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Reevaluation of Geothermal Potential of Çubukludağ Graben (Western Anatolia, Turkey)

Adil Ozdemir[1]*, Fahri Arabaci[1], Yildiray Palabiyik[2]

[1]*Adil Ozdemir Engineering & Consulting, Ankara, Turkey*
[2]*Istanbul Technical University, Department of Petroleum and Natural Gas Engineering, Istanbul, Turkey*

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Contact
*Adil Ozdemir
E-mail: adilozdemir2000@yahoo.com

ABSTRACT

This study aims to determine the geometrical, structural features, and geothermal potential of the Çubukludağ Graben. Within the study's scope, fault-fracture and layer planes were measured at 110 stop points and plotted to the rose diagram and Wulff net. Thus, geological sequence, fault orientations, types and geometries, intersection areas, and lateral and vertical displacements of the faults, tensional-compressional areas, main compression directions, and rotation regions were determined. The geological and morphotectonic maps of the region were prepared. The formation mechanisms of the hanging rhyolite and dacite caps, along with the large-sized tears in the middle and west of the graben, were also explained using those maps. The main tectonic structures and the faulting characteristics of the Tuzla, Deliömer, Gümüldür and Değirmendere Fault Zones that boundary these structures, and the relations between the geological setting and the geothermal system are detailed. In the light of the new field data obtained, a new geological model of the graben has been constructed, and the geothermal potential has been reevaluated.

1. Introduction

The study area's morphological structure has developed as a result of the interaction of N-S directional extensional and rotational movements towards the Aegean-Cyprus Arc (Fig. 1). The region was formed with the impact of normal faulting, resulting from N-S extension and strike-slip faulting formed due to the rotational movement towards southwest (Genç et al., 2001). As a result of these phenomena, the following structures have been come into existence:

- Seferihisar High
- Çubukludağ Graben
- Three main tectonic structures which have emerged as the Değirmendere High

The boundaries of the main tectonic structures are controlled by the following structures from west to east:

- NE-SW trending right-lateral strike-slip, Seferihisar Fault Zone,
- N-S/NE-SW trending right-lateral strike-slip, Tuzla Fault Zone,
- NE-SW trending dip-slip normal faulting, Değirmendere Fault Zone,

- E-W/WEW-ESE trending dip-slip normal faulting, Gümüldür Fault Zone,
- E-W/ENE-WSW trending right-lateral strike-slip, Deliömer Fault Zone.

Order of the structural occurrence mechanisms of the graben is as follows:

- Grabening,
- Volcanism (filling the valleys with acidic lavas),
- Strike-slip faulting,
- Anti-clockwise rotation along the Deliömer-Tuzla Fault Zone between Yeniköy-Doğanbey,
- Normal faulting and glacial period (?) regional uplift after glaciation,
- Deep tearing in NE direction from the middle of the study area and hanging acidic lavas,
- Erosion,
- Gravitational flows and slides along the slope of tensional splitting areas,
- Processes of filling into the graben and eventual morphological structure.

In the study, fault-fracture and layer planes were measured and plotted to the rose diagram and Wulff net. Therefore, the determinations of geological sequence, fault orientations, faulting type, fault geometry, tensional-compression areas, rotation zones, intersection areas of faults, lateral and vertical slips, main compression directions and activity have been realized. The formation mechanisms of the hanging rhyolite-dacite caps and large-sized tears in the middle and west of the graben have been interpreted using geological and morphotectonic maps. Hence, the relationships between the main tectonic structures and the faulting types of the fault zones, geological setting, and geothermal system have been investigated. Geological cross-sections are constructed to explain the main tectonic elements, faulting features that bound these structures, and total vertical slips using the two-deep well data drilled in the graben and the field geology information. Ultimately, the geothermal potential is evaluated based on 3D modeling visualized.

2. Geological Setting

The graben's geological map is revised by plotting all the faults detected in the field on the map prepared for the Çubukludağ Graben from the previous study (Bulut, 2013). Detailed observations are made at 110 stop points, and the unconformity and/or faulted contact relations of the geological units are investigated. During the stop observations, 114 planes of faults-fractures and 52 layers have been measured. In estimating the total displacement of the faults controlling the geological units and the faulting parameters, lithological data of the wells drilled at the depths of 1215 m and 2872 m have been used.

In the previous studies (Eşder and Şimşek, 1975; Bulut, 2013), the formation mechanism of rhyolitic and dacitic lavas defined as the volcanic dome was investigated. In other words, it was attempted to be figured out if these lavas originated from an in-situ dome or the near volcanic areas in the region. Since the faults forming and bordering the graben are NE-trending, the graben extending in the NE direction caused a series of aligned hilly areas in the NE direction in the study area. Thus, this situation created a misinterpretation of those structures as volcanic domes, and it was thought that the axial centers have NE-trending. Hence, the chimney as the heating rock of lava and geothermal system under the hills defined as the volcanic dome causes the idea that there are magma pockets under the lava domes. However, there is no evidence that these hilly areas, which are defined as rhyolitic and dacitic domes, are axial centers during this study's field survey. It has been concluded from the field geology studies that, in fact, the structures called domes are hanging valleys flowing into the graben due to regional uplift as a result of tectonism (Fig. 2).

Menderes Metamorphics, which form the region's basement, crop out the İzmir Flysch at the WNW side. Both units were buried in the Çubukludağ Graben around 750 m by the vertical slip fault during the graben formation process starting from the Lower Miocene.

The İzmir Flysch with the Menderes Metamorphics and the overlying Karacadağ dolomitic limestones at the study area's EWE boundary presents a faulted contact relationship. The İzmir Flysch, which was superimposed on these two units before graben formation, was faulted normally and dropped under the graben during its formation process. The fact that the units belonging to the Menderes Metamorphics do not surface while the İzmir Flysch constitutes the basic unit on the WNW boundary indicates that the graben has an asymmetrical basin character. In other words, it is estimated that the vertical slip in the Değirmendere Fault Zone, which bounds the EWE side of the graben, is higher than the Tuzla fault, which once operated as a vertical slip, and the graben may have developed asymmetrically (Fig. 2).

Bahçecik and Yeniköy Formations along with Cumaovası Volcanics having a thickness ranging from 850 (valley floors) to 1500 m (peaks of hilly areas) are filled into the Çubukludağ Graben, which exhibits an asymmetrical structure, as a consequence of the subsidence of more than 750 meters developed during the graben occurrence process.

While the Bahçecik Formation unconformably comes over the Karacadağ dolomitic limestones with the İzmir Flysch and Menderes Metamorphics, which form the basement unit in the east of Gümüldür, it rests on the İzmir Flysch between Payamlı Village and Tuzla Fault Zone in the west with an unconformable or faulted contact.

The Yeniköy Formation comes over all the units as an unconformity or faulted contact, whereas Cumaovası Volcanics unconformably cover its upper levels. These contacts are clearly observed at the bases of the volcanics suspended in caps in the large tearing areas that have been formed between Güneydağı Hill and Akyar-Köşk Cliffs and Güneydağı and Köydolayısı Hills at a depth of 400-450 m from the surface. Cumaovası Volcanics unconformably cover all the older units in the region. It is observed that the Cumaovası Volcanics unconformably locate over the Menderes Metamorphics, İzmir Flysch, and Yeniköy Formation along the Gümüldür-İzmir road as very sharp contacts.

3. Structural Geology

In the previous studies (Uzel and Sözbilir 2008; Bulut, 2013), there is an intersection the area between the Tuzla Fault that bounds the study area from the northwest and the Değirmendere Fault Zone from the southwest. A total of 6 long right-lateral slip and E-W trending, perpendicular to these faults, which are four strike-slip faults in a NE-SW direction, striking ones are shown as left-lateral strike-slip faults. However, the following sections of this study will detail the fact that no strike-slip or any morphological, morphotectonic, geological, structural, and tectonic findings that pass through the study area and extend parallel to the Tuzla fault, indicating any faulting are encountered. Moreover, the Deliömer Fault, shown as the left-lateral, is right-lateral strike-slip faulting.

Observations have been made at 110 different points to reveal the faulting type, geometry, mechanism, and kinematic features in the study area in detail and determine the geothermal system's position according to the faults (Fig. 3). The authors revised morphotectonic and geological maps of the study area in light of the stop points' information.

