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Uludağ extensional metamorphic core complex: preliminary field observations

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Research Article

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ABSTRACT

In the northern margin of Uludağ Massif in northwest Anatolia, the Bursa Detachment having top-to-the north, northeast normal sense of shear separates the lower plate high-grade metamorphic rocks of Series-A (Uludağ Group) from the upper plate low-grade metamorphic rocks of Series-B (Karakaya Complex). The deeper section of Uludağ Massif is represented by the Oligocene metagranites at the southern parts of the massif that is exposed due to the youngest high-angle Soğukpınar normal fault. The massif is a typical extensional metamorphic core complex similar to the counterparts in the west and northwest Anatolia such as the Menderes, Kazdağ, and Çataldağ core complexes due to close timing of exhumation and a similar sense of shearing.

1. Introduction

The Uludağ Massif and the mountain is an NW-SE trending prominent geological/geomorphological feature in the southern Marmara region in NW Türkiye (Figure 1). There is a 2442 meters elevation difference between the peak of Uludağ Mountain and the adjacent Bursa plain. The massif was mapped and the rock units were differentiated by Ketin (1947). The high-grade metamorphic rocks (Series-A) are composed of gneiss, amphibolite, and marbles. The low-grade metamorphic rocks (Series-B) comprise mica schist, phyllite, and marbles. Additionally, the Detritic Series after Ketin (1947) is composed of clastic units and limestones. As a result of further field observations, Ketin (1984) concluded that a thrust contact exists between Series-A and B, and then revised the geological map of the Uludağ Massif accordingly. Later, a nappe movement from SE to NW between Series-A and B rock units was proposed for the Uludağ massif (Şengör and Cin, 1988).

Imbach (1997) provided a more detailed description of the rock units in the Uludağ massif. The equivalent of Series-A is composed of muscovite and biotite gneiss, garnet-bearing quartzite, amphibolite, muscovite-bearing calcite-marble at the summit, and dolomite-marble with layers of kyanite-bearing tremolite schist at the northern margin of the Uludağ Massif. He also reported a post-Ordovician coral fossil. The low-grade rocks, equivalent to the Series-B, are composed of mica schist, phyllite, calcite-marble, epidote and glaucophane schist, serpentinite, and greenschist (Imbach, 1997).

Okay et al. (2008) dated the Series-A rocks from the Uludağ Group by single-zircon step-wise Pb-evaporation. Ages of gneisses in Series-A scatter strongly between Cambrian and Jurassic (Okay et al., 2008). Rocks of Series-B are differentiated as the Permian-Triassic lower and Triassic upper Karakaya Complex. Okay et al. (2008) also dated syn- and post-kinematic granites: The syn-kinematic granite called

