstones of the Upper Miocene-Lower Pliocene Gediz Formation along the detachment fault. Along the high-angle normal fault extending between Kurttepe and Sinekli, the schists of the Menderes Massif and the units of the Upper Pliocene-Quaternary Kaletepe Formation is brought side by side (Fig. 3). Kaletepe Formation was deposited in front of the high-angle normal fault under fault control (Fig. 2). Contact relationships of marbles and schists are locally faulted and/or angular discordant and concordant (Fig. 4).

Fig. 3. Schists of Menderes Massif juxtaposed with Upper Miocene-Lower Pliocene tuffites and conglomerates of the Quaternary Asartepe formation displaced by the high-angle normal fault

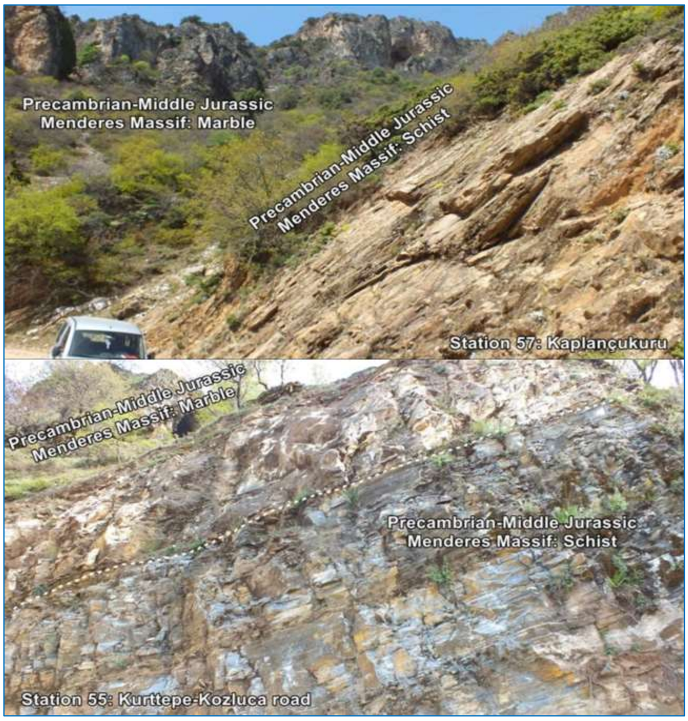

Fig. 4. Unconformably overlapping marbles above schists of Menderes Massif

Schists and marbles along the transfer fault, which is thought to extend along the Asar Stream; the marbles and the Gediz Formation, and the schists and the units of the Gediz Formation are brought side by side with fault contact. The schists and marbles are juxtaposed along the transfer fault along the Dokuzpinar Stream (Fig. 2).

The basement unit of the study area consists of the schists of the Menderes Massif. Metamorphic units' outcrop in a large area in the footwall block of the detachment fault extending through the southwestern border and the nearest southwest of the study area. The unit consisting of schists and phyllites outcrops between Kurucaova-Kepez, south of Söpüce, around the Kayadibi, Sinekli-Kurttepe, Bahçedere, Kaplançukuru and Kozluca (Fig. 5).

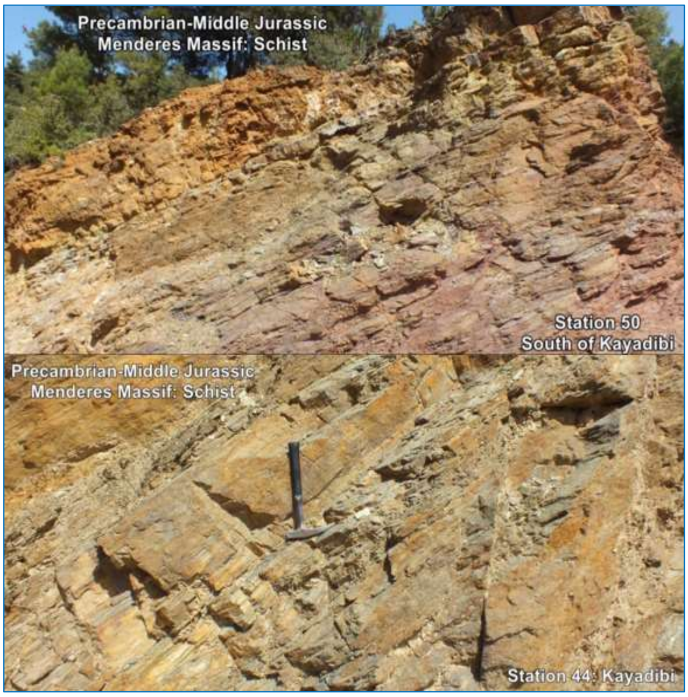

Fig. 5. A view from schists of Menderes Massif

In the areas close to the southeast boundary of the study area, the metagranites of the Menderes Massif outcrop in the region between Elmacık-Türkmen-Kepez-Küçükbahçe. Metagranites exhibit a structure that has been transformed into augen gneiss. The unit is locally faulty contact with marbles and schists (Fig. 2). The unit which is very typical at the Station-22 point near the Elmacık-Dikmen Hill is exposed in the Turkmen-Kepez-Küçükbahçe Road cuts (Fig. 6). These parts are highly altered due to excessive deformation and superficial conditions.

In the south of Söpüce of the southern border of the study area, the metaophiolites of the Menderes Massif are outcropped. Metaophiolites in the detachment fault zone have gained an extremely fractured, cracked, and blocky structure as a result of faulting (Fig. 7). Metaophiolites and schists are observed side by side with faulty contact.

In the area to the southeast of Asar Creek dividing the study area into two parts, marbles of the Menderes Massif are widely outcropped in the regions between Kurucaova-Türkmen-Alakıraç-Söpüce, around Kepez, and on both sides of Bahçedere and Dokuzpınar creek. The unit is located in Ayıdağı, southeast of Kayadibi; along Bahçedere; around Söpüce. It is typically spread in the Kurucaova and Alakıraç-Türkmen regions. The marbles exhibit a massive, blocky, brecciaceous, and bedded structure in and around the study area. They form caps in the peak parts of the mountainous areas, around Ayıdağı and Kaplançukuru (Fig. 8).

While marbles and schists show faulted contact along the detachment fault in and around the southwestern border of the study area; along the NW border of the Dokuzpınar Stream, they are overlain unconformably the schists. However, along the Kurttepe-Kozluca Road, they have conformably covered the schists in the footwall block of the high-angle normal fault. Along the strike-slip faultings followed by Bahçedere-Dokuzpınar Streams, marbles and schists are juxtaposed. Marbles along the detachment fault have generally blocked, and very fractured-cracked and brecciated across high-angle normal fault zones; and have a stratified structure in the parts away from fault zones.

Fig. 6. A view from metagranites of Menderes Massif

Fig. 7. Views from metaophiolites of Menderes Massif

In the very limited areas of the study area, the units of the Upper Miocene-Lower Pliocene Alaşehir-Gediz formation outcrops around Kayadibi, Kurttepe (Fig. 9). The unit could not be mapped since it was observed only in very limited areas across the fault zones. The unit consists of conglomerates and sandstones. There are lots of pebbles derived from schist, marble, and metagranites in the unit. The pebbles are poorly graded, angular, and have locally a stratified and fractured structure.

Fig. 8. Views from marbles of Menderes Massif

The units of the Upper Miocene to Lower Pliocene Gediz Formation in the study area distribute along the Kayadibi-Sinekli-Evrenli Line on the NW side of the Asar Stream dividing the study area. In the parts near the southwestern border of the study area, the unit presents faulted contact with the schists along with the detachment fault. The conglomerate and sandstone layers of the unit are tilted towards the detachment fault. It is observed very typically around the unit at the entrance to Kayadibi and Evrenli (Fig. 9). In the study area, Gediz Formation starts with basal conglomerates at the bottom. Pebbles are composed of schist, marble, granite, and ophiolitic pebbles. Gediz Formation begins with pebbles at lower levels and continues with sandstones towards the upper (Fig. 10). The sandstones are bedded, and the layers reach thicknesses ranging from several centimeters to several meters. The layers are thick or very thick, and have the N60W 40SW and N75W 50SW directions. They are tilted into SW towards fault zones.