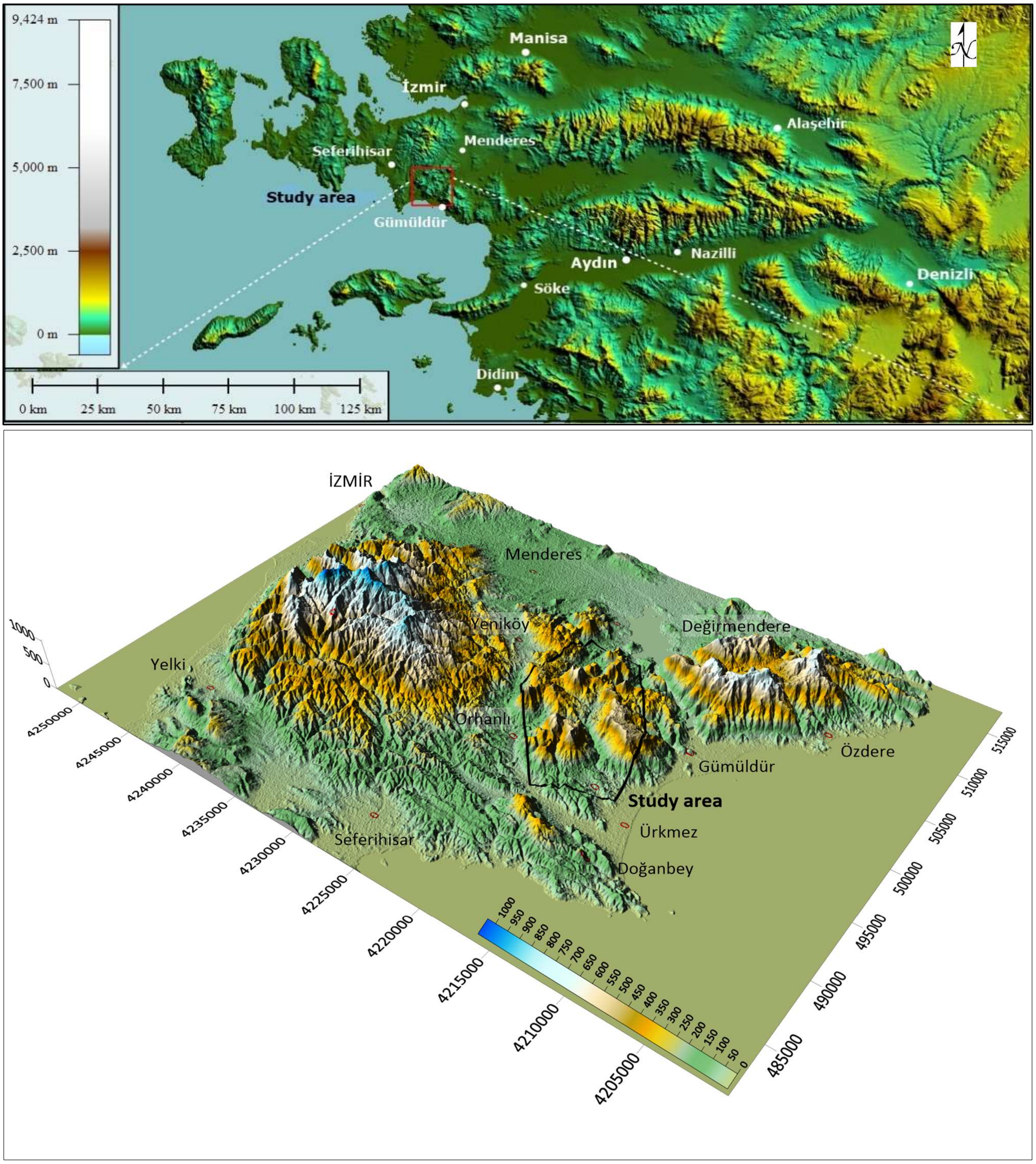

Fig. 1. Location map of the study area

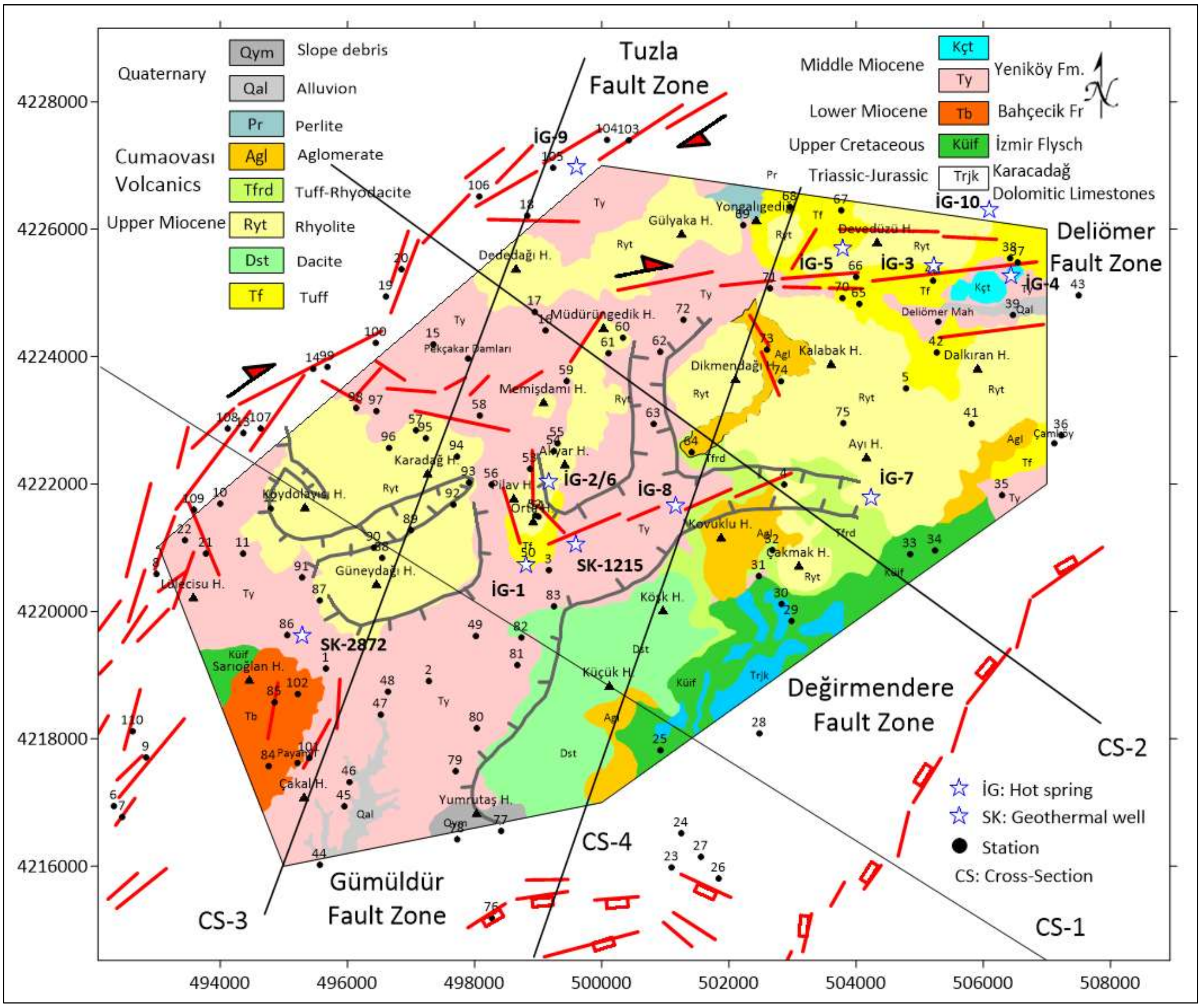

Fig. 2. Geology map of the study area (modified from Bulut, 2013). See text for types and structural features of fault zones

3.1. Faults

The morphotectonic map prepared using geomorphological and geological findings jointly obtained from 110 stop points (Fig. 3) reveals the study area's fault types and geometric features in detail. The Seferihisar High bounds the NE-SW trending Çubukludağ Graben in the west and the Değirmendere High in the east. The WNW side of the graben is the right-lateral strike-slip Tuzla fault zone and the Değirmendere Fault Zone, whereas the ESE side, which has a dip-slip normal faulting character on the SSE side, are controlled by the Gümüldür Fault Zone characterized by a dip-slip normal fault mechanism. The northern boundary of the graben is governed by the right-lateral strike-slip Deliömer Fault Zone formed by the right-lateral strike-slip tectonic movement in the Tuzla Fault Zone (Fig. 2).

The Çubukludağ Graben, Seferihisar, and Değirmendere Highs have been formed by the effect of the N-S extensional regime dominant in the Aegean / West Anatolia regions. The Çubukludağ Graben, a small graben is located between the Gediz and Küçük Menderes Grabens representing large grabens. It is formed at the west end as a result of subsidence between Değirmendere and Tuzla Fault Zones, displaced by the right-lateral dip-slip normal fault with a NE-SW-trending, depending on the NNE-SSW-trending extension in both major grabens. The Tuzla Fault Zone currently featured by a displacement with right-lateral strike-slip faulting was predominantly dip-slip normal faulting during the formation of the Çubukludağ Graben.

The counterclockwise movement of the Tuzla Fault Zone, characterized by right-lateral strike-slip between Yeniköy-Yeniorhanlı-Doğanbey and between Yeniorhanlı and Deliömer, has caused the formation of ENE-WSW-trending and right-lateral strike-slip (Uzel and Sözbilir, 2008) instead of a left-lateral strike-slip Deliömer Fault Zone.

The Gümüldür Fault, which bounds the graben from the SSE and controls the Çubukludağ Graben and Değirmendere Uplift, has a displacement as dip-slip normal faulting. The study area is situated in the footwall block of the Gümüldür Fault Zone. The Menderes Metamorphics and İzmir Flysch, which form the basis of the region brought to the surface by the Değirmendere Fault Zone, have been further uplifted by the effect of the Gümüldür Fault. Both units, located at a depth of 840 m (according to the well data) in the

Çubukludağ Graben, have surfaced in the south-southeast area. In other words, these findings indicate that the contact between Menderes Metamorphics and İzmir Flysch within the Çubukludağ Graben is vertically displaced around 750 m.

A counterclockwise rotation in the graben is formed by the right-lateral strike-slip of the Tuzla Fault Zone due to large-scale left and right bends between Yeniköy-Yeniorhanlı-Doğanbey and a change of direction from NE-SW to N-S and transtensional and transpressional domains. Because of firstly clockwise rotation and secondly the fall of the south-southeast block of the Gümüldür Fault, and finally limitation by the Değirmendere Fault developed along the right-lateral strike-slip and ENE-WSW-trending Deliömer Fault Zone and the right-lateral strike-slip and NE-SW/N-S-trending Tuzla Fault Zone, the functioning of the Menderes Metamorphics has become like a barrier, it was uplifted from the center of the graben, deeply torn, fragmented, and 1-3 km-wide, 400-450 m elevated, NE-trending wide, deep, and formed steep tearings. The tearings advanced from SW to NE, narrowed towards NE, and torn in N-S, E-W directions have developed in the form of shear down to shallow depths that do not deeply penetrate due to the tear faults in N-S, E-W, NW-SE, NE-SW directions. In other words, these tear faults represent short length-faults that do not extend to their depths.

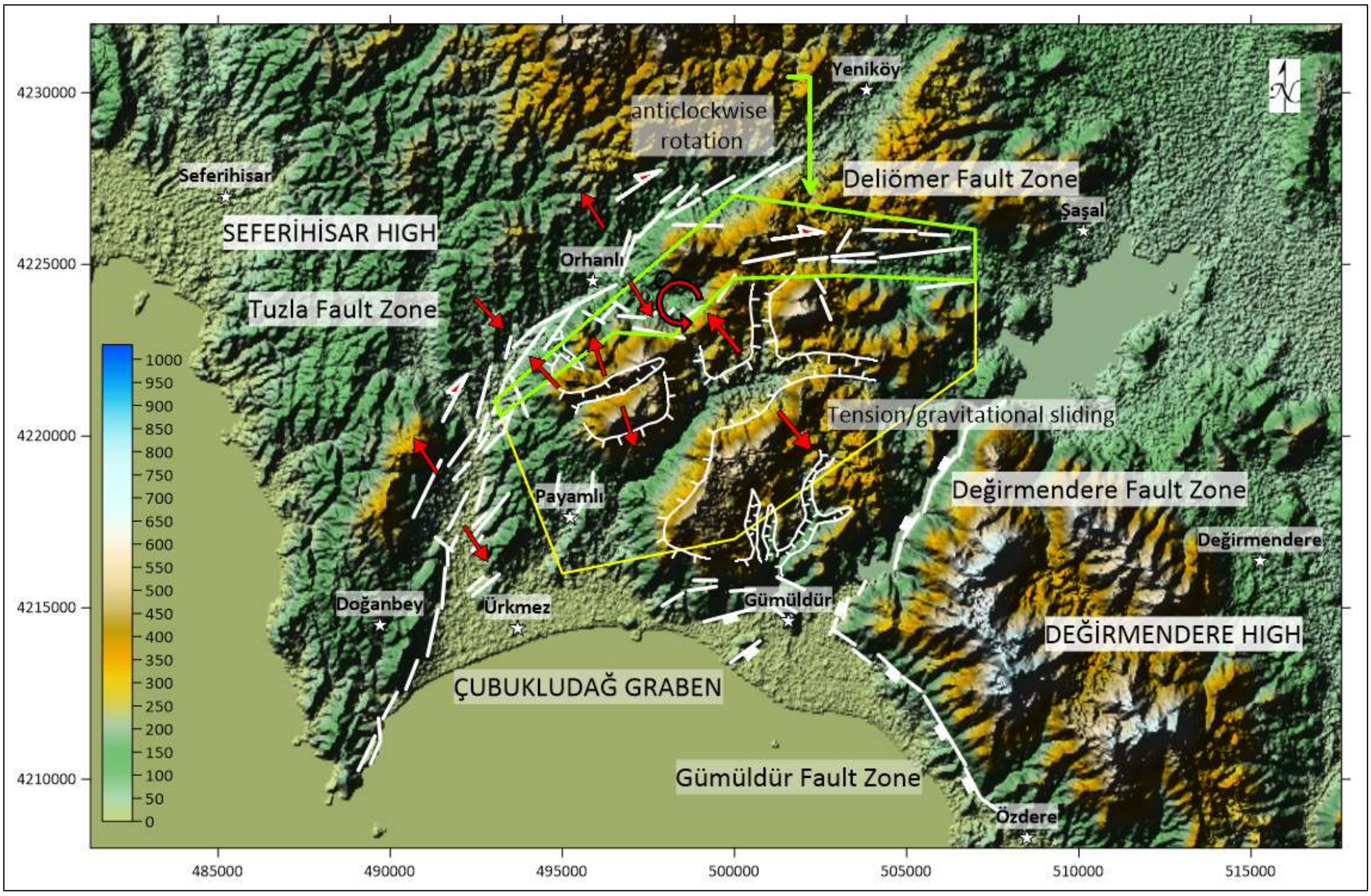

Fig. 3. Morphotectonic map of the Çubukludağ Graben between Seferihisar and Değirmendere highs

Rhyolitic and dacitic lavas, which previously flowed into shallow and flat valleys due to the uplift and deep tearing in the graben, formed morphological structures in the form of a cap over the summits of the hills. In other words, the structures defined as domes in the area can actually be considered as hanging morphological structures formed by the uplift-erosion processes and have no roots. It is also anticipated that the rhyolitic and dacitic lavas flowed into the graben area from very distant places.

3.1.1. Tuzla Fault Zone

Tuzla Fault Zone changes its direction from NE-SW to N-S between Ortaca and Temşealtı. These changes in the directions create a transpressional area in this area. In Ortaca Hill, on the east side, the N20E/60SE and N30W/82NE trending faults juxtapose the İzmir Flysch with the Yeniköy Formation (Figs. 3 and 4). In contrast, the N65E/35SE trending fault causes the İzmir Flysch's thrusting above the Quaternary units and Yeniköy Formation on the west side of the area. The abundance of Cumaovası Volcanics within the brecciated zone formed along the fault zone indicates that the faulting is still active today. The presence of earthquakes with 6.0-6.5 magnitude along the Tuzla Fault Zone at a depth of 10-15 km points out that the tearing along the fault zone descends to the lower-upper crust boundary. In the south of Yeniorhanlı, N25E 65/75SE and N70E/ 85NW trending strike-slip faults of the Tuzla Fault Zone that cut the Yeniköy Formation are observed. The N70E/85NW-trending fault is the main faulting trace of the Tuzla Fault Zone, and N25E 65/75SE faults represent antithetic faults. Along with the faulting, red conglomerates of the Yeniköy Formation juxtapose with gray conglomerate-sandstones. Faulting of the N48E/68SE right-lateral strike-slip of Tuzla Fault Zone, which cuts the Yeniköy Formation, is observed in Temşealtı Village, Ortaca Hill. In the vicinity of the Ilıca Village, deformations in the form of folds are developed in the strata in the N45E/30NE direction due to the right-lateral strike-slip character of the Tuzla Fault Zone, which juxtaposes red sandstones with the claystones of the Yeniköy Formation (Fig. 5).