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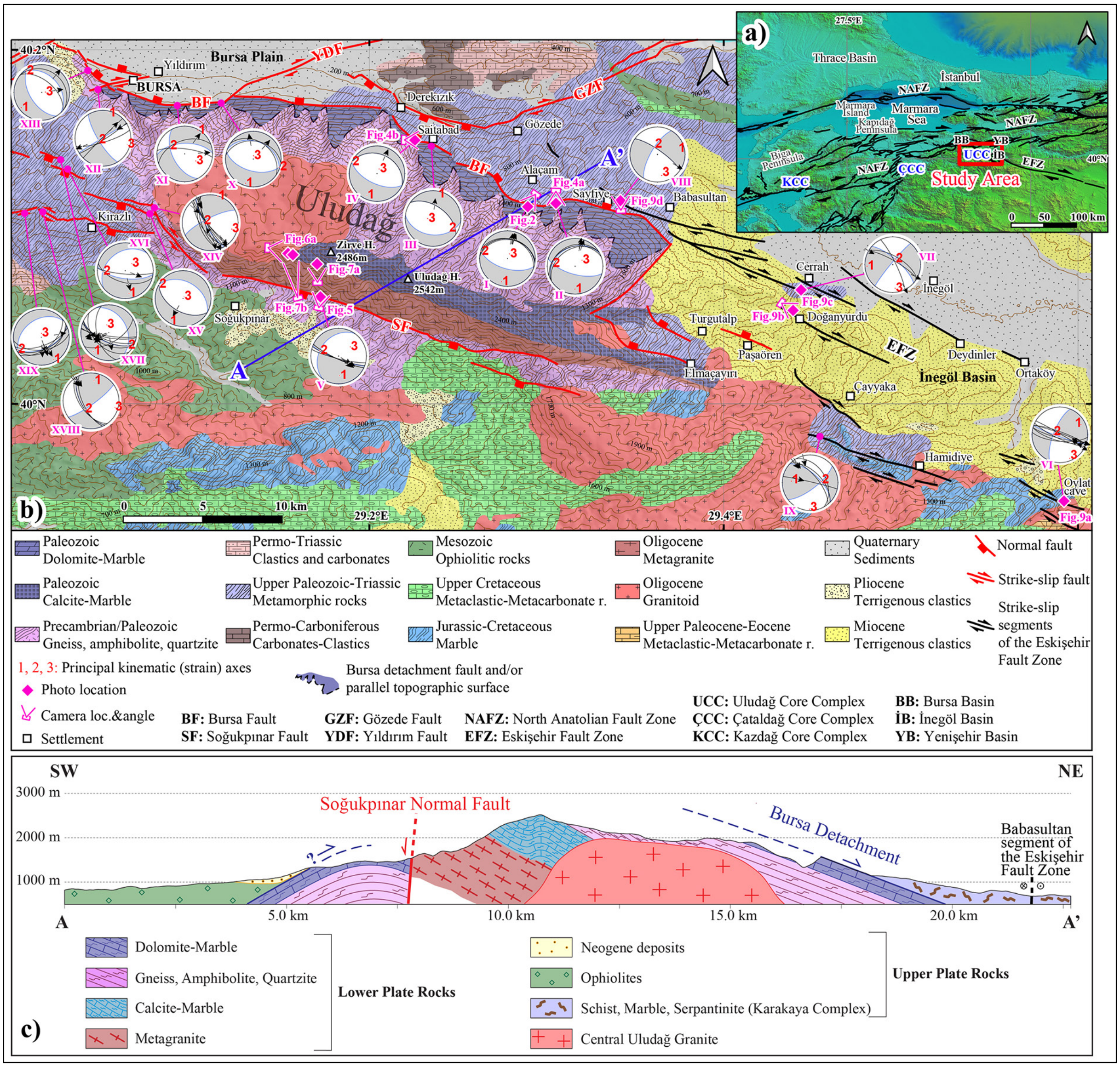

Figure 1- a) Location map of the study area in the southern Marmara region, b) geological map of Bursa and surroundings (Türkecan and Yurtsever, 2002) (fault lines are from Seyitoğlu et al., 2020). The digital elevation model was obtained from the 3-arc-second SRTM data. The circles represent the equal area lower hemisphere spherical projection of the fault planes and slickenlines. Gray (contractional) and white (extensional) areas and blue circles belong to the fault plane solution obtained by kinematic analysis of the fault data using FaultKin software (Marrett and Allmendinger, 1990; Allmendinger et al., 2012). The 1, 2, and 3 indicate the orientation of kinematic (strain) axes. See Table 1 for numerical data. EFZ (black lines): Eskişehir Fault Zone; YDF: Yıldırım Fault and GZF: Gözede Fault of North Anatolian Fault Zone, c) Simplified geological cross-section of the Uludağ Metamorphic Core Complex. For location see Figure 1b.

the South Uludağ Metagranite provides Rb/Sr ages of 34.7 ± 0.5 - 27.9 ± 0.5 Ma from muscovite and 29.5 ± 0.4 - 27.4 ± 0.3 Ma from biotite. $^{206}Pb/^{238}U$ zircon ages from the South Uludağ Metagranite are 38.8 - 30.4 Ma. The post-kinematic Central Uludağ Granite provides Rb/Sr ages of 27.2 ± 0.3 Ma and 27.5 ± 0.5 Ma from biotite and muscovite, respectively. Apatite fission-track (AFT) ages range from 28.9 ± 3.7 Ma to 9.2 ± 1.8 Ma (Okay et al., 2008). By using these age data and field observations, Okay et al. (2008) and Topuz and Okay (2017) claim that the Uludağ Massif represents an exhumed Oligocene ductile right-lateral shear zone of the Eskişehir Fault. On the other hand, Yurdagül (2004), Yaltırak and Ceyhan (2011) and Yılmaz (2017) interpret that the Uludağ Massif is an extensional metamorphic core complex.