The tuffites of the volcanic units of Gediz Formation outcrops in the north of Kepez-Küçükbahçe. The unit is juxtaposed with schists and metagranites of the Menderes Massif along the high-angle normal faulting of the Küçükbahçe-Kepez line (Fig. 11).

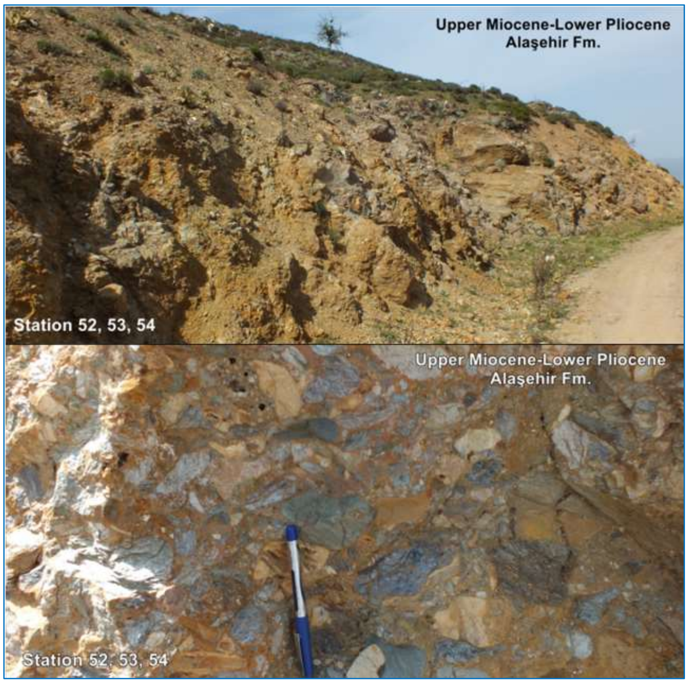

Fig. 9. Views from conglomerates of Alaşehir-Gediz Formation

Fig. 10. Views from sandstones of Gediz Formation

On the east side of the line extending between Kurttepe and Bahçedere, Upper Pliocene-Quaternary sediments deposited under the control of high-angle normal faults (Fig. 12). The unit consisting of sandstone, mudstone, conglomerate, claystone, and siltstones is horizontally layered andyellow, and covers the older units unconformably.

In the north, Quaternary gravels representing fan deposits are exposed between the Narlıdere-Küçükbahçe-Belenyaka. The unit consists of loosely consolidated pebbles and are horizontally layered. Pebbles are well-rounded and well-sized (Fig. 13). Between Söpüce and Alakıraç, there are slope debris on the plains. The unit consists of gravel, sand, and clay (Fig. 14).

Fig. 11. Views from tuffites of volcanic units of Gediz Formation

Fig. 12. A view from the sandstone-claystone-siltstone units of the Kaletepe Formation

Fig. 13. A view from the conglomerates of Asartepe Formation

3. Structural Geology

To reveal the faulting type, faulting geometry, faulting mechanism, and kinematic features in the study area and to determine the location of the possible geothermal system according to faulting, detailed observations were carried out at 66 different stations (Fig. 15). In the light of the information obtained from the stop points, morphotectonic and geology maps of the study area in the 1/25,000 scale have been prepared (Fig. 2).

3.1. Faults

In the morpho-tectonic maps prepared using the geomorphological and geological findings obtained from 66 stop points, the fault types and geometrical properties of the study area are elaborated. 3 different types of faulting in the study area have developed as follows:

(1) Low-angle normal faults (Detachment fault)
(2) High-angle normal faults
(3) Transfer faults

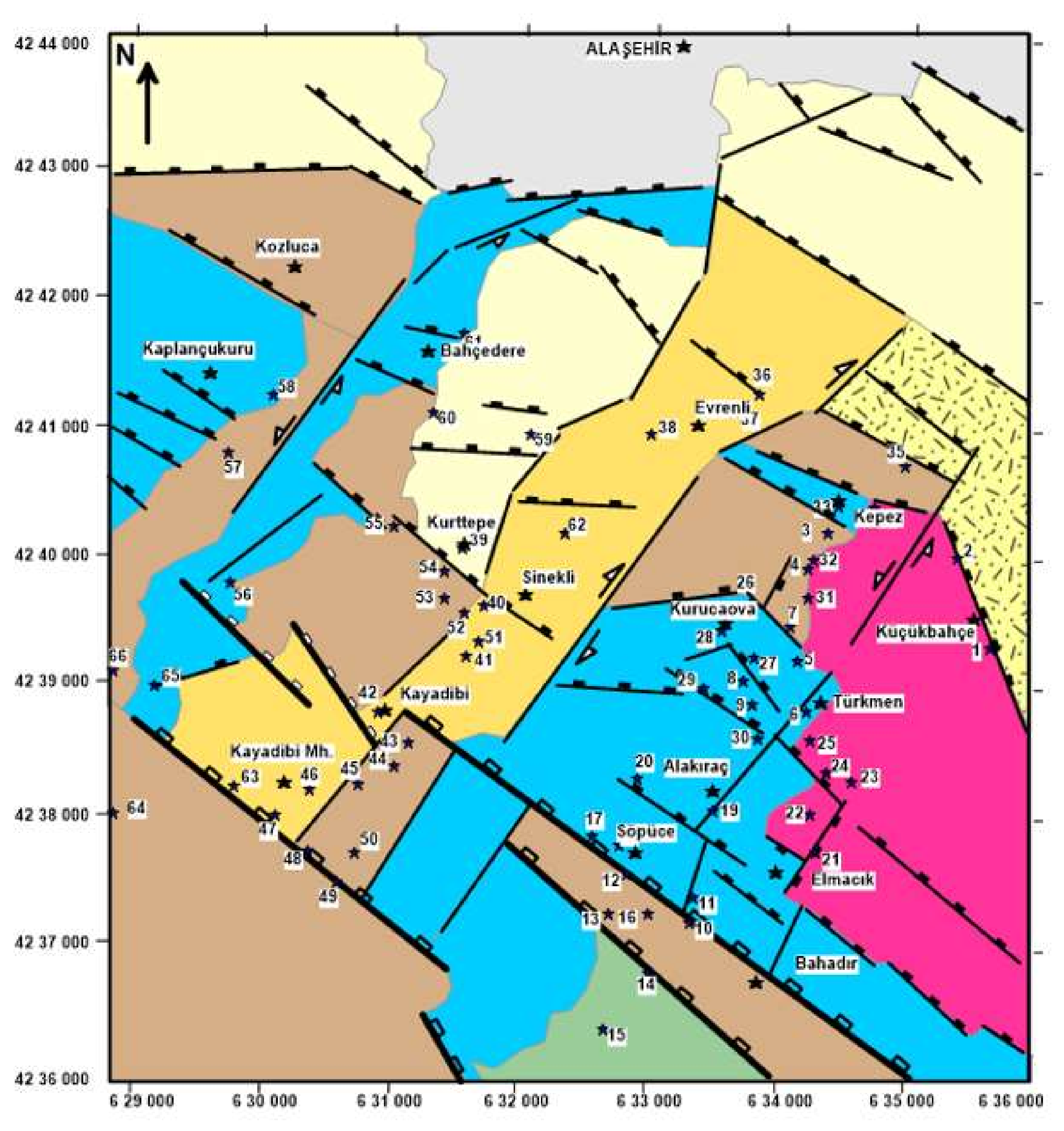

Fig. 15. Locations of the stop points/stations in study area. Light notched dark lines: detachment fault; dark notched fine lines: high-angle normal faults and arrowed lines: transfer faults (see Section 3.2 for cross-sections)

Detachment, low angle, and high-angle normal faults have NW-SE trends, and transfer faults have NE-SW strikes. Low-angle detachment faults have dips of 40-45 degrees averagely and 60-70 degrees in high-angle normal faults and 75-90 degrees in the transfer faults. NE blocks of low and high angle normal faults have down-thrown. The study area has been displaced vertically to NE by stepping faulting towards the surface faulting of the 1969 earthquake, starting from the detachment fault extending in the southwest. This vertical displacement is around 1500-2000 m.