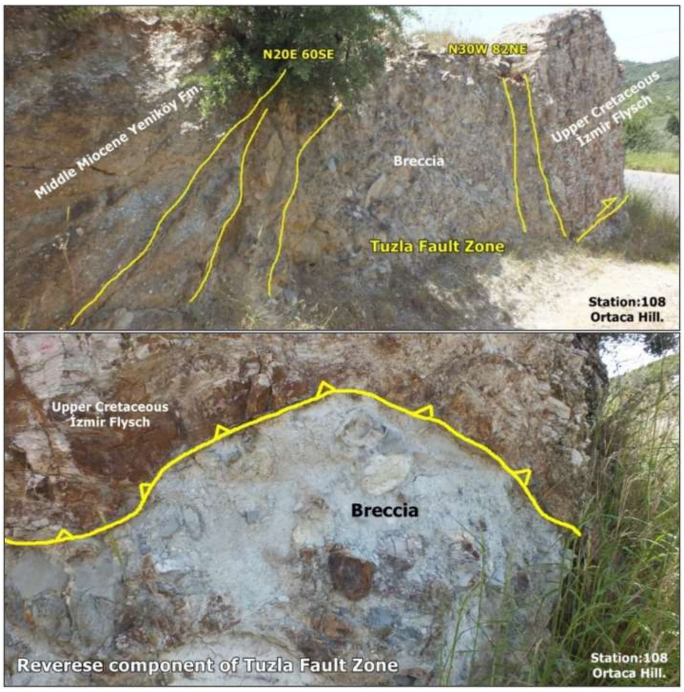

Fig. 4. Strike-slip faulting of the Tuzla Fault, which juxtapose the İzmir Flysch and the Yeniköy Formation (X: 494118, Y: 4222870)

In the vicinity of Kocaçay Creek (Yeniorhanlı), the west portion of the NE-trending elongated hill formed by the diabase block belonging to the İzmir Flysch is cut by the N30E/68NW oriented right-lateral faulting of the Tuzla Fault, and the fault plane is exposed (Fig. 6). In the vicinity of Kayalı Village, conglomerates are steep with the Yeniköy Formation due to the Tuzla Fault Zone. In the Kocakaya Hill, shear fractures in the direction of N15E/70SE of the Tuzla Fault Zone cutting the İzmir Flysch are observed. This orientation is within the transpressional area, where the Tuzla Fault Zone is the N-S striking. The orientation of the shear fractures is well compatible with the main strike of the Tuzla Fault Zone. To the west of Lülecisu Hill, the Yeniköy Formation has been cut and displaced by the N20W/80NE trending faulting of the Tuzla Fault Zone. The layers oriented in the N20E/55GE direction are tilted towards faulting. On the downstream side of Nur Creek, the N12D/58NW trending fault juxtaposes the İzmir Flysch with the Yeniköy Formation whereas, at the point of Station-11, Yeniköy Formation and Cumaovası Volcanics juxtapose along the N70E/60SE trending fault southwest of Köydolayısı Hill. During the faulting, the volcanic units have a brecciated character. As someone moves away from the fault zone, rhyolites present a massive appearance.

Fig. 5. Faulting and layer deformation due to right-lateral strike-slip of the Tuzla Fault Zone cutting the Yeniköy Formation (X: 492623, Y: 4218118)

Fig. 6. A view from the fault plane of the Tuzla Fault Zone that cuts the diabase block of the İzmir Flysch (X: 496606, Y: 4224943)

3.1.2. Deliömer Fault Zone

The Deliömer Fault is morphologically distinctive around 750 m in the north of Deliömer Village. Deliömer Fault with right-lateral strike-slip juxtaposes Cumaovası Volcanics with the units of Yeniköy Formation. Ilıkpınar Hot Spring is located along with faulted contact. Tuffs and rhyolites present a faulted contact relationship in this area (Fig. 7).

Rhyolites and tuffs of the Cumaovası Volcanics are juxtaposed along the N65B/70ND trending Deliömer Fault with the right-lateral strike-slip followed by Havlıç Creek. At Stop-70 point, the EW 70S-trending right-lateral strike-slip faulting of the Deliömer Fault Zone juxtaposes the tuff and tuffites of the Cumaovası Volcanics with rhyolites along the

Havlıç Stream. NS 75E-trending left-lateral strike-slip shear fractures cutting the E-W-trending main fault are also measured. The tuff layers are steeply observed by dipping towards the E-W trending main fault and have dips of 55 degrees. Tuffs are completely cut by numerous strike-slip shear fractures along the fault zone. N80W/60NE-trending and reverse component right-lateral strike-slip faultings of right-lateral strike-slip of Deliömer Fault Zone, which cut the tuff and tuffites of Cumaovası Volcanics, are observed along Karakaya Stream. Reverse component slips are measured up to 2 meters of lengths along with the faulting in the outcrop. Numerous K65B/70ND and N75D/40NW oriented small-scale synthetic faults cut the tuffites.

Fig. 7. Views from the right lateral strike-slip Deliömer Fault, which juxtaposes the tuffs and rhyolites of the Cumaovası Volcanics (Station 40, X: 505210, Y: 4225191; Station 67, X: 503766, Y: 4226296)

Right lateral strike-slip faults striking N65B / 85NE cutting and displacing the limestones of the Yeniköy Formation, indicating the presence of the Deliömer Fault Zone are observed along the Suluçay Creek (Deliömer Village). The Miocene limestones have a blocky and brecciated structure by lateral slip faulting. Along the fault, tuffs of Cumaovası Volcanics are juxtaposed with units of Yeniköy Formation.

3.1.3. Gümüldür Fault Zone

On the right bank of the Gümüldür Dam body, stepping faults orientated K15E/60NE, K70B/45ND, N80B/60NE, N60B/68NE, and N85B/45NE which are parallel to the Gümüldür Fault Zone trending, which cut schists and quartzites of Menderes Metamorphics, are observed. Along the Gümüldür Fault, the metamorphic units forming the region's basement outcrop (Fig. 8). In the deep well of 1215 m, these units have been drilled at a depth of 850 m. This finding indicates that the basement buried deeper by the Değirmendere Fault Zone in the Çubukludağ Graben has been brought up a little bit more by the Gümüldür Fault.

Fig. 8. A view from the faulting of the Gümüldür Fault Zone cutting the Menderes Metamorphics (X: 501098, Y: 4215980)

3.1.4. Değirmendere Fault Zone

Karacadağ dolomitic limestones are juxtaposed with İzmir Flysch along the Değirmendere Fault Zone, which exhibits a dip-slip normal faulting character in the Tahtalı Dam area (Fig. 9) while limestones of İzmir Flysch overthrusts the Menderes Metamorphics at the bottom of the sequence. This finding indicates that the Değirmendere Fault Zone, which bounds the Çubukludağ Graben from the east, uses the plane of the older thrust fault's weakness.

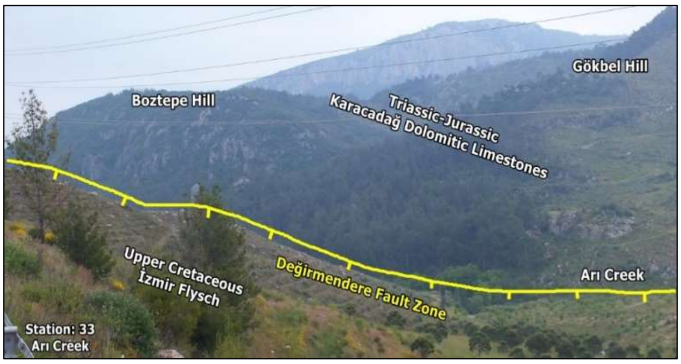

Fig. 9. A view from the Değirmendere Fault Zone which juxtaposes the Karacadağ dolomitic limestones and the İzmir Flysch (X: 504850, Y: 4220898)

Dacite and columnar rhyolite lavas of the Cumaovası Volcanics are juxtaposed with the faulted contact along the N30E 75SE trending fault of the Değirmendere Fault Zone in the vicinity of Tahtalı Dam. Someone can clearly observe the fault plane between the two units, whereas tuff nodules can be observed above the fault plane. As a result of faulting, rhyolitic columnar cooling structures are steeply exhibited towards the fault. On the other hand, dacites have been broken by the faults and has a blocky structure (Fig. 10).

3.2. Fracture/Fault Planes-Layer Surface Measurements and Kinematic Analysis

Faults and layers' planes have been measured at 110 different stopping points to reveal the structural features and the geothermal potential of the area (Table 1). The 114 fracture/crack/fault plane measurements at 52 stop points and 52-layer plane measurements at 43 stop points have been conducted. A rose diagram is prepared, and the orientations of the fracture planes are plotted on the Wulff net to determine the dominant fault/fracture/layer planes from the 12 different oriented fracture and layer planes along with the principal stress directions in the region (Figs. 11 and 12). As can be seen from the rose diagram of the fault-fracture planes, it is obvious that dominant the fault-fractures in 4 main directions are as follows: (1) N00-30E; (2) N00-30W; (3) N60-75E; (4) N75-90. (1) N00-30E-trending faults; (2) N00-30W-trending faults and NS/NE-SW-trending left-lateral strike-slip faults; (3) N60-75E; (4) N75-90W-trending cracks representing the cracks of E-W oriented right-lateral strike-slip Tuzla and Deliömer Fault Zones.

Fig. 10. A view from the faulting of the Değirmendere Fault Zone, which juxtaposes dacites and columnar rhyolite lavas of Cumaovası Volcanics (X: 505241, Y: 4220957).

The layers in the area are dominant in 3 different directions as (1) K15-30B, (2) K45-60B, and (3) N45-60E. The horizontal strata become steep away from the faults near the Tuzla and Deliömer Fault Zones. The predominant orientation in fault-fracture planes measured within the zone is N40-60 along the Tuzla fault zone, and it is observed to be generally dipped to the SE. Besides, antithetic faults exist with NW-SSE and E-W-trending perpendicular to the main fault within the fault zone. N40-60E-trending fault-fractures are right-lateral, while the NNE-SSE and E-W-trending fault-fractures present left-lateral strike-slip faulting characters. On the other hand, NW-ESE and N-S-trending fractures are observed in the right-lateral strike-slip Deliömer Fault Zone while NW-ESE-trending fault-fractures exhibit right-lateral, and N-S-trending fault-fractures show left-lateral strike-slip faulting characters. The absence of a dominant crack system associated with any faulting throughout the tearing passing through the graben center indicates no strike-slip faulting passing through the tearing. Along the contact of the dacite and Yeniköy Formation between the Akyar and Köşk Cliffs, the slope by the topography has moved downwards, and gravity slidings has developed. N-S-trending shear fractures are measured, indicating a few km long shear fault between Orta and Akyar Hills.

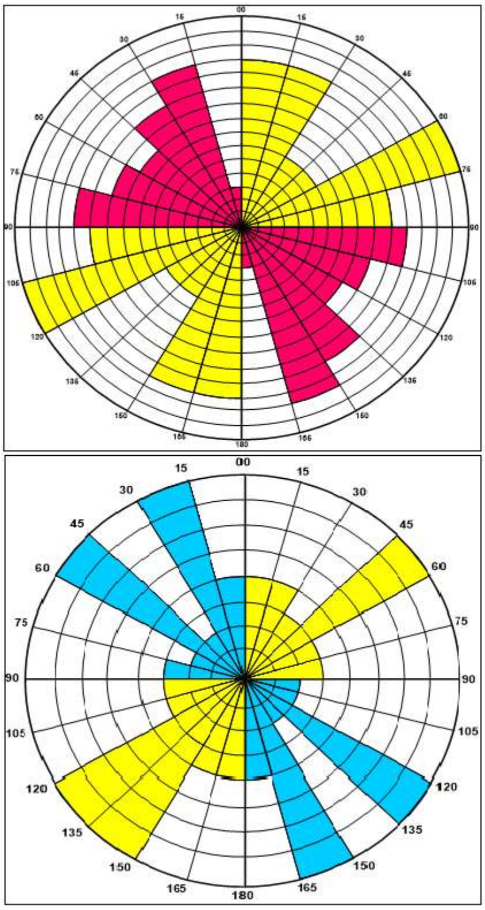

Fig. 11. Rose diagram of fracture, fault, and layer planes measured in the study area

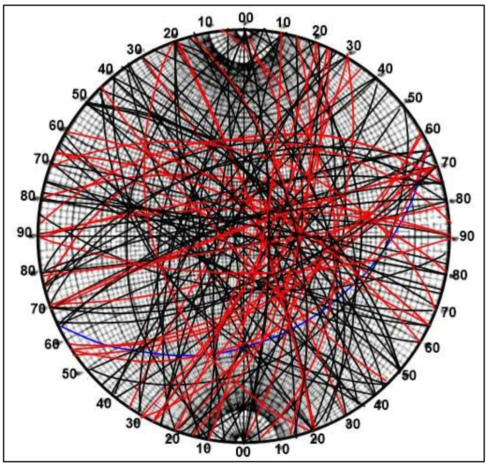

Fig. 12. The distribution of fracture and fault planes measured in the study area on the Wulff net

N-S-trending tear faults are observed in the vicinity of Payamlı, which cut the Bahçecik and Yeniköy Formations. NW-SE and NE-SW trending faults are monitored around the Gümüldür Dam, indicating the presence of the Gümüldür Fault, which cuts the Menderes Metamorphics. Considering that N60-90E trending faults are right-lateral and N0-30E/W trending faults are left-lateral strike-slip faults, area is understood to be compressed in the NW-SSE direction and expanded in the NNE-SSW direction (Fig. 13).