Similar to the different views on the exhumation mechanisms of the Uludağ Massif, there are also diverse views about the strike-slip shear zones in the region. Although there is no agreement about the number of branches of the North Anatolian Fault Zone (NAFZ) in the southern Marmara region (see Seyitoğlu et al., 2016 for an evaluation), most of the classical studies accept that the Bursa area is under the influence of the NAFZ (Şengör, 1979; Şengör et al., 1985; Barka and Kadinsky Cade, 1988; Barka, 1992). However, recent studies suggest that the NE-SW trending fault zones in the Biga peninsula create an arc shape toward the east by turning to the NW-SE direction, as seen particularly by the Bursa, İnegöl, and Oylat normal faults, implying they belong to the Eskişehir Fault Zone (EFZ) (Emre et al., 2013, 2018).

In this paper, our preliminary field observations from north and south of the Uludağ massif support the interpretation that the massif is an extensional core complex, and we discuss its relationship with the NAFZ and EFZ.

2. Field Observations

The Bursa Fault (BF) (Emre et al., 2011*a*) is mapped as a single structure and is responsible for the topographical difference between Uludağ Mountain and Bursa plain. However, our field observations indicate that the BF in the north of Uludağ Massif can be divided into two sections.

The western sector of BF at the west of Yıldırım Fault (YDF) in the south of Bursa city centre is a high-angle normal fault that cuts low-angle schistosity/shear surfaces of the dolomite-marbles determined by Imbach (1997). These high-angle normal faults are developed as a normal faulted margin of the pull-apart basin under the influence of NAFZ. The NE-SW trending NAFZ, the youngest structure in the region, creates Yenişehir, eastern Bursa, and western Bursa pull-apart basins (Yılmaz and Koral, 2007; Selim and Tüysüz, 2013; Seyitoğlu et al., 2020). The western part of BF is reactivated as part of the Bursa Detachment (see below) because its surface relicts are still recognizable (Figure 1).

In the eastern sector of the BF at the east of Saitabad, the low-angle (25-30°) normal fault surfaces are exposed where the uppermost lithology of Series-A (Ketin, 1947), the dolomite-marbles determined by Imbach (1997) create triangular facets (Figures 1, 2a and 2b).

The slicken-lines plunge down-dip and indicate a top-to-the north/northeast normal sense of shear (Figures 2c, 2d, and 3; Table 1) suggesting the eastern sector of BF is a detachment fault separating from the high-grade metamorphic rocks of Series-A (Uludağ Group) in the footwall to the low-grade metamorphic rocks of Series-B (Karakaya Complex) in the hanging wall (see also Yıldırım et al., 2005). The large outcrops of the Bursa Detachment Fault can be seen in the south of Alaçam village and Saitabad (Figures 2 and 4). This is a common feature seen in the Menderes (Bozkurt and Park, 1994; Ring et al., 2003; Seyitoğlu et al., 2004), Çataldağ (Kamacı and Altunkaynak, 2019), and Kazdağ (Yaltırak, 2003; Kurt et al., 2010) core complexes in western Türkiye. Therefore, Bursa Detachment Fault can be regarded as the first sign that the Uludağ Massif is a typical extensional metamorphic core complex.

The deeper section of the Uludağ Massif (hereafter the Uludağ Metamorphic Core Complex - UMCC) is represented by metagranites exposed in the southern part. The final exposure of this deeper section is due to the younger south-dipping high-angle Soğukpınar Fault (SF) which is a normal fault with negligible left-lateral component (Figures 1 and 5; Table 1).