The detachment fault extends from Bahadır in the southeast to the south of Kaplançukuru in the northwest, following the south of Söpüce and Kayadibi. The detachment fault forms a zone of approximately 1.5 km in width and exhibits en-echelon segments by making steps. The detachment fault is typically observed in the south of Söpüce. It has developed between schists and marbles. The marbles have been downthrown around 300-400 m in this part (Fig. 16).

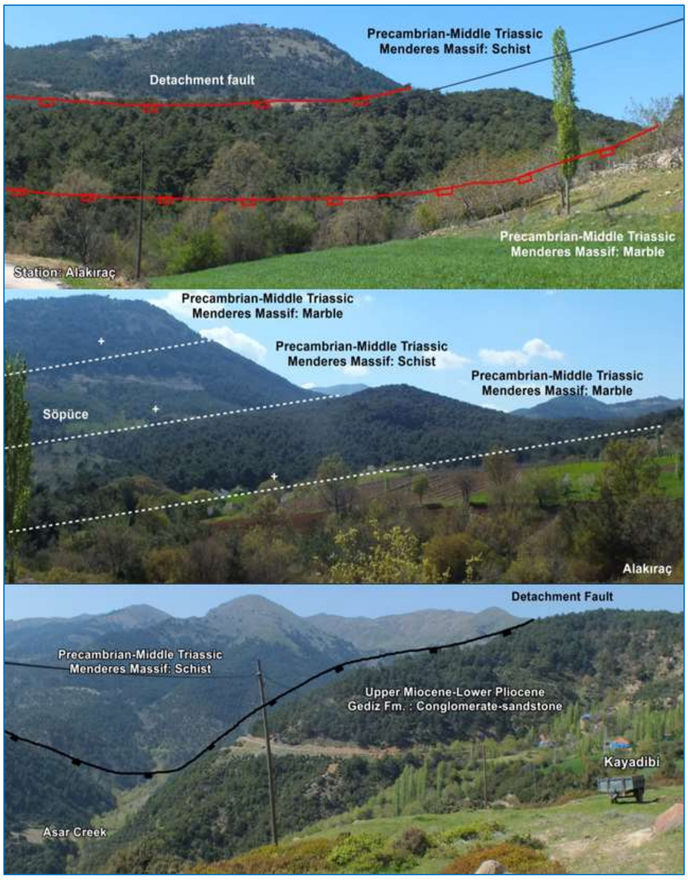

Fig. 16. Views from the detachment fault in the study area

The detachment fault continues to the west by forming a zone about 2 km-wide in the south of Kayadibi. The detachment fault, which shows segmentation by making steps in this region, juxtaposes the schists with Gediz Formations (Fig. 17). High-angle normal faulting in front of the detachment fault in the Ayıdağı Mountain has caused it to downthrown about 300-400 m towards NE in the form of stepping marbles. The units of the Gediz formation were tilted towards the detachment fault.

The detachment fault extends towards NW between the south of Kayadibi and Kaplançukuru, and continues towards the west. In this region, the detachment fault developed between schists and marbles, and the marbles are downthrown to the NE by a few steps (Fig. 18).

Two main high-angle normal faults have developed in front of the detachment fault in the study area. The first high-angle normal faulting follows Kurucaova in the north, Sinekli-Kurttepe in the east, and Adamkaya Hill in the west. Along the fault, schists are juxtaposed with Gediz and Kaletepe Formations, and a vertical offset is about 300 m. In the west, marbles have been downthrown along this fault. Around Kurttepe, the marbles and the Upper Pliocene-Quaternary Kaletepe Formation reflects a faulted contact (Fig. 19).

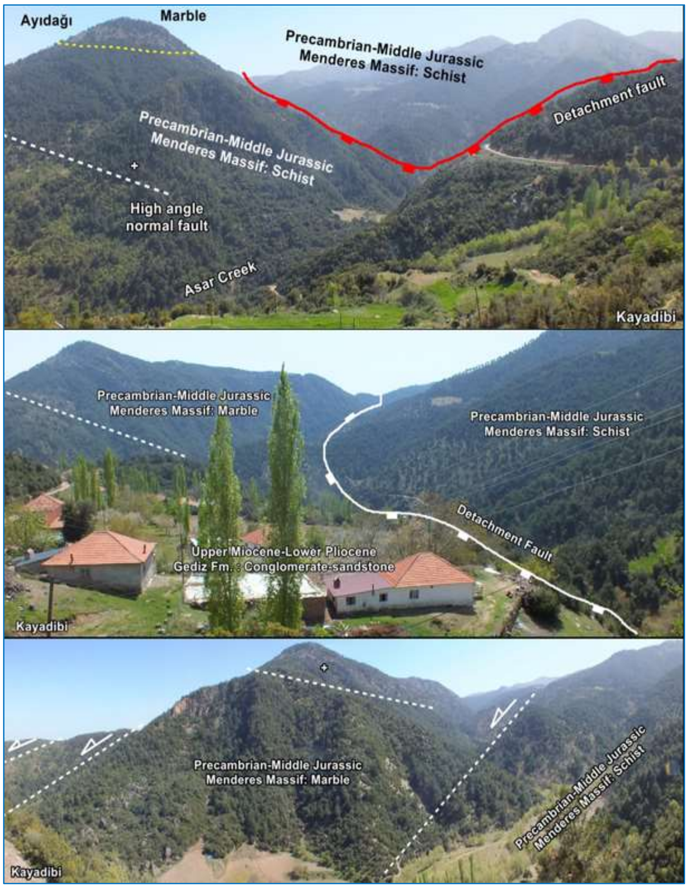

Fig. 17. Views from the detachment fault and high-angle normal faulting in the study area

Fig. 18. A view from detachment fault and high angle normal fault between Kaplancukuru and Bahçedere (A look of faults from Bahçedere towards Dokuzpınar Stream). Red arrows: detachment fault; white arrows: high-angle normal faults

Around Sinekli, along this fault, schists juxtapose with the units of Gediz Formation (Fig. 19). Throughout this fault, the metamorphic units have completely crushed, sheared, and altered by gaining a breccia character. Numerous small-scale normal faults cut by fractures developed within the fault zone (Figs. 20 and 21).

The first high-angle normal fault and stepping faults are observed in the east of Kayadibi, towards from Ayıdağı to the northeast. In this region, these faults caused the marbles to displace vertically and continuously towards NE (Fig. 22).

Fig. 19. Views from high-angle normal fault and stepping faulting that juxtaposes the schists and Kaletepe Formation

Fig. 20. A view from a high-angle normal fault juxtaposing the schists and Gediz Formation, around Sinekli Village

A high-angle normal faulting is observed, which cuts the Gediz Formation in Kayadibi Village. Sandstones and conglomerates of the unit were displaced, and conglomerates were upthrown upward in the footwall block (Fig. 23). Along the fault, conglomerates, claystones, and breccia units are brought side by side. Around Türkmen Village, schists and marbles display a faulted contact. In the Alakıraç-Elmacık Region, schists and marbles are juxtaposed with metagranites (Fig. 24). Between Kurucaova and Kepez, high-angle normal faulting developed between metagranites and schists is very distinctive (Fig. 25).

Fig. 21. Views from normal faults and brecciate zones developed in schists and Kaletepe Formation

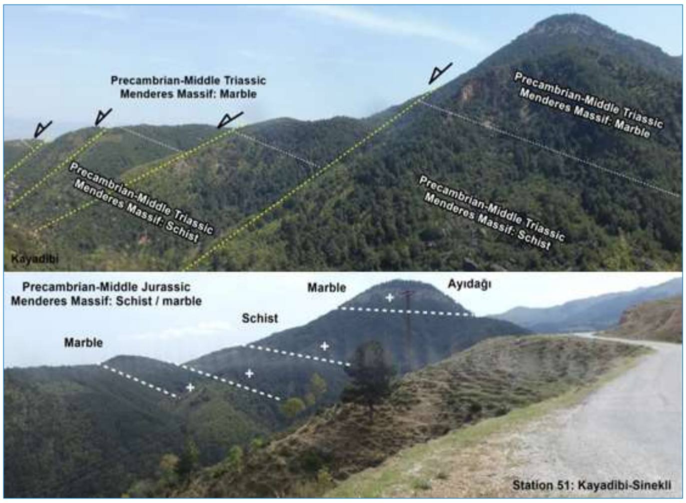

Fig. 22. Views of high angle normal fault and stepping faulting around Kayadibi Village

Fig. 23. A view from high-angle normal faulting that cuts the Gediz Formation

Fault and bedding planes were measured at 66 different stop points to explain faulting properties, fault geometry, and faulting environments that will carry geothermal fluid up along with reservoir and cover rocks, porosity, permeability properties, and geothermal potential of the study area (Table 1). 64 fault/fracture planes and 18 bedding planes measurements were conducted and plotted on the rose diagram and Wulff net to determine the dominant fracture planes and the direction of compression.