Table 1. Fracture/fault planes and layer surfaces measured in the study area

Station No	X	Y	No	Orientation faults/joints	Orientation bedding planes	Explanation
S-1	4 95 662	42 19 103	1	N18E 47NW	N5W 22SW	SK-Well
			2	N12E 37GE		Bedding faulting
			3		N20E 20SE	
			4		N40E 30NW	
S-2	4 97 281	42 18 906	1			Slope debris
S-3	4 99 168	42 20 648	1		NS 35W	Rhyolitic tuff
S-4	5 02 869	42 21 991	1	N50W 55NE		
			2	N20W 80NE		
			3	N20W 70SW		Small scale faulting
S-5	5 04 785	42 23 501	1		N35W 35SW	Tuff concreations
S-6	4 92 327	42 16 944	1	NS 65W		İzmir Flysch
S-7	4 92 457	42 16 771	1	N15E 70SE		Diabase block
S-8	4 92 997	42 20 587	1	N20W 80NE	N20E 55SE	Horizontal fault
S-9	4 92 834	42 17 708	1	N12E 58NW		İzmir Flysch
S-10	4 94 000	42 21 690	1		N48W 11NE	Yeniköy Formation
S-11	4 94 359	42 20 907	1	N70E 60SE		Faulted contact (Rhyolite)
S-12	4 94 794	42 21 612	1	N50W 90SW		
			2	N75E 78NW		Rhyolite
			3	N35W 85SW		
S-13	4 94 364	42 22 800	1			Conglomerate block
S-14	4 95 463	42 23 806	1		N50E 40SE	Yeniköy Formation
S-15	4 97 351	42 24 191	1		N42E 60NW	Yeniköy Formation
S-16	4 99 115	42 24 411	1		N25W 75NE	Yeniköy-Rhyolite contact
S-17	4 98 946	42 24 700	1			Contact, spring
S-18	4 98 829	42 26 212	1			Yeniköy-Rhyolite contact
S-19	4 96 606	42 24 943	1	N30E 68NW		İzmir Flysch (Diabase)
S-20	4 96 850	42 25 371	1			İzmir Flysch
S-21	4 93 774	42 20 907	1		N70W 55NE	Yeniköy Formation
			2		EW 25N	
S-22	4 93 445	42 21 117	1		N6W 28NE	Yeniköy Formation
			2		N10E 35GE	Red conglomerates
S-23	5 01 098	42 15 980	1	N15E 60SE		
			2	N70W 45NE		Menderes Metamorphics
			3	N60B 68NE		Gümüldür Fault Zone
			4	N85B 45NE		
S-24	5 01 250	42 16 518	1			Triassic-Jurassic limestones
S-25	5 00 923	42 17 820	2			Triassic-Jurassic limestones
S-26	5 01 838	42 15 807	1			Menderes-Cumaovası contact
S-27	5 01 560	42 16 147	1			Menderes
S-28	5 02 480	42 18 084	1	N70W 78NE		
			2	N5E 30NW		
			3	N50W 60NE		
			4	N75W 90NE		
S-29	5 02 984	42 19 850	1			Triassic-Jurassic limestones
S-30	5 02 827	42 20 117	1		N60W 40SW	İzmir Flysch
S-31	5 02 470	42 20 554	1			Cumaovası V. aglomerate
S-32	5 02 684	42 20 962	1		NS 30W	Tuff-aglomerate contact
S-33	5 04 850	42 20 898	1			İzmir Flysch-Menderes cont.
S-34	5 05 241	42 20 957	1			İzmir Flysch (Shale)
S-35	5 06 295	42 21 823	1			Aglomerate contact
S-36	5 07 230	42 22 762	1	N30E 75SE	N40W 30SW	Faulted contact between
			2	N30E 75SE	N20W 60SW	dacite and rhyolite
			3		N55W 60SW	
S-37	5 06 541	42 25 478	1	N65W 85NE		Deliömer Fault (Yeniköy)
S-38	5 06 422	42 25 542	1	N45W 45SW		
			2	N75E 65NW		Cumaovası Volcanics, tuff
			3	N60W 70SW		
S-39	5 06 467	42 24 653	1		N50W 35NE	Yeniköy Fm. Limestones
S-40	5 05 210	42 25 191	1	N75W 85SW	N70E 62NW	Cumaovası Volcanics Ilıkpınar hotspring
			2	NS 30E		
S-41	5 05 816	42 22 945	1			Cumaovası Volcanics
S-42	5 05 269	42 24 064	1		N50E 40SE	Rhyolite-tuff contact
S-43	5 07 500	42 24 960	1			Columnar rhyolite lavas
S-44	4 95 567	42 16 022	1	N40E 80NW	N65E 30SE	Yeniköy Formation
			2		N45E 30SE	
S-45	4 95 952	42 16 940	1	N70E 65SE		Yeniköy Formation
			2	N10E 80SE		Fault plane
S-46	4 96 033	42 17 320	1		N10E 58SE	Yeniköy Formation
S-47	4 96 525	42 18 379	1		N45W 35NE	Yeniköy Formation
S-48	4 96 638	42 18 740	1		N55W 35NE	Yeniköy-rhyolite contact
S-49	4 98 021	42 19 613	1	N20W 45SW	N75W 25NE	Fault- Yeniköy Formation
S-50	4 98 850	42 20 750	1			Kalabak Cliff -faulted
S-51	4 99 006	42 21 487	1			Tuff-folding
S-52	4 98 955	42 21 504	1	N50W 55NE	NS 42W	
			2	N25E 75NW		Orta H-Akyar H.
			3	N45E 85SE		Shearing cracks
			4	N20W 82NE		Fault plane, R=27
			5	N25W 45NE		
			6	N80E 42NW		
S-53	4 98 873	42 22 237	1		N75W 15NE	Yeniköy Formation
S-54	4 99 247	42 22 517	1	N50E 30SE	N80W 50NE	Yeniköy-Tuff contact
S-55	4 99 304	42 22 637	1			Brecciated tuffs
S-56	4 98 267	42 21 991	1			Brecciated tuffs
S-57	4 97 079	42 22 843	1			Yeniköy-Rhyolite contact
S-58	4 98 082	42 23 075	1	N20W 35NE		Yeniköy Formation
S-59	4 99 448	42 23 615	1			Rhyolitic tuff
S-60	5 00 334	42 24 296	1	N5W 85SW		Broken and blocky
			2	NS 75E		rhyolitic tuff
S-61	5 00 106	42 24 053	1			Dacitic tuff
S-62	5 00 919	42 24 074	1		N50E 15SE	Yeniköy Formation
S-63	5 00 816	42 22 942	1			Rhyolite
S-64	5 01 414	42 22 498	1			Rhyolite
S-65	5 04 051	42 24 827	1			Alluvium-tuff contact
S-66	5 04 000	42 25 250	1			Hotspring 5
S-67	5 03 766	42 26 296	1	N65W 70NE		Deliömer Fault

			2	N80W 60NE		Dextral fault with reverse componenet
			2	N75E 40NW		
S-68	5 02 961	42 26 345	1			Tuff
S-69	5 02 225	42 26 063	1	N80E 80NW	N48W 15NE	PerlitE
			2	N15W 60NE		
			3	N75E 72NW		
			4	N70E 50NW		
S-70	5 03 785	42 24 918	1	N70E 85NW	N50E 50NW	Rhyolite
			2	N45W 80SW	N20E 55SE	Tuff
			3	NS 75E		
			4	EW 70S		Deliömer Fault between rhyolite and tuff
			5	N80E 85SE		
S-71	5 02 646	42 25 070	1	N20E 85SE	N25W 65NE	Yeniköy Formation/Fault
S-72	5 01 285	42 24 577	1			Yeniköy Formation
S-73	5 02 598	42 24 107	1	N25E 82NW		Cumaovası Volcanics N70E trending tuff
			2	N50W 75NE		
			3	N70E 80NW		
			4	N35W 65NE		
			5	N25E 75SE		
S-74	5 02 819	42 23 612	1			Aglomerate
S-75	5 03 799	42 22 955	1			Tuff
S-76	4 98 270	42 15 186	1		N55 35SE	İzmir Flysch/Bahçecik Formation contact
S-77	4 98 417	42 16 553	1			Dacite (Akyar Cliffs)
S-78	4 97 727	42 16 421	1	N20W 45NE		Yeniköy Formation Yumrutaş H.-Akyar Cliffs Gravitational sliding
			2	N30W 70NE		
			3	N40W 65NE		
S-79	4 97 702	42 17 492	1	N70W 70SW		Yeniköy Formation Gravitational sliding
			2	N85W 60SW		
S-80	4 98 035	42 18 166	1	N5E 58SE	N35E 35SE	Yeniköy Formation
			2	N35W 65SW		
S-81	4 98 672	42 19 157	1	N70E 70SE		Fault plane, R=5
			2	N65E 60SE		
			3	N10E 85NW		Cumaovası Volcanics Easit. Transfer fault and shearing cracks
			4	N35W 80SW		
			5	N65W 70SW		
S-82	4 98 736	42 19 590	1	N80W 82NE		Dacite
			2	N40E 70NW		Pillow lavas
S-83	4 99 249	42 20 080	1	N43W 62NE		Dacite-Yeniköy Formation
			2	N5E 75SW		faulted contact
S-84	4 94 762	42 17 571	1		N15W 20NE	Bahçecik Fm. Limestones
S-85	4 94 854	42 18 573	1	N30E 48SE	N20W 35NE	Bahçecik Formation Fault
			2	EW 70N		
			3	N60E 54SE		
			4	N60E 60SE		
			5	N5W 40NE		
			6	N15W 60NE		
			7	N65E 45SE		
S-86	4 95 054	42 19 627	1			Yeniköy Formation
S-87	4 95 565	42 20 172	1		EW 20N	Yeniköy Formation
S-88	4 96 546	42 20 840	1			Rhyolite
S-89	4 97 001	42 21 277	1	N15W 75NE		Tuff-Rhyolite (Alteration) Gravitational sliding
			2	N45W 65SW		
			3	N40W 45SW		
S-90	4 96 415	42 21 000	1	N65W 75SW		Brecciated rhyolite
S-91	4 95 288	42 20 533	1			Slope debris
S-92	4 97 666	42 21 676	1	N20E 55NW		Trachyandesite
			2	N10E 45NW		
S-93	4 97 912	42 22 022	1	N80E 85SE	N20W 47SW	Trachyandesite
			2	N20W 65SW		
S-94	4 97 725	42 22 429	1	N30E 57NW	N45E 48NW	Rhyolitic tuff
			2	N82W 88NE		
			3	N65E 70NW		
S-95	4 97 234	42 22 717	1	N40W 80NE	N65E 58NW	Rhyolite
S-96	4 96 655	42 22 566	1			Rhyolitic tuff
S-97	4 96 456	42 23 143	1			Rhyolite-Yeniköy contact
S-98	4 96 138	42 23 193	1		N75E 73NW	Yeniköy, steppened beds
S-99	4 95 686	42 23 837	1	N70E 85NW	N20W 42NE	Tuzla Fault Yeniköy Formation
			2	N25E 75SE		
			3	N25E 65SE		
S-100	4 96 446	42 24 215	1			Tuzla Fault, Asılçay Creek.
S-101	4 95 400	42 17 700	1			Tuzla Fault, N-S trending
S-102	4 95 220	42 18 702	1	N75E 50NW		Yeniköy Formation
S-103	5 00 426	42 27 396	1	EW 75N		Tuzla Fault, Yeniköy Formation
S-104	5 00 083	42 27 401	1	N20E 65SE	N25W 65NE	Steepened beds
S-105	4 99 235	42 26 963	1	EW 80N		Yeniköy Formation
S-106	4 98 073	42 26 513	1	N80W 90SW		Yeniköy Formation/Alteration
S-107	4 94 637	42 22 871	1	N50E 72SE	NS40E	Yeniköy Formation
S-108	4 94 118	42 22 870	1	N30W 82NE	N50E 40SE	
			2	N35E 80NW		Tuzla Fault
			3	N20E 60SE		Faulted contact between İzmir Flysch and Yeniköy
			4	NS 60E	N20E 45SE	Formation
			5	N65E 60SE	NS 35E	
			6	N65E 35SE		Dextral fault with reverse
S-109	4 93 586	42 21 596	1	N40E 68SE		Yeniköy Formation
S-110	4 92 623	42 18 118	1	N65E 88SE	N45W 30NE	Yeniköy Formation