The metagranites showing the youngest AFT data (9.2 ± 1.8 Ma: Okay et al., 2008) are located on the uplifted footwall of the SF. The distinct morphological feature of the SF and the absence of strike-slip displacements on the valleys perpendicular to the fault support our field observations that the SF has a normal character. Moreover, the counterparts of SF in the west, separated by the left-lateral transfer faults, provide additional structural data that the SF is a major normal fault structure controlling step-like topography (Figure 1b). In the footwall of the SF, well-developed synthetic faults and fractures may create a misperception of near-vertical contact between the calcite-marbles and underlying metagranites (Figure 6).

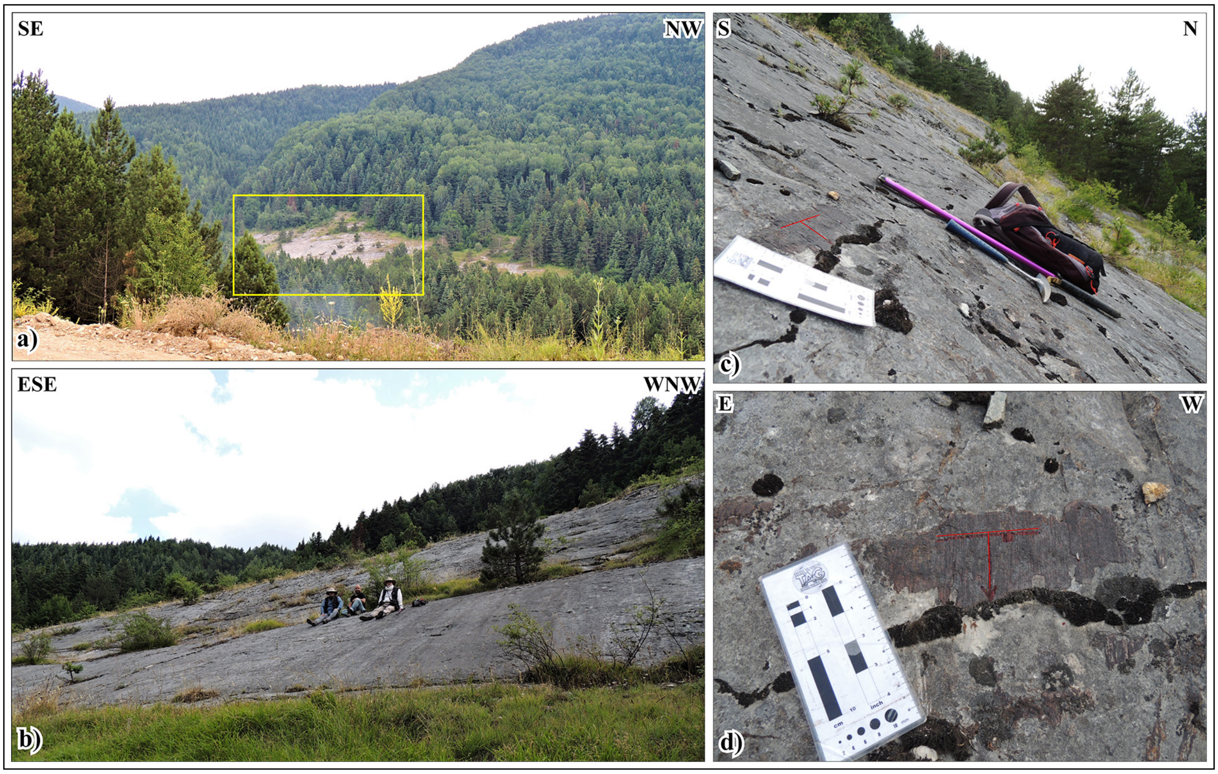

Figure 2- The Bursa detachment fault; a) its main outcrop at the south of Alaçam village, b) low angle nature of the Bursa detachment, c) the slicken-lines on the Bursa detachment and d) the slicken-lines indicating pure normal fault character. For location see Figure 1b.