Fig. 24. Views from normal faulting which juxtaposing schists with metagranites around Elmacık-Dikmen Hill

As clearly seen in the rose diagram; (1) 3 out of 64 faults/fractures with N0-10W 85-90E/W; (2) 3 with N5-10E 58-70NW; (3) 7 with N15-28W 37-85NE; (4) 2 with N15-25E 50-70NW/SE; (5) 3 with N30-40W 45-90NE/SW; (6) 2 with N30-40E 60-75NW; (7) 12 with N50-55W 47-88NE; (8) 6 withN45-55E 50-85NW; (9) 9 with N60-70W 45-85NE; (10) 5 with N60-65E 60-85NW; fracture/fault planes in 12 different directions were measured, also including (11) 8 with N75-85W 70-85NE, and (12) 4 with N80-85E 60-85NW (Table 1 and Fig. 26).

Fig. 25. Between Kurucaova and Kepez, a view from high angle normal faulting between metagranites and schists

As seen in the rose diagram, in the study area (1) N15-28W 37-85NE; (2) N50-55W 47-88NE; (3) N60-70W 45-85NE; (4) N75-85W 70-85NE and N45-55E 50-85NW trending fault and/or fractures seem to dominate (Figure 25). N50-55W 47-88NE, N60-70W 45-85NE, and N75-85W 70-85NE trending fractures represent detachment faults and high-angle normal faults; N45-55E 50-85NW trending faults/fractures are related to transfer faults.

As seen on the Wulff net, N50-55W 47-88NE and N45-55E 50-85NW trending fractures are dominant and inclined to NE and NW. Besides, N15-28W 37-85NE oriented fractures are also distinctive (Fig. 27).

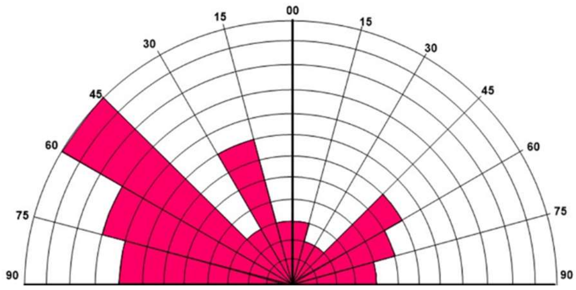

Fig. 26. Rose diagram of the fracture and fault planes measured in the study area

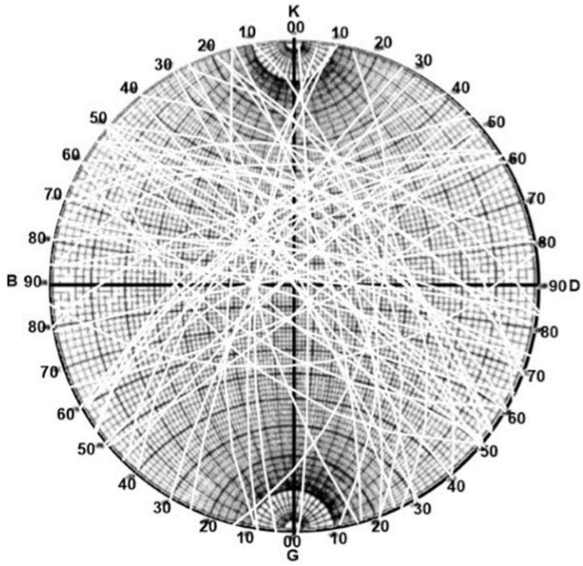

Fig. 27. Distribution of the fracture and fault planes measured in the study area on the Wulff net

This indicates that the region is under compression in the E-W direction, and NE-SW trending faults/fractures represent dextral feature while NW-SE trending faults/fractures exhibit sinistral character. Dips of the detachment fault are measured as averagely 45 degrees, 60-70 degrees in high-angle normal faults, and 80-90 degrees in transfer faults in the study area.

3.2. Geological Cross-Sections

(1) To detect the intersection zones of the NW-SE trending detachment fault zone in south-southwest boundary of the study area and high-angle normal faults cutting the detachment fault, and NE-SW transfer fault faults that tear both faults, (2) to explain burial faults of these fault systems going into the deep, 5 geological cross-sections have been prepared (Figs. 2 and 15). Using the findings obtained from

geology and tectonic researches in the study area, total displacement, and thicknesses of the geological units were estimated for 2000 m-depth to come subsurface geology of the study area into existence. As a matter of fact, the drilling studies carried out in the Gediz Graben revealed that the total vertical offset is between 1500 and 2000 m.

Table 1. Fault planes and dips measured in the study area

Station No	No	Location	Fault direction	Layer direction	Explanation
1	1	Küçükbahçe Village	N25W 37NE		Fracture plane
2	1	Küçükbahçe Village	N55E 50NW		Metagranite, fracture plane
3	1	Between Küçükbahçe-Kepez	N75W 20NE		Schist, fracture plane
	2		N85W 32NE		
4	1	Between Kepez-Kurucaova	N10E 68NW		Metagranite-fracture plane
	2		N55W 60NE		
	3		N85W 70NE		
5	1	Türkmen Village		N80E 30SE	Marble
6	1	Türkmen Village		N20E 40NW	Marble
	2			N80W 45SW	Schist
	3		N65E 75SE		Schist/Marble, faulted contact
	4		N50W 45SW		Mica schist
	5			E-W 72S	Quartzite
7	1	Entrance of Kurucaova Village		N55E 30SE	Schist
	2		N28W 68NE		Fracture planes
	3		N40E 60NW		
8	1	Kurucaova-Alakıraç Road		N60E 40SE	Marble
	2		N50W 50NE		Marble
	3		N60E 63NW		Fracture planes
9	1	Kurucaova-Alakıraç Road	N80E 85NW		Main fracture
	2		N30E 75NW		Fracture planes
	3		N50W 80NE		
	4			N45E 40SE	Marble
11	1	The SE of Söpüce Village	N15W 75NE		Metaophiolite
14	1	The SE of Söpüce Village		N70E 40SE	Schist-foliaceous
15	1	The S of the Söpüce Village	N20W 52NE		Fracture plane
	2			N25E 30NW	Metaophiolite
16	1	The S of the Söpüce Village		N75E 45SE	Schist
	2		N18W 65NE		Fracture plane
17	1	The W of the Söpüce Village	N30W 90SW		Breccia marble
21	1	Elmacık Village	N50W 72SW		Metagranite
	2		N60W 62SW		
22	1	Elmacık Village	N80E 55NW		Schist/metagranite, faulty contact
	2		N50W 50SW		
28	1	Kurucaova Village	N75W 80NE		Fracture plane
	2		N-S 90W		Fracture plane
	3		N40W 90NE		Main fracture
	4		N60E 80NW		Fracture plane
	5			N45E 25SE	Marble
29	1	Kurucaova - Alakıraç Road	N50W 70NE		Marble, Fracture planes
	2		N55W 82NE		
	3		N45E 85NW		
31	1	Kurucaova Village	N75W 85SW		Metagranite, Fracture plane
32	1	Kurucaova-Kepez Road	N25E 70NW		Metagranite, Fracture plane
	2		N60E 70NW		
	3		N60W 85NE		
	4		N85W 70NE		
	5		N60W 60NE		
	6		N5E 70NW		
34	1	Between Kepez-Küçükbahçe Villages	N60W 60NE		Marble, Fracture plane
36	1	Entrance of Evrenli Village		N75W 50SW	Gediz Formation
37	1	Entrance of Evrenli Village		N60W 40SW	Gediz Formation
40	1	Sinekli Village	N50W 88NE		Schist, Fracture plane
41	1	Sinekli-Kayadibi Road		N40W 20SW	Gediz Formation

The subsurface geology, which was modeled for depths of 2000 m in cross-sections, was carried out by using field study and 1/25 000 scaled morphotectonic and geology maps. The cross-section lines determined on the morphotectonic map were plotted to the 1/25 000 scaled geology map. Thus, cross-section lines are arranged to traverse each geological unit. In order to approach the geological structure up to the depth of 2000 m, cross-sections of 9 to 12 km in lengths were prepared.