Table 1. Fracture/fault planes and layer surfaces measured in the study area (continued)

No	Total	Strike	Dip	No	Total	Strike	Dip
1	3	N00-15W	40-85 NE/SW	7	12	N00-15E	30-85 NW/SE
2	12	N15-30W	35-82 NE/SW	8	12	N15-30 E	47-85 NW/SE
3	10	N30-45W	45-85 NE/SW	9	6	N30-45 E	48-80 NW/SE
4	8	N45-60W	45-90 NE/SW	10	6	N45-60 E	30-85 NW/SE
5	9	N60-75W	45-85 NE/SW	11	15	N60-75 E	35-85 NW/SE
6	11	N75-90W	45-90 NE/SW	12	10	N75-90 E	40-85 NW/SE

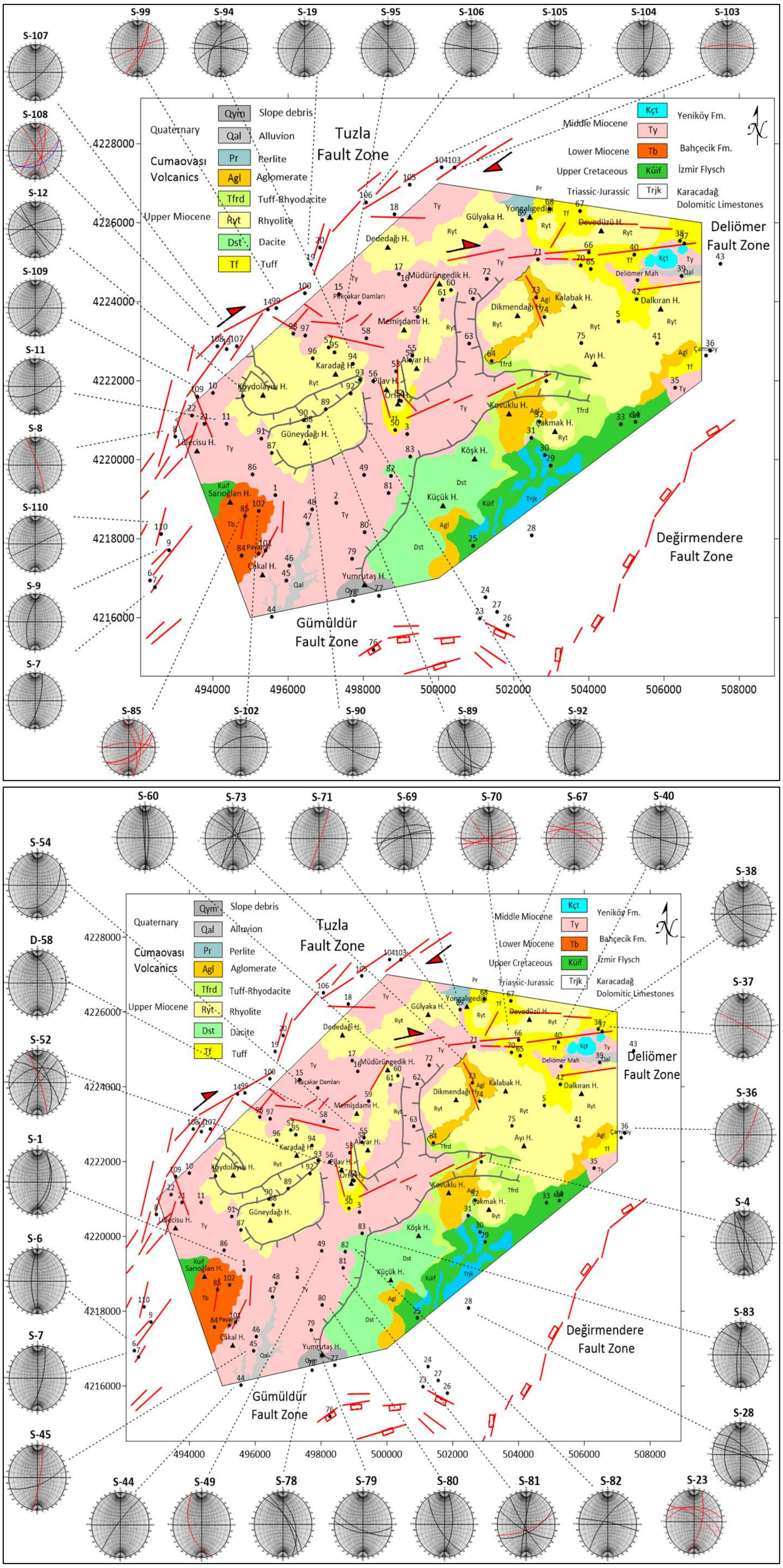

Fig. 13. Kinematic analysis of fault, fracture, and crack planes measured in the study area

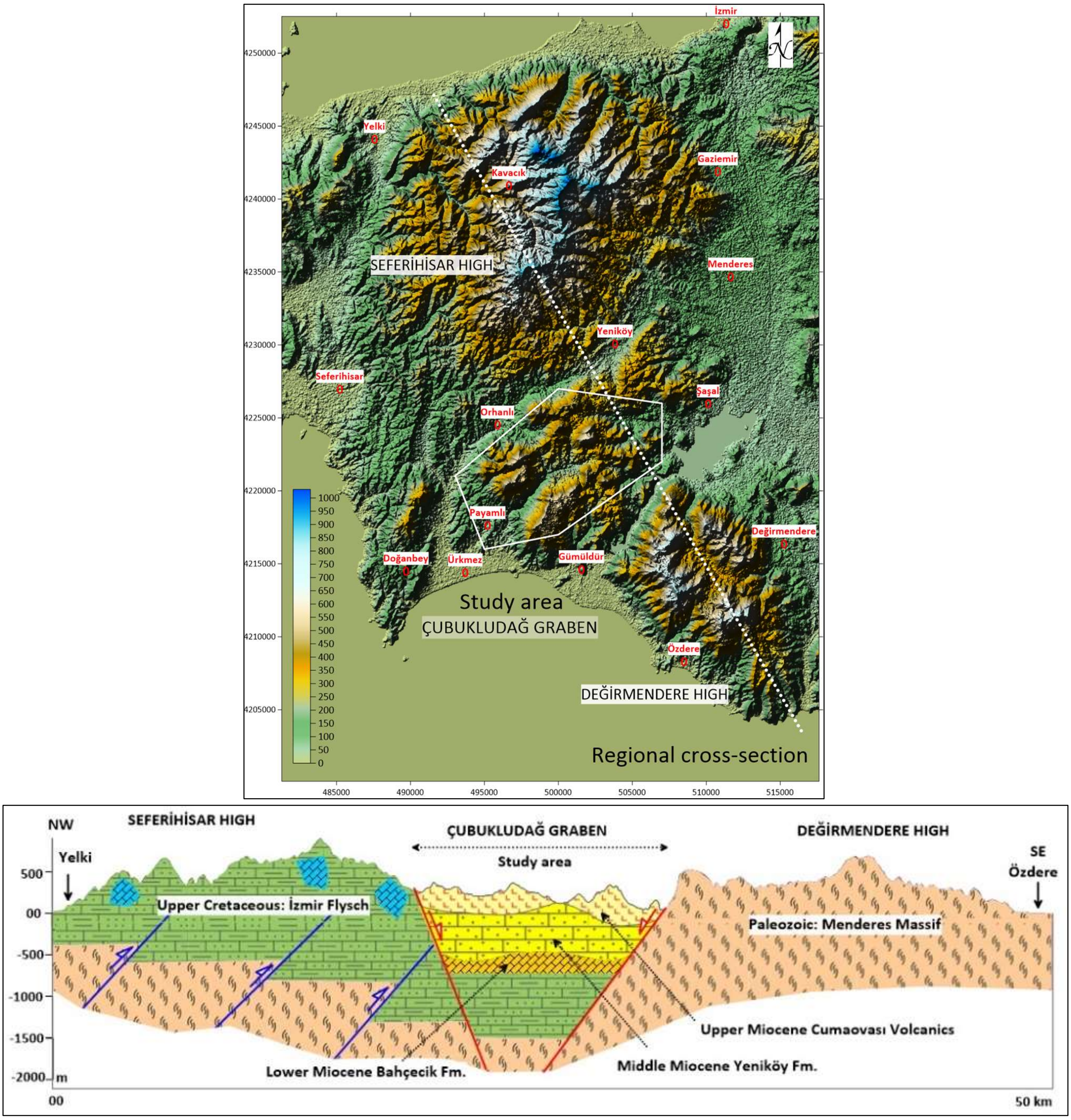

Fig. 14. NW-SE oriented geological cross-section of the study area and its surroundings

3.3. Cross-Sections and 3D Structural Model

An NW-SE directed regional geological cross-section has been prepared for the study area (Fig. 14). In this cross-section, the total vertical slip forming the Çubukludağ Graben is taken as 750 m. Three main structural elements controlling the geothermal system in the graben are clearly observed as follows: (1) Seferihisar High, (2) Çubukludağ Graben, and (3) Değirmendere High. The Seferihisar High bounds the study area from the west-northwest and the Değirmendere High from the east-southeast.

The Tuzla Fault Zone in the west-northwest of the area has juxtaposed the İzmir Flysch forming the Seferihisar High with the volcano-sedimentary units and constructed the Çubukludağ Graben. On the east-southeast border of the area, Menderes Metamorphics and volcano-sedimentary units present a faulted contact relation along the Degirmemendere Fault Zone.

Before the Çubukludağ Graben was formed (and deposition of the Bahçecik Formation), the İzmir Flysch was an overthrust onto the Menderes Metamorphics from NW to SE. This thrust is obvious in the east-southeast part of area.

Cutting of Menderes Metamorphics around the depths of 840-1000 m in the drilled wells indicates that there may be an estimated 750 m vertical slip along the Değirmendere Fault Zone that forms the Çubukludağ Graben. It is thought that the Tuzla Fault Zone may have moved by a dip-slip normal and/or left lateral strike-slip during the formation of the Çubukludağ Graben in the Lower-Upper Miocene. After Pliocene, the authors also consider that the Tuzla Fault Zone's right-lateral strike-slip has used the older weakness plane bounding the Çubukludağ Graben.