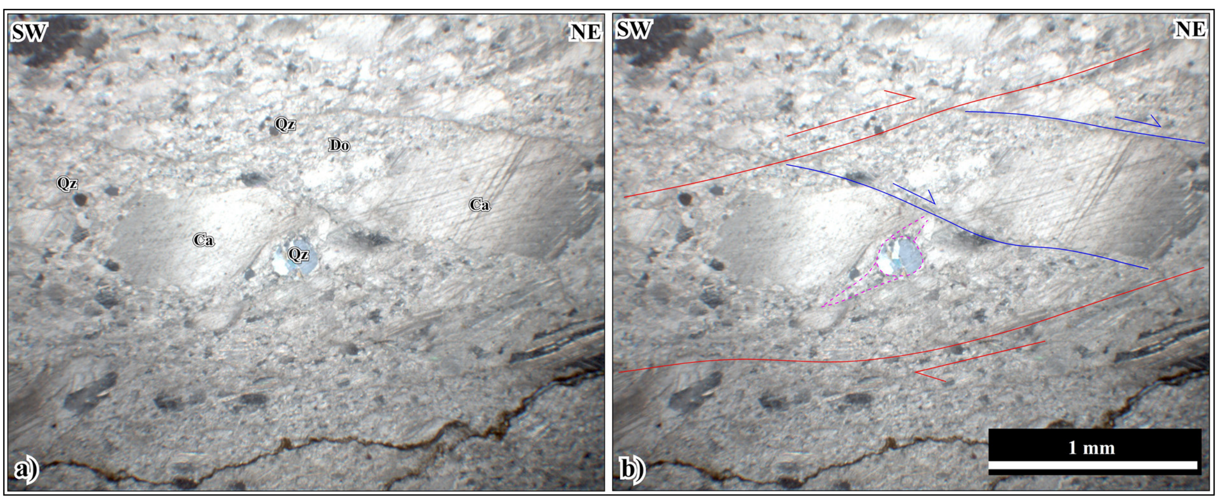

Figure 3- Oriented thin section photo from immediately under the Bursa detachment surface viewed in crossed polars; a) uninterpreted thin section (Qz: quartz, Ca: calcite, Do: dolomite), b) the overall shear zone is marked with red lines. In detail, the shear band type fragmented porphyroclast (i.e., displaced calcite porphyroclast -blue lines- interpreted after Passchier and Trouw, 2005; Figure 5.44), overprint the sigma type asymmetric porphyroclast (fuchia colour dotted lines) probably inherited from the earlier ductile stage.

In fact, the schistosity of the calcite-marble is tilted to the NE with a 30° dip angle (Figures 6 and 7). This slight NE dipping is observable throughout the southern UMCC and the contact with the underlying metagranite is nearly parallel to this schistosity (Figures 5a, 6, and 7). An oriented sample from the metagranite indicates a top-to-the northeast sense of shear. This might represent a granite intrusion into the ductile shear zone (Figure 8). The cross-section of the UMCC indicates that the deeper part of the