Cross-section A-A' represents an approximately 10.5 km-long NE-SW directional geological section between the Ayıdağı in SW and Badınca in NE, on the southeast side of Asar Creek (Figs. 2, 15, and 28). The lowest elevation is 150 m whereas the highest one is 1270 m, and it has been extended to a depth of -2000 m. There is an elevation difference of about 1100 m between the detachment fault in the SW (1270 m) and 1969 surface faulting in the NE (200 m).

This situation indicates that there is a minimum vertical offset of 1100 m in the study area. From SW to NE; the fault steps were observed at elevations between 1280-970 m; 970-790 m; 790-710 m; 710-600 m; 600-280 m, and 280-200 m. In these fault steps, from SW to NE, which indicate the lowest vertical offsets, 310 m; 180 m; 80 m; and 110 m; respectively, and there are 320 m- and 180 m-elevation differences. Based on those differences, it can be expressed that there may be a minimum vertical displacement of 700 m in this part of the study area.

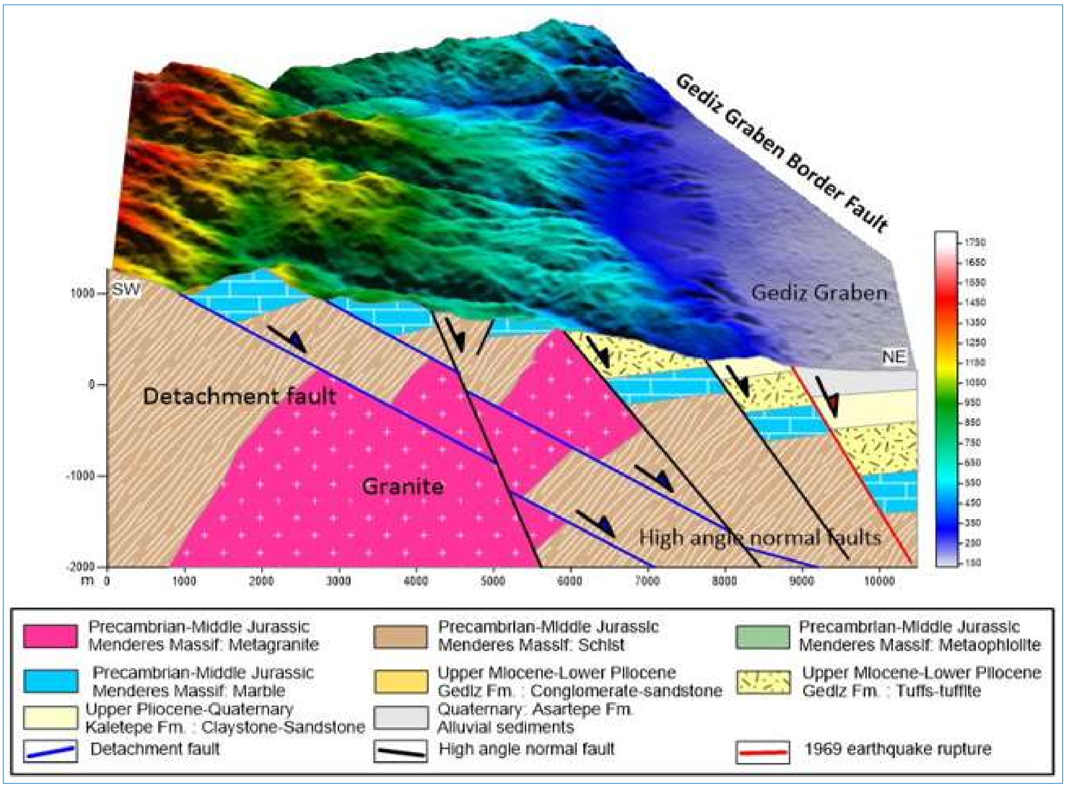

Fig. 28. A-A' geological cross-section with a length of 10.5 km between Ayıdağı Mountain and Badınca Village in NE-SW direction

It is seen that the marbles have been vertically downthrown approximately 400 m between Aydağı in SW and Kepez in NE. In NE of Kepez Village, they are covered by the Upper Miocene-Lower Pliocene volcanic units. It is thought that it is buried in the graben region around Badıca Village (Fig. 28). It is estimated that the metagranites outcropping between Kepez and Kurucaova in the cross-section may have been displaced as a result of cutting by detachment fault and high angle normal faults in the deep. In the NE part of the cross-section, Upper Miocene-Lower Pliocene volcanic units, Kaletepe formation, and Quaternary sediments are exposed. Nevertheless, these units are not located in the southeast of the Asar Stream. In the cross-section, NW-SE trending detachment fault, high-angle normal faults, and geometrical relations between them are very prominent. If accepted that the dip of the detachment fault is 40-45 degrees, and the dip of the high-angle normal faults is 60-70 degrees, it is estimated that the detachment faults are displaced as a consequence of cutting by the first high-angle normal fault at the depth of approximately 800 m and at the depth of 1650 m by the second high-angle normal fault.

Cross-section B-B' represents the approximately 12 km-long NE-SW directional geological section taken between Gavurharman Ridge in SW and Alaşehir in NE, between Asar Stream and Dokuzpınar Stream (Figs. 2, 15 and 29).

The lowest elevation is 180 m while the highest one is 1765 m, and the cross-section has been extended to a depth of -2000 m. The fact that there is an elevation difference of about 1585 m between the detachment fault (1765 m) in SW and the 1969 surface faulting (180 m) in NE indicates that there is a minimum vertical displecement of 1500-1600 m in the region where the study area is located.

From SW to NE; the fault steps indicating normal faults were observed at elevations between 1765-965 m; 965-850 m; 850-700 m; 700-660 m; 660-510 m; 510-330 m and 330-200 m. In those steps, from SW to NE, elevation differences indicate the lowest vertical displacement, 800 m; 115 m; 150 m; 40 m; 150 m; and 180 m, respectively. Depending on those differences, it can be said that there may be a minimum vertical displacement of 1000-1200 m in this part of the study area.

Along the detachment fault zone, the sequence consisting of schists juxtaposes with conglomerate-sandstones of the Gediz Formation. In this part, the conglomerate-sandstone layers were steeply tilted to the detachment fault zone. It is seen that the units of the Gediz Formation are vertically displaced about 400 m between Kayadibi in SE and Evrenli in NE. It is thought that Upper Miocene-Lower Pliocene units have been buried in the Gediz Graben in the SE of Evrenli Village.

In the cross-section, geometrical relations between NW-SE trending detachment fault and high-angle normal faults are very remarkable. The detachment fault has cut off by first high-angle normal fault. A few small-scale normal faults have developed parallel to each other in front of the detachment fault.

Around Alaşehir Province, 1969-earthquake surface faulting extended. The marbles overlain unconformably by the conglomerates and sandstones of the Upper Miocene-Lower Pliocene unit were vertically displaced and buried into the Gediz Graben by the parallel stepping faults. Considering that the dip of the detachment fault is 40-45 degrees, and the dip of the high-angle normal faults is 60-70 degrees, it is estimated that the detachment faults are displaced as a result of cutting by the first high-angle normal fault at the depth of approximately 1600 to 2000 m.

Cross-section C'-C represents an about 11 km-long NE-SW directional geological cross-section taken in the area near the northwest corner of the study area, between the Gevenli Hill in GB and Alaşehir Province in the NE (Figs. 2, 15, and 30).