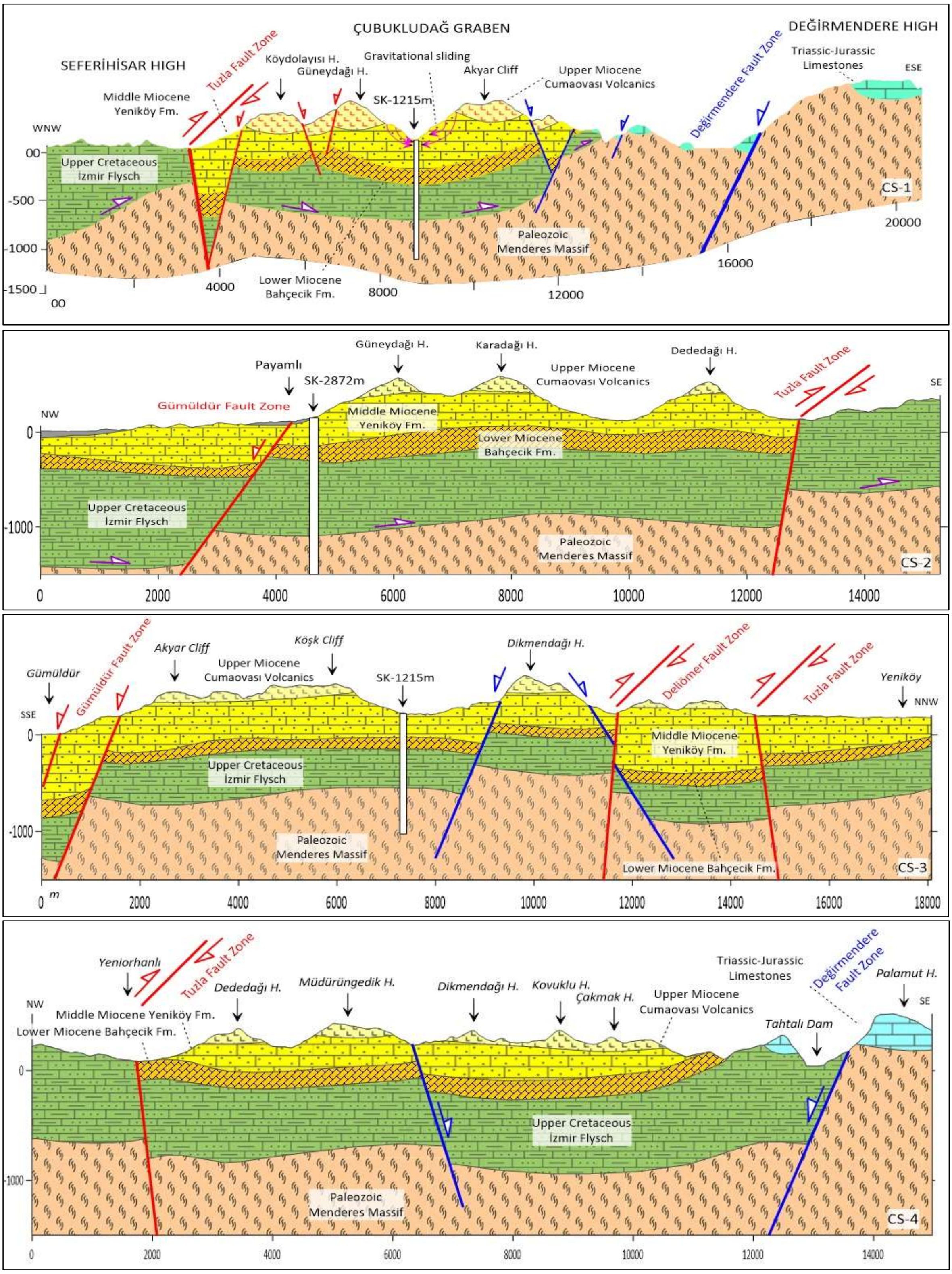

Fig. 15. Geological cross-sections of the study area (see Fig. 2)

The Çubukludağ Graben is located approximately 250-300 m below the Seferihisar and Değirmendere Highs in the west and east. The cutting of the İzmir flysch has been performed by both wells drilled in the graben at depths of 300-400 m, and they indicate that the total slip maybe around 750 m in dip-slip normal faults bounding the graben.

Geological cross-sections have been prepared along four different lines, two of which are in the WNW-ESE direction, and the others are in the NNW-SSE direction (Figs. 2 and 15). The cross-sections are used for the following issues.

- To reveal the main structural elements controlling the geothermal system in the Çubukludağ Graben,
- To determine the geometric properties and fault parameters of the Tuzla, Deliömer, Değirmendere, and Gümüldür Fault Zones that restrict the graben,
- To explain the formation mechanism of NE-SW-trending wide and deep tears that cause the rhyolitic and dacitic lavas in the graben presenting a cap-shaped and hanging morphological structure,
- To explain the environment and conditions that form reservoir rock depending on the total slips of the vertical slip faults bounding the graben using the drilled well data,
- To understand the exit ways of the geothermal fluid to the surface and recharge into the depths.

In the cross-sections 1 and 2 (Fig. 15), the Cubukludağ Graben, located between Tuzla and Değirmendere Fault Zones, presents an asymmetrical basin structure. While the metamorphics form the basement surface in the Değirmendere Fault Zone's footwall block, they are displaced approximately 750 m vertically in the hangingwall block. On the other hand, the basement is located closer to the surface, possibly at the depths of 400-500 m along the Tuzla Fault Zone, which borders the graben from the west.

There are steeply V-shaped tears having 1-3 km wide and 400-450 m deep on the surface narrowing towards the bottom between Güneydağı Hill-Akyar, Köşk Cliffs, and Güneydağı Hill-Köydolayısı/Karadağ Hills. Rhyolitic and dacitic lavas presenting a cap-like morphological structure are located at the same level on both sides of these tears, which have been formed at an altitude of 400-450 m whereas no morphological, morphotectonic, or geological formations, which indicate vertical or strike-slip faulting throughout the NE-SW trending tears of about 10 km length, exist. Therefore, these tears have nothing to do associated with faulting.

NE-SW trending deep and wide tears present morphological structures in the form of wide and flat paleovalleys that discharge into the sea in the Çubukludağ Graben in the Lower-Upper Miocene before the flow of the Upper Miocene rhyolitic and dacitic lavas. It is considered that rhyolitic and dacitic lavas flowed into these paleovalleys from afar, flattening them to fill the valleys. After the Upper Miocene and during the Pliocene period, the graben's center began to regionally uplift with the Tuzla and Gümüldür's Faults engagement in the south, relief inversion within the depression (Fig. 16). Thus, the ascending section was opened in the NW-SE direction, fragmented in the form of a canyon, continued to split, and wide and steep tears were formed. Therefore, rhyolitic and dacitic lavas on the high hills of the graben have remained suspended and formed morphological structures in the form of caps.

The effects of E-W trending dip-slip normal faults are observed in the NNE-SSE trending geological cross-sections (3rd and 4th cross-sections in Fig. 15) taken between Ürkmez-Kayalı Village (Yeniorhanlı) and Gümüldür-Yeniköy. Güneydağı Hill of the Gümüldür Fault presents a dip-slip normal fault character that bounds it from the south, and the southern part of the Köydolayısı Hill and Akyar Cliffs is approximately 400 m. It is predicted that they have vertically displaced the northern parts of Karadağ Hill and Dikmendağı Hill around 250 m.

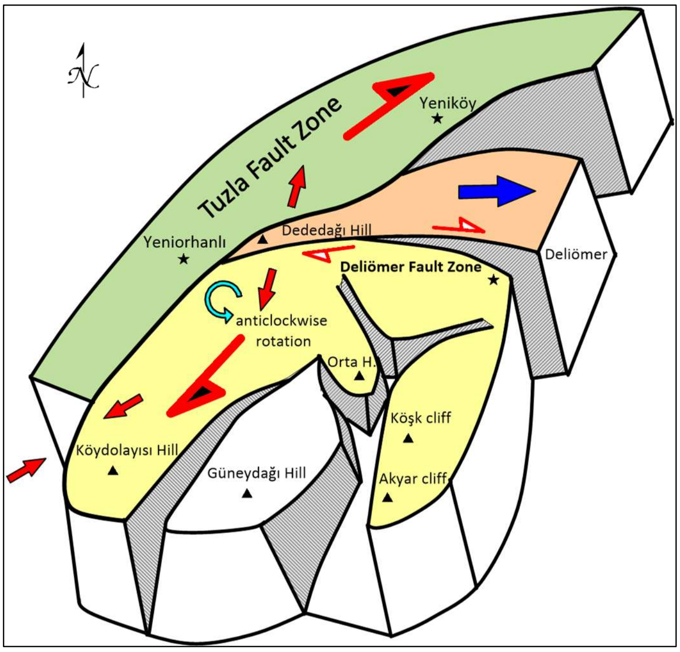

Fig. 16. 3D structural model of the Çubukludağ Graben

The authors think that the Gümüldür Fault is much more effective in forming tears in the graben. Similarly, rhyolitic and dacitic lavas, which occupy a cap position on the hills' peaks, have been suspended at the same levels. The İzmir flysch and the Menderes Metamorphics forming the graben's basement may be deeper in the south than in the north thanks to a more considerable amount of vertical slip in the Gümüldür Fault. Normal faulting is observed in the north of Dikmendağı Mountain that Deliömer Fault Zone bounding the Dededağı with normal faulting, and the Tuzla Fault Zone cuts Kardağ Hills from the north.

4. Geothermal Potential

Ten hot springs are available throughout the faulted contacts and shear fractures (Fig. 2).

- 4 out of 10 control the graben from the north along the right-lateral strike-slip of the Deliömer Fault Zone.
- The extensional and compressional areas of the right-lateral strike-slip of the Tuzla Fault controls from the west-northwest, numerous hot springs, geothermal wells, and hot spring near the NW corner of the graben and.
- Five hot springs are located throughout the N-S and E-W-trending small shear fractures in the shear's shallow depths forming the divergence in segments at the northeastern end caused by the shear opening the tears in the center of the graben.

Two geothermal wells, 1215 m and 2872 m in depths, were drilled in the graben. The well with 1215 m-depth was drilled at the intersection of the NNE and NW-SE-trending shear fractures in the part where the tear of approximately three km-width is divided into segments (Fig. 2). The surface temperature of the two-phase (water + steam) fluid is above 100 ºC. The production zone has been determined as 1150-1190 m. The flow rate was measured as 29 lt/sec, and there is no artesian production (Bulut, 2013). In the well of 2872 m in-depth, the well is at 35 - 265 m in depths, 230 m thick-units of the Bahçecik and Yeniköy Formations; at 265 - 1025 m in depths, 760 m thick-İzmir Flysch and units of Menderes Metamorphics from 1025 m to a depth of 2872 m was drilled. There was a complete circulation loss in the drilling throughout the contact between İzmir flysch and Menderes Metamorphics between the depths of 828-845 m, possibly with thrust faults. At the bottom of the well, a temperature of around 100 ºC was measured, and it was completed dry (unpublished data).

Under the young tectonic regime, the temperature gradient increase caused by mantle uplift due to crustal thinning plays the most critical heater role in the Aegean Region. In the study area, the heater process can be considered as the uplifting of the mantle. In the thrust faulted contact between the İzmir Flysch and the Menderes Metamorphics of the Paleotectonic period, which outcrop over a very large area in Western Anatolia, both formations at the upper levels of the metamorphics (also Triassic-Jurassic limestones in the form of olistoliths) and the lower levels of the İzmir Flysch, the metasandstones, green schists, and thick limestones have significantly been deformed, sheared, broken, and, fragmented, and have ultimately gained a brecciated character. This contact, which has cracks, fractures, faults, and brecciated texture that creates secondary porosity, forms suitable reservoir rock characteristics in the region in terms of both permeability and porosity. Bahçecik, Yeniköy, and Cumaovası Volcanics filling the Çubukludağ Graben represent the cover units (Fig. 17).

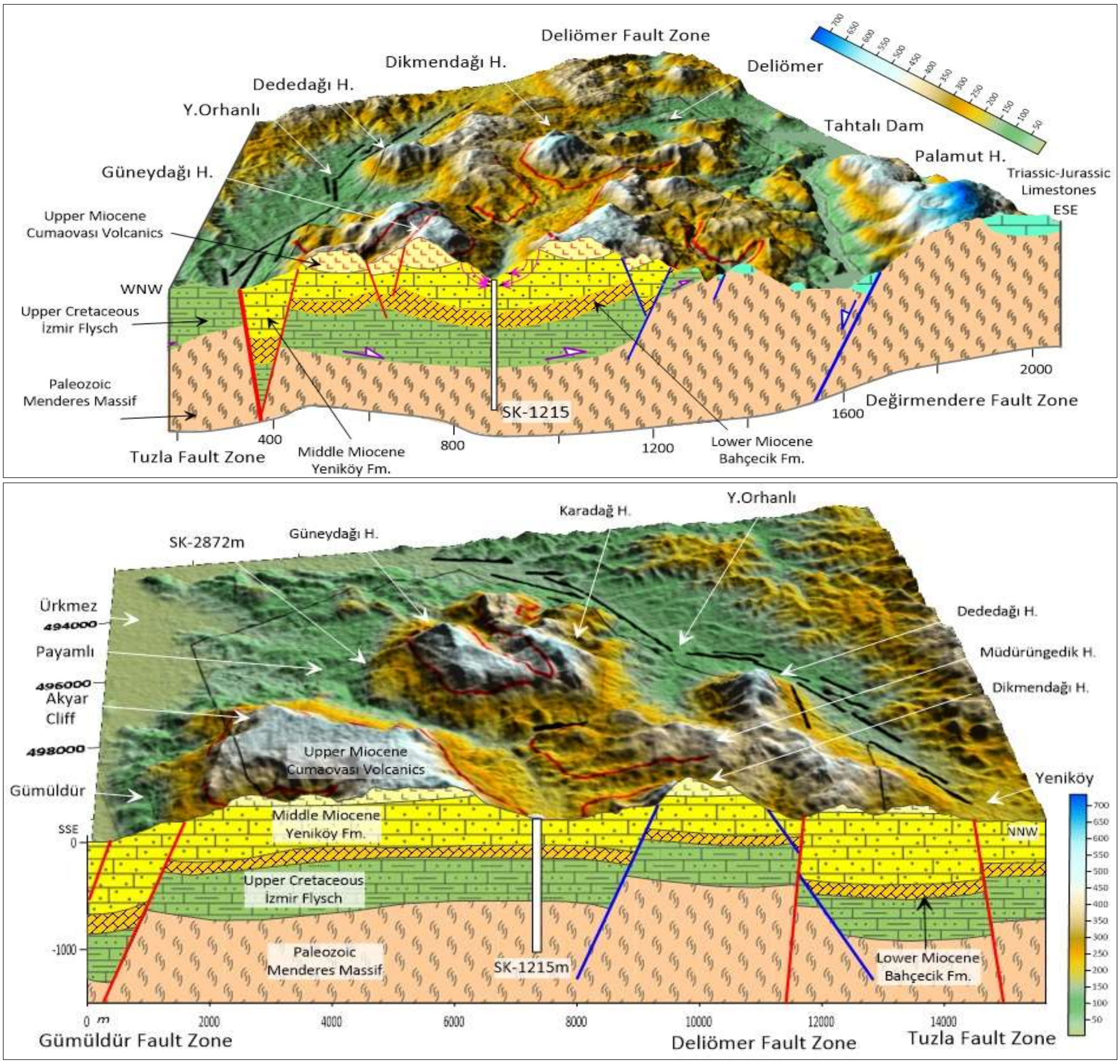

Fig. 17. Geological cross-sections and 3D models prepared to establish the conceptual geothermal model