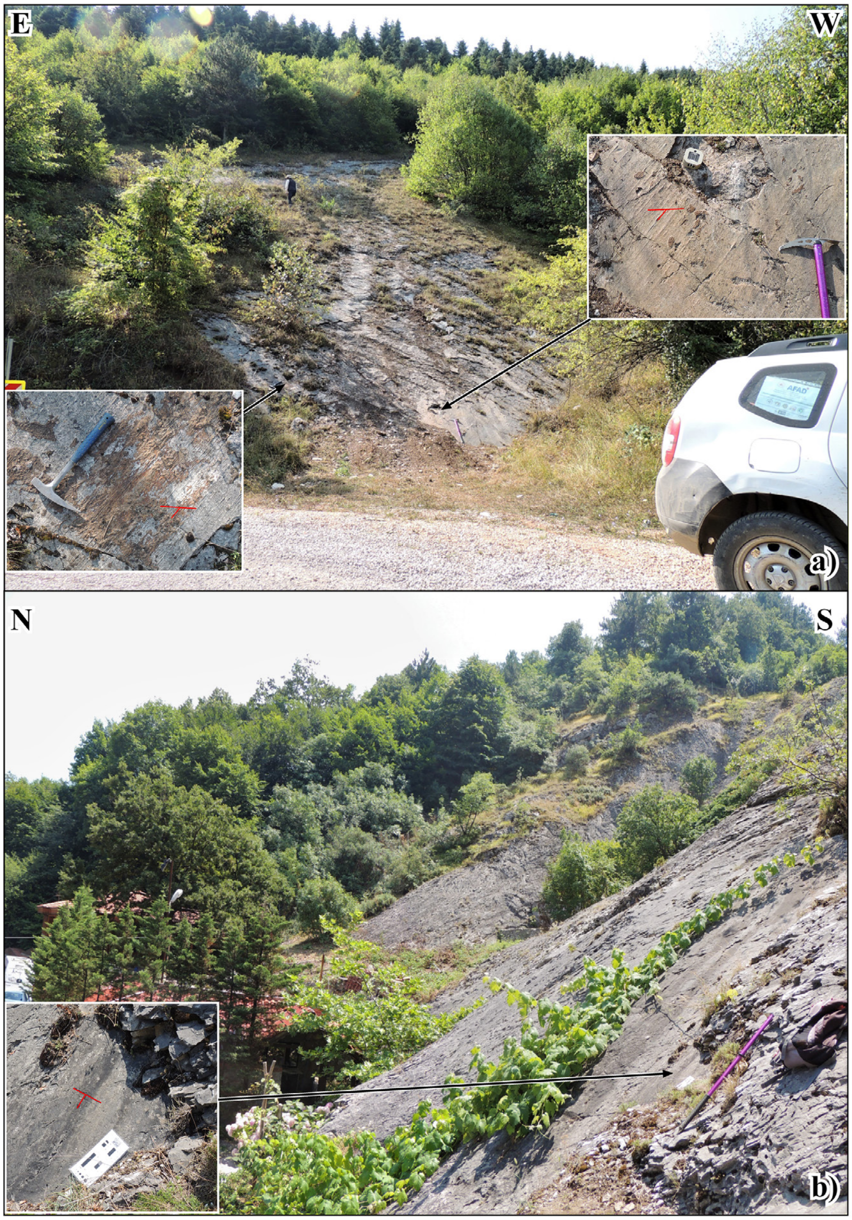

Figure 4- a) The Bursa detachment fault in the SE of Alaçam village. Insets show the oblique normal fault character of the detachment, b) the Bursa detachment in Saitabad village at Şelale location. Note that the angle of the detachment surface is getting lower towards the up. For locations, see Figure 1b. Inset indicates a close-up view of the pure normal sense of slip.

complex shows ductile shearing (metagranites) while the uppermost part shows brittle shearing along with the Bursa Detachment (Figure 1c). This overall structure strongly suggests that the Uludağ massif is an extensional metamorphic core complex (Figure 1c).

In the east of the UMCC, the İnegöl Neogene half-graben (Kaymakçı, 1991) contains several active faults. According to Emre et al. (2011*a, b*), the İnegöl and Oylat normal faults combined with the SF were considered as the elements of the EFZ by Okay et al. (2008) and Emre et al. (2018).

Our field observations, however, demonstrate that the NW-SE trending active fault segments in the İnegöl basin are nearly pure right-lateral strike-slip faults evidenced by kinematic data from the fault surfaces (Table 1).