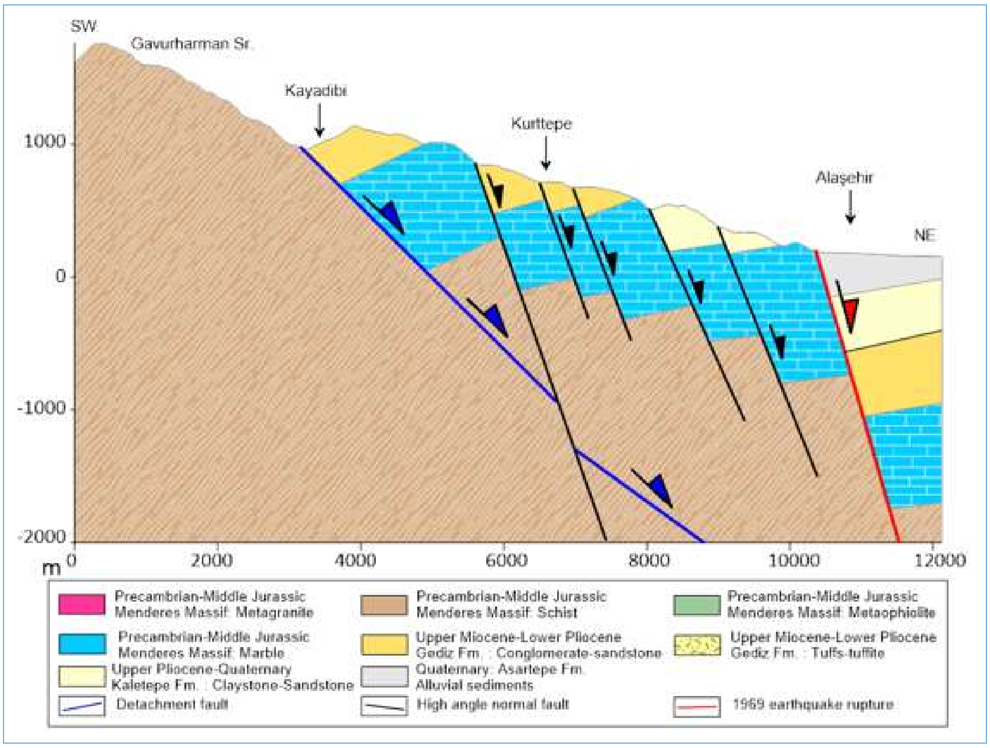

Fig. 29. B-B' geological cross-section with 12 km in length between Gavurharman Ridge and Alaşehir Province in NE-SW direction

The lowest elevation is 230 m while the highest one is 1535 m, and it has been extended to a depth of -2000 m. There is an elevation difference of about 1305 m between the detachment fault in the SW (1535 m) and the 1969-earthquake surface faulting in the NE (230 m). These elevation differences marks that there is a minimum vertical displacement of 1300 to 1500 m in the study area. From SW to NE; the parallel fault steps were observed at elevations between 1535-1275 m; 1275-640 m; 640-365 m, and 365-230 m. Inferred from elevation differences at these fault steps from SW to NE, it can be interpreted that the lowest vertical displacements are 260 m; 635 m; 275 m, and 135 m, respectively. Based on these elevation differences, it can be told that there may be a minimum vertical displacement of 900-1000 m in this part of the study area.

Along the detachment fault zone, schists juxtapose with marbles. It is observed that the marbles are vertically displaced about 400-500 m between Lülükkaya Hill in SW and Kozluca Village in NE. It is considered that they are buried in the Gediz Graben in the N of Kozluca Village.

In the cross-section, geometrical relations between NW-SE trending detachment fault and high-angle normal faults are very distinct. The detachment fault has been cut and displaced by the first high-angle normal fault. The second high-angle normal faulting has developed in front of the detachment fault. 1969-earthquake surface faulting extends around Alaşehir Province. The marbles have been downthrown by stepping faults and buried into the Gediz Graben. Considering that the dip of the detachment fault is 40-45 degrees, and the dip of the high-angle normal faults is 60-70 degrees, it is predicted that the detachment fault cut by the first high-angle normal fault at the depths of 1750 m and 2700 m and 3600 m depth by the second high-angle normal fault.

To determine the presence of the transfer faults and the NE-SW trending normal faults in the study area, two further cross-sections (cross-sections D'-D and E-E') with NW-SE trending were taken.

Section D'-D which is parallel to the first high-angle normal fault in front of the detachment fault represents an approximately 11.5 km-long NE-SW directional geological section taken between Elmacık in GD and Kaplançukuru in NE (Figs. 2, 15 and 31).

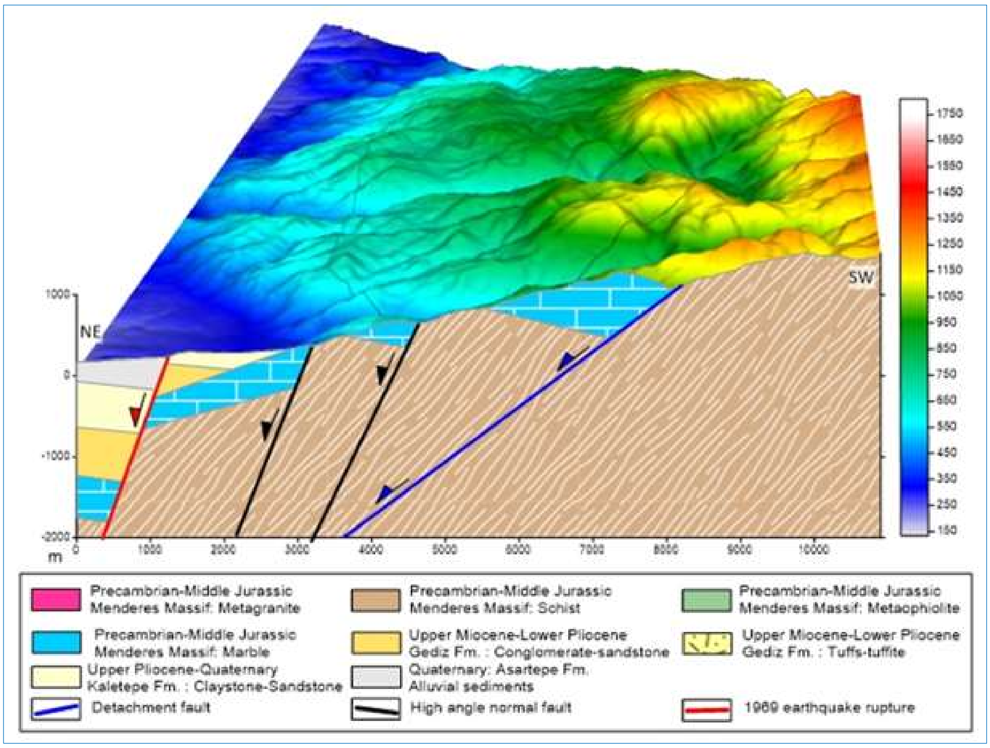

Fig. 30. C-C' geological cross-section in the NW of Dokuzpınar Stream, between Gevenli Hill and Alaşehir Province in NE-SW direction