4.1. Evaluation of geothermal potential from a tectonic perspective

Since rhyolitic and dacitic lavas shown up in the form of hanging caps in the graben were defined as domes in the previous studies (Eşder and Şimşek, 1975; Bulut, 2013), a conceptual geothermal model was built by assuming that there were magma chambers under these structures. However, according to the field observations in this study, rhyolitic and dacitic lava caps do not present a dome structure. Hence, our opinion is that four critical fault systems control the geothermal system in the Graben as follow:

- Tuzla Fault Zone,
- Deliömer Fault Zone,
- Gümüldür Fault Zone,
- Değirmendere Fault Zone.

In other words, the geothermal system is not controlled by a system defined as a rhyolitic-dacitic dome structure and a magma chamber beneath it, nevertheless, entirely by the right-lateral strike-slip faulting tectonics between the Çubukludağ Graben and the Seferihisar High. The effect of the Tuzla Fault Zone in the region is much more than other faults, extending to earlier tectonic periods. Thus, the development of transtensional and transpressional areas due to the left and right steps and counter-clockwise rotation between Yeniköy-Doğanbey and the formation of the Deliömer Fault Zone increases the geothermal importance of the NNW part lying in Dededağ. Therefore, the graben presents an asymmetrical structure, and the tear is towards the Deliömer side. The cover units are thicker, suggesting that this part's geothermal potential may be high (Fig. 18).

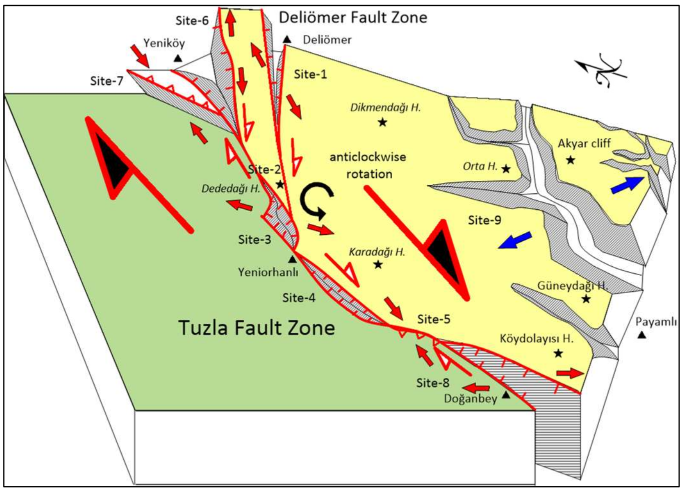

Fig. 18. Fault geometry of Tuzla Fault Zone, left and right turn areas, opening areas, intersection zones of faults, and tearing areas controlling the geothermal system in the Çubukludağ Graben

Considering the well data at a depth of 1215 m is located in Çamalan Creek at 150 m altitude and dacites at 568 m altitude form an eastern high of Köşk Cliffs. In the center of the graben, 400 m-thick Cumaovası Volcanics and 400 m-thick Yeniköy + Bahçecik Formation along with 450 m-thick İzmir Flysch exist. It is anticipated that the basement becomes shallow due to the asymmetrical structure of the basin as one goes towards the Tuzla fault from the center of the graben to the WNW. In contrast, it deepens as one goes from the center to the north towards the Deliömer Village. When the spreading area of Cumaovası Volcanics is examined, volcanic units are relatively preserved on the ESE and NNE sides of the significant tear between Güneydağı-Akyar/Köşk Cliffs. Lower Yeniköy Formation is completely eroded in the western half of the tear except Güneydağı, Köydolayısı, Karadağ, Dededağ, and Müdürüngedik Hills, and the Yeniköy Formation appears in large areas. Conversely, it shows that the WNW edge of the graben is considerably uplifted compared to the east due to the Seferihisar High. These facts indicate that the Tuzla Fault Zone has been moving before the graben occurrence period to the present, and therefore, it has penetrated up to deep depths. These results document that the Tuzla Fault controls the geothermal system in the region.

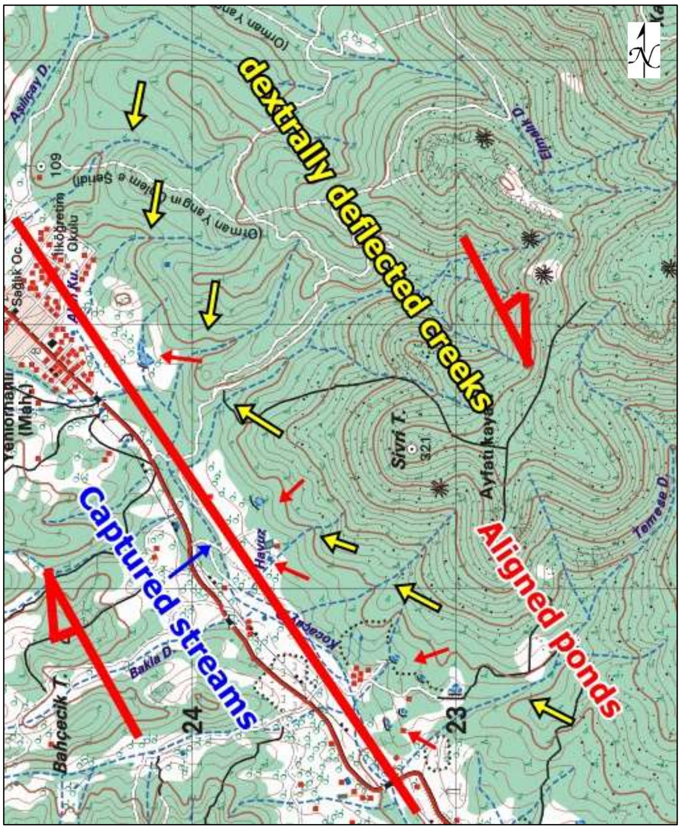

Fig. 19. Right-side captured and displaced streams, linear stream, and a series of aligned ponds around Yeniorhanlı

The tear developed from SW to NE, and depending on the extension, shear tears were formed along Orta, Akyar, and Çamalan Streams, penetrating N-S and E-W trending shallow depths. The tear faults in the area represent short length faults that do not extend to the reservoir rock's depths. Thus, for the fluid in the 1215 m deep-well drilled in intersecting area of N-S and E-W trending shear faults that descends to the depths to bring the fluid, it may be a fluid carried by these N-S and E-W tear faults and the Deliömer Fault Zone in the north. It is observed that the İzmir Flysch, which is a reservoir rock in the graben, and the Menderes Metamorphics forming the basement may be deeper in the south than in the north owing to the higher vertical slip on the Gümüldür Fault. The Tuzla Fault Zone makes a bend to the left at 450 m - 500 m width (Fig. 18). Depending on this bend, the northern part of Dededağ Hill (site 2) is formed as a releasing bend. The western area of Yeniköy has been compressed due to this bend and counterclockwise rotation (site 7, transtension) while the east region (site 6, transtension) releases. A positive flower structure is formed in the compression area, and a negative flower structure in the releasing area.

The Tuzla Fault Zone changing direction from N40-50W direction to N-S direction has caused a clockwise rotation starting from site 3. As the lateral slip in the Tuzla Fault Zone increases, the Deliömer Fault Zone (area 1) with E-W-trending has begun to form in the following stage of the rotational movement. E-W directional linear trends of Havlıç and Deliömer Streams also prove the existence of this fault. The rotational movement has also occurred both on the south-southeast side of Dededağı Hill (site 3) and the formation of extension (transtension) along Deliömer Creek in the east. The Deliömer Fault Zone, which has formed due to the Tuzla Fault Zone's counter-clockwise rotation and continues to develop, is getting younger from west to east. In other words, the Deliömer Fault Zone continues to tear from west to east (site 1). Furthermore, the observation of intense hot springs along the Deliömer Stream supports this view.

In Yeniorhanlı, Ortaca, and Temşealtı Villages, Karadağ (Sivri) and Köydolayısı Hills, and Tuzla Fault Zone, a narrow and long elliptical releasing area in 3 km x 300 m area (site 4) have occurred due to small-scale left bends and shear movement in the main faulting. This part forming the west-southwest boundary of the graben is within the Tuzla Fault Zone's primary deformation zone. Ortaca along this line (between Ortaca and Sivrice Hills) and Kocaçay Stream shows a linear flow in NW-SE direction conforming to Tuzla Fault. In contrast, small rivers in the NW-SE direction with a vertical extension to these streams are captured and displaced laterally right. Moreover, an extensive series of ponds are aligned up along this line (Fig. 19).

As Tuzla Fault Zone turns from the N40-50E direction to the N-S direction, a bend to the right has been formed between 1.5 km southwest of Yeniorhanlı (Ortaca Hill) and Temşealtı Villages, approximately 4 km-long, 250-500 m wide (site 5). Also, İzmir Flysch overthrusts, Quaternary sediments and conglomerate-sandstone units of Yeniköy Formation (transpression).

Asymmetric releasing areas (site 8), which manifest a negative flower structure due to the anticlockwise rotation and the developed extension (transtension), are formed in the Doğanbey part of the Tuzla Fault Zone. As a result of the anticlockwise rotation in the Tuzla Fault Zone and the vertical movement in the Gümüldür Fault, which passes through south-southeast, the graben was opened in the direction of WNW-ESE and regionally uplifted. Finally, it started to tear from the center. Thus, tears (site 9) as wide and steep valleys extending were created in the NE-SW direction from the graben's center to both sides. Gravitational flow and slides have been developed into the valleys. The tearing progressed from SW to NE and occurred around Orta Tepe-Akyar Hills due to the opening, N-S-trending left-lateral shear faults along Orta and Akyar Hills shallow shear faults, 3-4 km in length and not deep along the Çamalan Stream.

4.2. Evaluation of geothermal potential from regional gravity and aeromagnetic data

The contour maps specifically prepared from regional gravity and aeromagnetic data measured by the General Directorate of Mineral Research and Exploration of Turkey (MTA) for the study area have been used to interpret subsurface geology and geothermal potential of the area. The gravity map (Fig. 20) contains young sediments composed of lower-density sedimentary origin rocks (Neogene units and altered parts of the Paleozoic basement) and metamorphic (slate, phyllite, etc.) rocks represented by dark blue, light blue, and green colors. In the areas featured by orange, red, and yellow colors, an anomaly is characterized by the rocks having relatively higher densities (blocky flysches, marble, and metamorphics). Graben is mostly located in an area with low-density rocks. The NW section of the graben can be evaluated as suitable for reservoir development (areas in blue and dark blue on the map) considering the geological and tectonic data.

The aeromagnetic map prepared for the study area (Fig. 21) demonstrates the anomalies that originated from entirely non-magnetic sedimentary (sandstone, limestone, siltstone, mudstone, claystone, conglomerate, shale, etc.) and metamorphic (crystallized limestone, marble, quartzite, schist, etc.) rocks represented by blue, green, and light green colors. In the areas represented by yellow, red, and white color tones, the rocks with magnetic properties (pebbly volcanics, ophiolites, magmatic rocks, etc.) exist. The heat source for the geothermal resources in and around the graben should be related to the Seferihisar High because there is an anomaly caused by rocks with magnetic properties (white areas on the map) in the northwest of the graben. This anomaly was also shown in the study of Ozdemir et al. (2020). Consequently, the NW part of the graben is considered suitable in terms of geothermal potential when the anomaly is jointly evaluated with the geological-tectonic data obtained from field geology studies and the locations of geothermal resources.