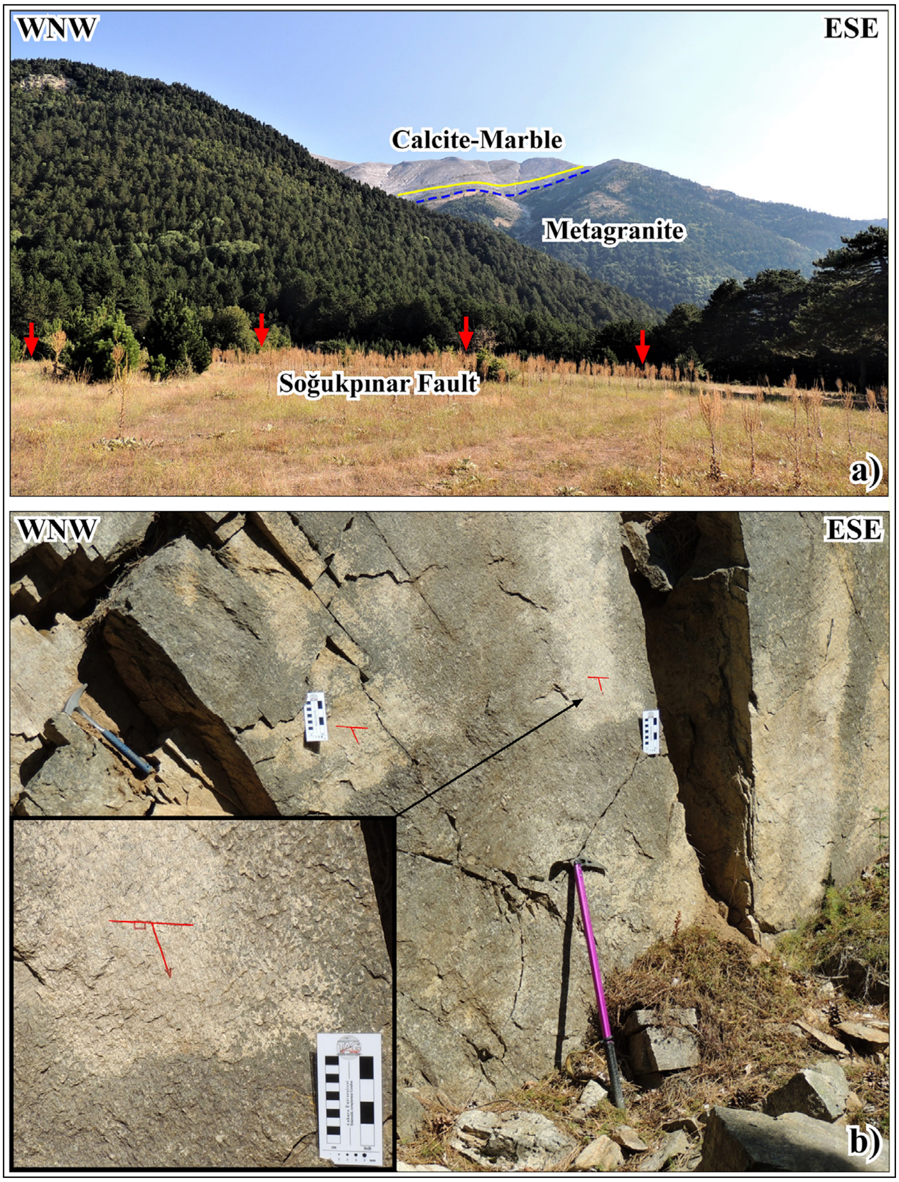

Figure 5- a) Morphological expression of the Soğukpınar normal fault. Red arrows indicate its location. The background of the photo shows the contact of calcite-marble and metagranite which is nearly parallel to the schistosities of calcite-marble dipping to NE. See Figure 1b for location, b) structural data shows normal fault character of the SF. Inset is the close-up view of the fault surface developed on metagranite.

For example, the Oylat-1 segment of the EFZ has a topographically distinct fault surface displaying right-lateral strike-slip kinematics data the entrance of the Oylat cave (Figures 1 and 9a).

The Doğanyurdu segment cuts the Neogene sedimentary units indicating that the EFZ post-dates the deposits of the Neogene İnegöl basin (Figures 1 and 9b). The Cerrah segments are located west of İnegöl and exhibit well-developed fault surfaces displaying nearly pure strike-slip kinematics (Figures 1 and 9c). The Babasultan segment passes close to the Bursa Detachment and provides a significant fault surface NE of Sayfiye indicating its right-lateral strike-slip character (Figures 1 and 9d). The overall position of the EFZ is composed of the NW-SE trending en-echelon right-lateral strike-slip segments that reach the north of the UMCC. In other words, the

Table 1- Fault kinematic data obtained from the field. Kinematic axes have been determined by using FaultKin software (Marrett and Allmendinger, 1990; Allmendinger et al., 2012). N: Normal, RL: Right lateral, LL: Left lateral. See Figure 1b for graphical representations.