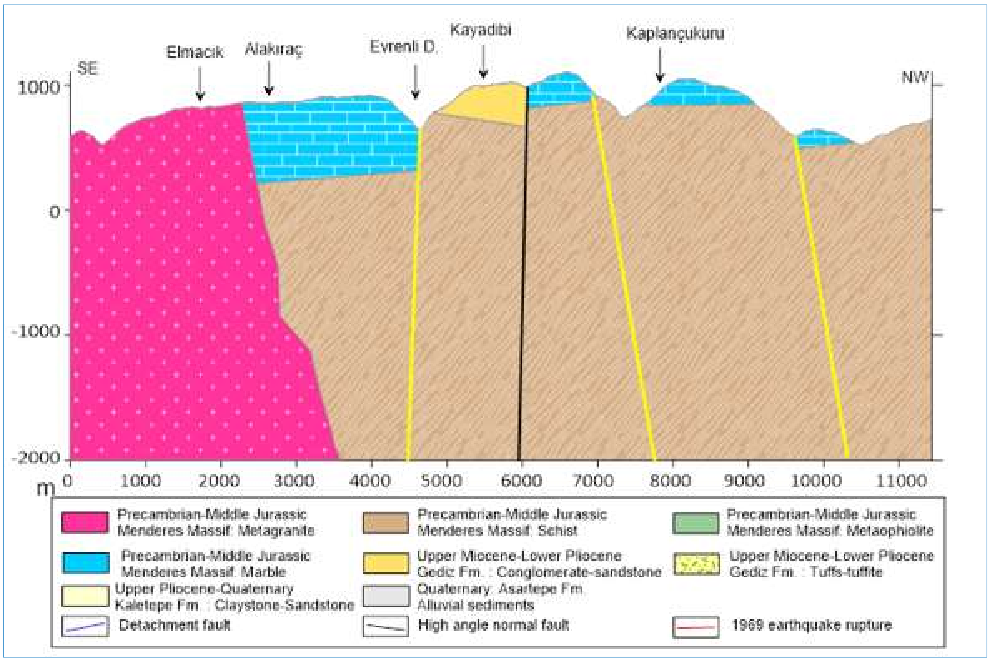

Fig. 31. 11.5 km-long, D-D' geological cross-section between Elmacık and Kaplançukuru Villages in NW-SE direction

In the cross-section, Kayadibi, which is the middle point that corresponds to the highest point between Asar and Dokuzpınar creeks, is 1100 m, SE valley margin of Asar Stream (the east of Evrenli) is 915 m, and elevation difference is 185 m. The NW margin of Dokuzpınar Stream is 1050 m and the elevation difference is 50 m. The NW margin of the Asar Stream is 1000 m and the SE margin is 915 m, the SE margin is approximately 85 m below. The Dokuzpınar Stream is 1100 m and the NW margin is 1050 m, and there is a 50 m elevation difference. These results indicate the presence of normal component strike-slip faults along both streams. Moreover, the coexistence of different geological units along the Asar and the Dokuzpınar Streams also show the existence of these faults. Marbles on the SE margin of the Asar Stream juxtapose with Upper Miocene-Lower Pliocene conglomerate-sandstones on the NW edge. In the SE section, metagranite intrusion has taken place into the Menderes massif. While the marbles located high in the form of caps, they have been downthrown about 185 m and 50 m towards SE and NW sides.

Cross-section E'-E represents geological cross-section in the NE-SW direction taken as parallel to the first high-angle normal fault in front of the detachment fault between the Turkmen Village in SE and Kozluca Village in the NE (Figs. 2, 15, and 32).

In the cross-section, the NW margin of the Asar Stream is 785 m and the SE margin is 705 m elevation, and the SE margin is approximately 80 m below. The SE and NW margins of the Dokuzpınar Stream are 740 m above sea level. The elevation difference observed along the Asar Stream indicates the presence of normal component strike-slip faulting. Moreover, the coexistence of different geological units along the Asar and the Dokuzpınar Streams also points out the existence of these faults. The marbles at the SE edge of the Asar Stream and marbles and schists along the Dokuzpınar Stream juxtapose with the Upper Miocene-Lower Pliocene conglomerate-sandstones at the NW margin. In the SE part of the study area, metagranite intrusion is observed within the Menderes Massif.

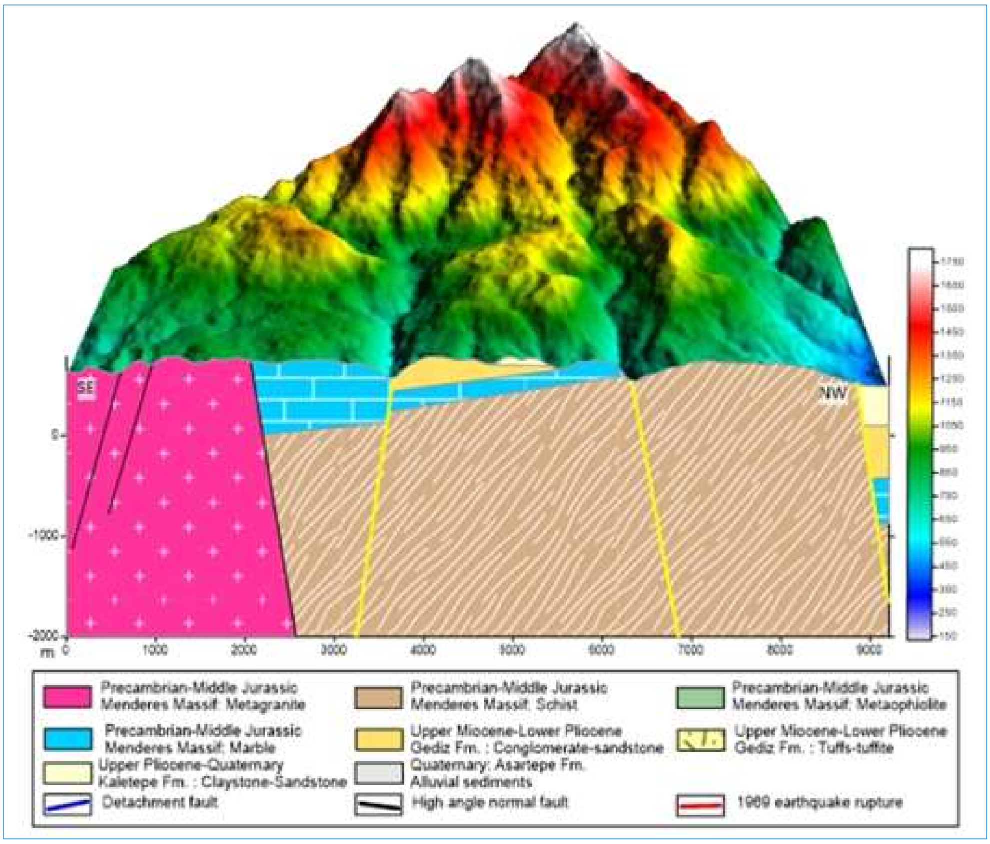

Fig. 32. 9 km-long, E-E' geological cross-section between Turkmen and Kozluca in NW-SE direction

4. **Geothermal Potential**

Within the scope of the field studies, alteration zones have been identified in the study area. In the areas 1 and 2 (Fig. 2), it is observed that alterations have been formed at the intersection of the detachment fault, high angle normal faults, and transfer faults that indicate the presence of geothermal fluid in the marbles. Alterations are intensive in the area between Kurucaova-Alakıraç-Türkmen Villages (Fig. 2, area 1). They are especially observed intensively around station 27, 30, 5, and 8, respectively (Fig. 15). This part corresponds to the region where a large amount of slip develops and high-angle normal faulting cuts the detachment fault. Also, this faulting is cut by the NE-SW trending transfer fault extending between Söpüce-Alakıraç-Kurucaova-Kepez Villages. In other words, intense alterations have been formed along the fault intersection zone. Along the fault zone, it is also observed that the marbles have an extensively cracked and sheared structure divided into blocks and, they are brecciated (Fig. 33).

Intensive alterations have also been observed in Bahçedere Village and its vicinity (Fig. 2, area 2). The alteration zone corresponds to the area in the hangingwall block of the detachment fault, possibly between the 2nd and 3rd main normal faulting cutting the detachment fault, and where the western boundary is cut by the transfer fault (Fig. 2). Alteration is fully developed in the marbles. They exhibit a blocky and breccia structure as a result of faulting. Alterations are typically observed at the 60th and 61st stop points (Figs. 15 and 34).

Intense alterations have also been observed on the Söpüce-Bahadır road and the south of Söpüce (Fig. 2, area 3). Alterations have developed within the detachment fault zone, in approximately 2 km zone, within marbles and metaophiolites. Alterations in the form of hematitization and limonitization have occurred in the marbles. Marbles and metaophiolites have a completely fragmented, blocky, and breccia structure (Fig. 35).