In this study, the interpretation method proposed by Svancara (1983) and Töpfer (1977) is used to convert the 2D (two-dimensional) residual gravity anomalies into the depth values for the estimation of the basin and structure depths. In this method, the sedimentary basin's depth or structure can be determined by using simple relations established between gravity anomaly and parameters if density contrast is known. The first stage of the interpretation gives the characteristic parameters of the anomaly. An A-B profile is obtained from the study area's residual gravity anomaly map (Fig. 20). According to the anomalies of the residual gravity map of the graben, the maximum depth of the potential geothermal reservoir (D) has been calculated as 901.04 m (Fig. 22), which is compatible with the geological and tectonic data obtained from the field study (Fig. 23).

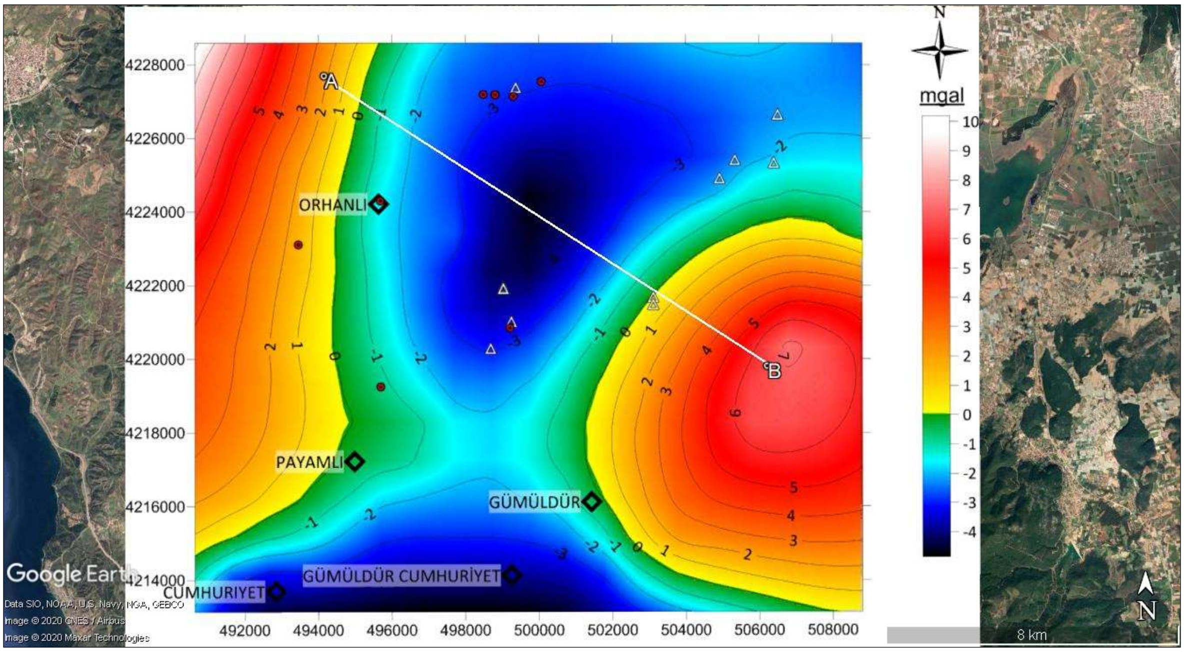

Fig. 20. Color contour map of regional gravity anomalies of the Çubukludağ Graben. Red circles: wells drilled in the graben, white triangles: hot springs

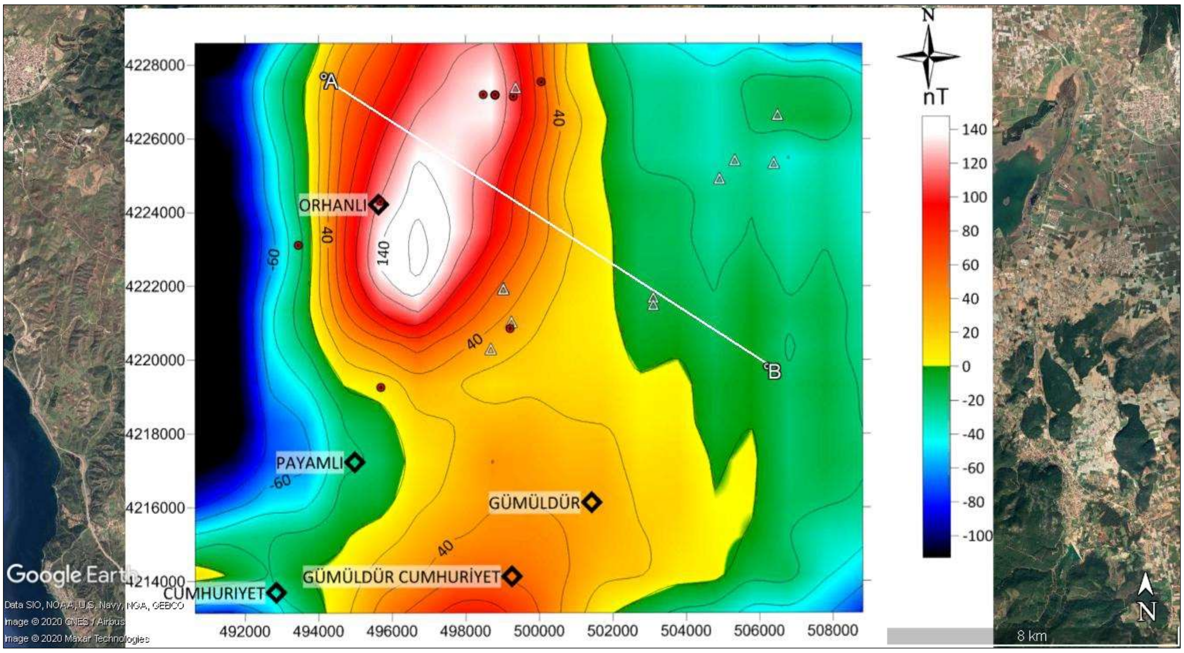

Fig. 21. Color contour map of the aeromagnetic anomalies of the Çubukludağ Graben. Red circles: wells drilled in the graben, white triangles: hot springs

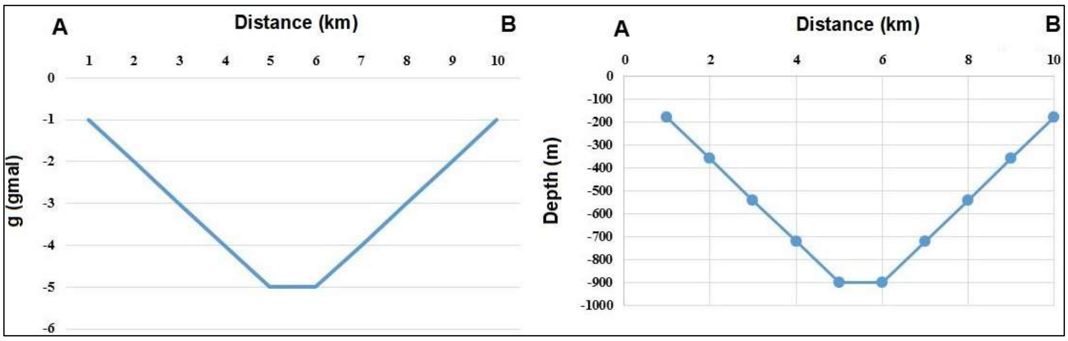

Fig. 22. Maximum depth of the potential geothermal reservoir (see Fig. 20)

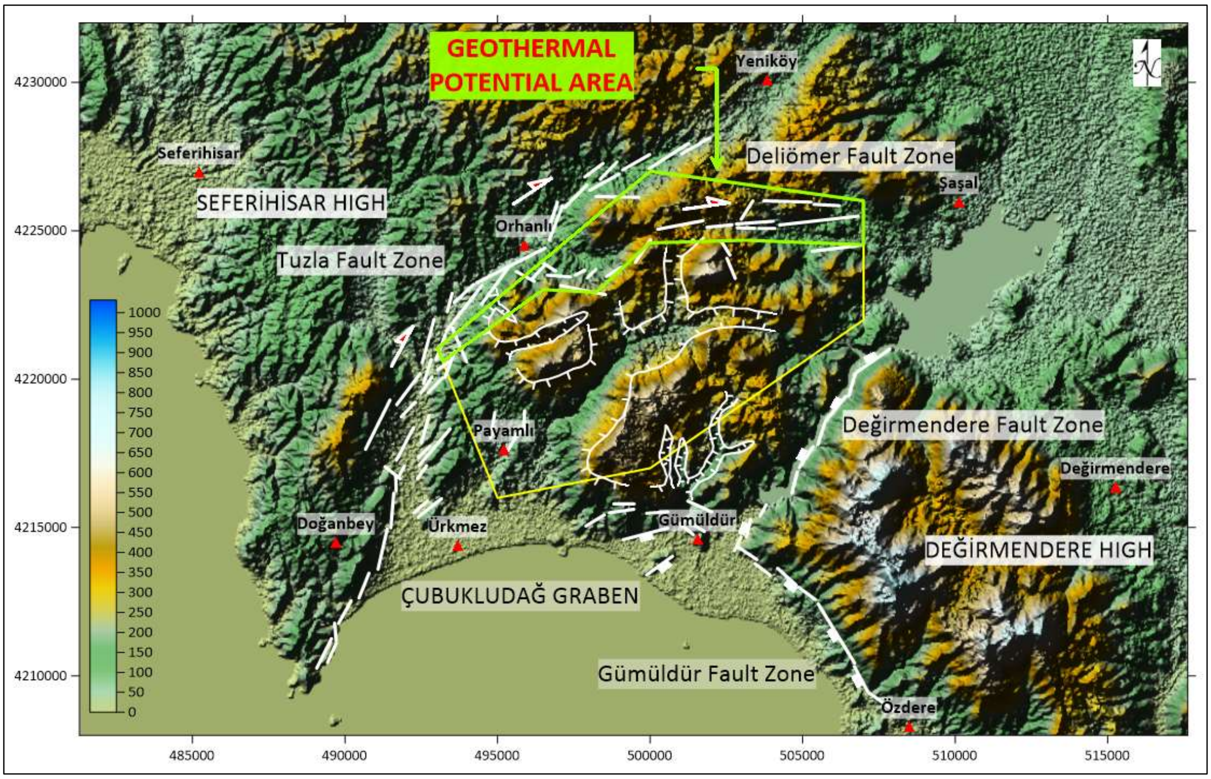

Fig. 23. Potential high-temperature geothermal area (green polygon) occurred in the graben due to the counterclockwise rotation resulting from the left turn of the Tuzla Fault Zone

5. Conclusion

Current morphological structure of Çubukludağ Graben has been formed by the mechanisms; 1) Grabening, 2) Volcanism (filling the valleys with acidic lavas), 3) Strike-slip faulting, 4) Anti-clockwise rotation along the Deliömer-Tuzla Fault Zone between Yeniköy-Doğanbey, 5) Normal faulting and glacial period (?) regional uplift after glaciation, 6) Deep tearing in the NE direction from the middle of the study area and suspension of acidic lavas 7) Erosion, 8) Gravitational flow and slides along the glades, 9) Settlement processes of filling to the Graben, respectively. Since the faults forming and bounding the graben are NE-trending, its extending structure in the NE direction has caused a series of hilly areas aligned with the NE direction in the study area misinterpreted as volcanic domes, and it was thought that the axial centers have NE-trending. Thus, under the hills defined as the volcanic dome, the chimney, as the heating rock of lava and geothermal system, has changed the research direction to the possibility of magma pockets' existence under the lava domes. However, during the field survey of this study, there is no evidence that these hilly areas, which were defined as rhyolitic and dacitic domes, are axial centers. Therefore, according to our study results, the geothermal system in the graben is controlled by four important fault systems, 1) Tuzla Fault Zone, 2) Deliömer Fault Zone, 3) Gümüldür Fault Zone, and 4) Değirmendere Fault Zone, respectively. In other words, the geothermal system is not controlled by a system defined as a rhyolitic-dacitic dome structure and a magma chamber beneath it, nevertheless, entirely by the right-lateral strike-slip faulting tectonics between the Çubukludağ Graben and the Seferihisar High. To sum up, especially the NW part of the graben can be assessed as a suitable site for high-temperature geothermal reservoir development according to the interpretations of geological, tectonic, gravity, and magnetic data.

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