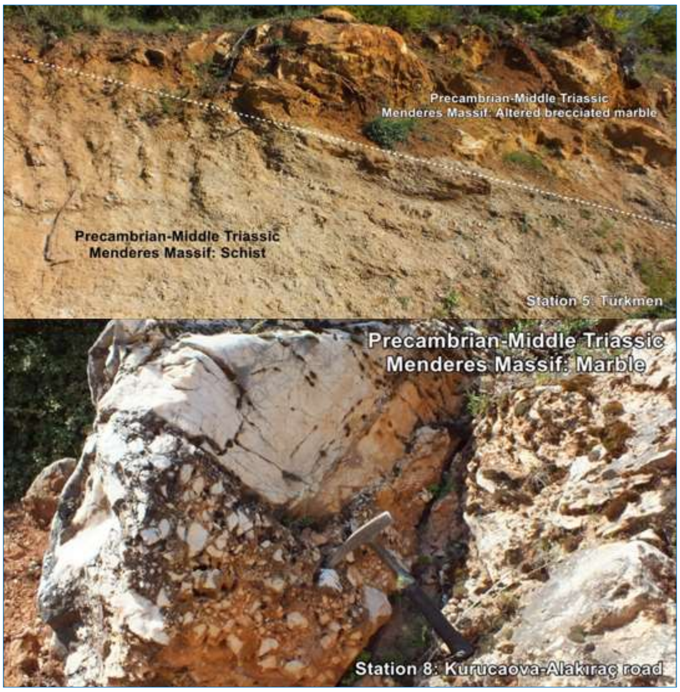

Fig. 33. Views of breccias and altered marbles within area 1 (see Fig. 2)

Fig. 34. A view from blocky, breccia, and altered marbles within area 2 (see Fig. 2)

In the study area, small-scale alteration areas were observed locally in four different regions. In area 6, alterations are observed in the marbles. In this part, the marbles were downthrown to the north by a few stepping faults and cut by the transfer fault followed by the Dokuzpınar Stream. In the area 4, in the region where the first high-angle normal faulting cutting the detachment fault is present, alterations have been observed along the fault zone that juxtaposed the marbles and schists with the Kaletepe Formation. Throughout the fault zone, the marbles and schists have a breccia character (Fig. 2). At the stop point 45 (Fig. 15), small-scale alterations were observed along the normal faulting zone that cuts the Upper Miocene-Lower Pliocene units (Fig. 36).

The study area is located on the hangingwall part of the detachment fault zone. It has two main high-angle normal faults cutting the detachment fault and transfer faults followed by the Asar and Dokuzpınar Streams. The geothermal fluid temperatures are 27 to 160 °C in the wells drilled at the depths of 400 m and 2100 m (Fig. 2). Along these faults, it is considered that intensive alterations along with suitable environment and conditions for recharge have been developed. Therefore, it can be inferred that the study area has a high geothermal energy potential. All the units in the study area have been severely deformed by the impacts of the main faults and have gained a very fractured structure.

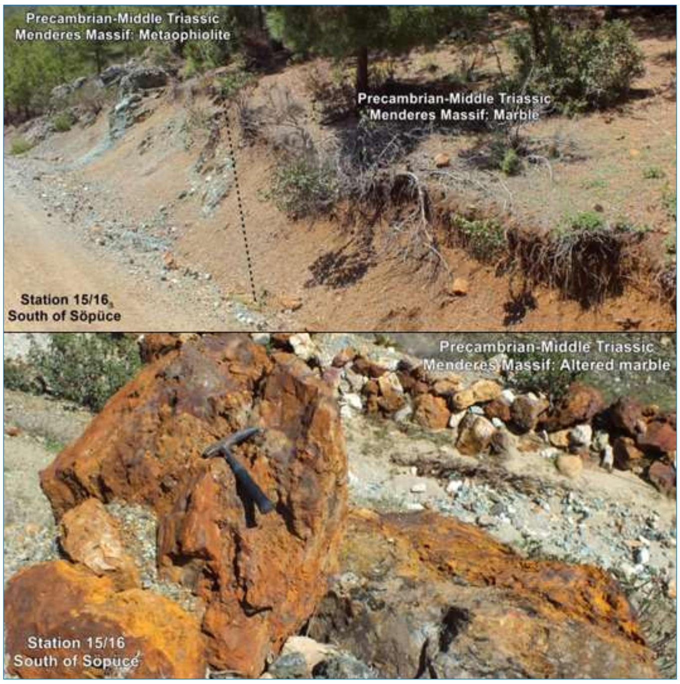

Fig. 35. Views from breccias and altered marbles in area 3 (see Fig. 2)

Fig. 36. A view from the alterations observed in Upper Miocene-Lower Pliocene units

Alteration's areas were generally observed in the areas close to the intersection regions of transfer faults which tear high-angle normal faults in the north, and cut the detachment fault. Due to the detachment faults in the southwest, NW-SE trending high-angle normal faults which display the stepping faulting from the southwest to the north, and the NE-SW trending transfer faults cutting both these faults show different characters and were activated at different periods. Intersection zones of these three different main faults constitute high potential geothermal areas in the study area.

In the study area, it is seen that both metamorphic units and marbles have been extremely deformed, faulted and broken, fragmented, and brecciated as a result of faulting by the detachment fault and high-angle normal faults. These units have created a suitable reservoir rock in terms of both permeability and porosity. Upper Miocene-Lower Pliocene and Upper Pliocene-Quaternary units, which unconformably overly these units in the northwest of the study area, represent the possible cap rocks.

It is thought that the mica schists and marbles located in high-angle normal fault zones are cut by the detachment fault zone and can represent the primary reservoir rocks in the intersection zones of transfer fault zones of both faults because, along the high-angle normal fault zones and intersection zones, the marbles and mica schists are characterized by an extremely deformed, faulted, fractured, and fragmented structure, and broken into blocks and have a brecciated structure by several shear cracks. As a result of the intense deformation of the marble and micaschists, they have gained additional secondary porosity and permeability with appropriate environments for being a reservoir rock. As a matter of fact, these parts correspond to the areas in the first and second regions, where densely altered zones are observed (Fig. 15).

In the central part of the study area, the units of Gediz formation extending along the Kayadibi-Sinekli-Evrenli line and the units of Kaletepe formation in the surrounding of Bahçedere constitute possible cap rocks.

5. Conclusions

The study area is located between the detachment fault extending on the southwestern border and the surface faulting of the 1969-earthquake rupture on the northeast margin. Between these two systems, two major high-angle normal faults and several small-scale normal faults are observed and all these faults are cut by two large transfer faults.

Very important alteration areas indicating the presence of geothermal fluid have generally been developed in the marbles at the intersection areas of transfer faults that tear the high-angle normal faults in the north and which cut the detachment fault.

Dokuzpınar and Asar Streams constitute the main drainage systems of the study area and very dense streams are observed in the regions. There are main creeks along the detachment fault zone. Therefore, no recharge problems for the geothermal system are expected. The presence of the Sarıkız hot spring at the intersection of these faults in the study area supports this opinion.

The investigation area is located on the hangingwall part of the detachment fault zone. Two main high-angle normal faults cut the detachment fault. The geothermal fluid temperatures are 27 to 160 °C in the wells drilled at the depths of 400 m and 2100 m and developed intensive alterations and suitable environment and conditions for the recharge along the transfer faults followed by the Asar and Dokuzpınar Streams. Consequently, the study area has high geothermal potential. Drilling depths must be continued until triple junction at the depths where transfer faults cut high-angle normal faults and low-angle detachment faults because these intersection areas represent the tensional regions and potential geothermal areas that will carry the geothermal fluid up.

The geophysical survey should be made in the intersection zones of detachment fault, high-angle normal faults, and transfer faults and in three regions where dense alterations and cracks are observed; in (1) the area between Kurucaova-Alakıraç-Türkmen (2) Bahçedere, and (3) south of Söpüce. Taking into account that the dip of the detachment faults is 40-45 degrees, and the dip of the high-angle normal faults is 60-70 degrees, it is estimated that the detachment faults are cut and displaced by the first and second high-angle normal faults at the depth of approximately 800 to 2000 m. Hence, the future geophysical measurements should be conducted at the depths of 1500-2500 m.

Finally, detailed hydrogeological investigations should be carried out to determine locations of recharge areas, related faulting system that can carry the geothermal fluids up, and reinjection wells.

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