			Field data					Kinematic (strain) axes					
#	Latitude (°N)	Longitude (°E)	Fault plane		Striae		Slip	S1		S2		S3	
			Strike (°)	Dip (°)	Trend (°)	Plunge (°)		Trend (°)	Pl. (°)	Trend (°)	Pl. (°)	Trend (°)	Pl. (°)
I	40.11214	29.28819	290	30	20	30	N	195	15	285	3	24	75
			275	32	12	32	N						
			279	29	16	29	N						
			280	30	18	30	N						
II	40.11334	29.30464	240	26	13	20	N	180	19	277	19	49	63
			250	30	19	24	N						
			238	37	14	27	N						
III	40.14619	29.23621	305	53	7	49	N	22	6	114	14	269	74
IV	40.14817	29.22592	295	30	25	30	N	205	15	295	0	25	75
V	40.06108	29.17085	104	89	106	67	N	174	36	290	31	49	39
			115	88	118	60	N						
			110	88	113	53	N						
			115	88	118	54	N						
VI	39.94315	29.59160	290	85	109	13	RL	64	17	274	71	157	9
			105	80	110	27	RL						
			105	72	116	30	RL						
			95	71	108	33	RL						
			290	81	109	8	RL						
			115	79	117	8	RL						
			300	87	119	10	RL						
VII	40.06526	29.44241	300	78	118	10	RL	198	1	107	44	290	46
			300	65	300	0	RL						
			334	81	153	8	RL						
VIII	40.11444	29.34139	305	77	120	19	RL	77	4	337	66	169	23
IX	39.98197	29.45140	330	42	345	13	RL	275	33	83	57	181	5
			283	87	287	50	RL						
			315	57	322	10	RL						
			320	67	326	14	RL						
X	40.17048	29.11797	278	35	350	34	N	198	9	107	3	2	80
			305	35	41	35	N						
XI	40.16811	29.09215	277	75	87	34	N	29	3	297	39	123	51
			250	50	37	33	N						
XII	40.17882	29.04836	73	78	248	22	N	13	9	245	76	104	11
			57	85	59	17	N						
			225	88	43	45	N						

Table 1- Continued.

XIII	40.18644	29.04205	310	55	82	47	N	233	9	324	5	84	79
			306	20	39	20	N						
XIV	40.11200	29.07727	139	82	143	25	LL	16	1	284	70	107	20
			143	82	146	20	LL						
			160	65	331	18	LL						
			145	63	311	25	LL						
			160	58	332	13	LL						
			148	80	196	77	LL						
			160	75	168	29	LL						
			155	80	159	20	LL						
XV	40.10759	29.07618	120	51	210	51	N	210	6	300	0	30	84
XVI	40.13230	29.02794	105	55	165	51	N	171	19	268	21	43	62
			95	80	112	59	N						
XVII	40.13995	29.02483	100	75	236	69	N	219	15	124	18	346	66
			98	80	252	68	N						
			115	63	236	59	N						
			110	68	244	61	N						
			135	45	260	39	N						
			165	55	262	55	N						
			60	60	169	59	N						
			115	53	254	41	N						
XVIII	40.10912	29.01376	150	61	324	10	LL	9	28	216	59	105	12
			145	57	321	7	LL						
			155	66	328	15	LL						
XIX	40.10754	29.00333	50	55	80	35	N	151	10	242	6	2	79
			83	52	176	52	N						
			70	65	162	65	N						
			60	45	150	45	N						
			65	53	160	53	N						

EFZ around İnegöl has a strike-slip character and there is no genetic relationship with the SF in the south of UMCC.

These observations also confirm the strike-slip kinematics of the EFZ at its northwestern edge as also demonstrated previously in the Eskişehir settlement and its southeastern edge (Seyitoğlu et al., 2015; Esat et al., 2016).

3. Discussion

Although further studies are needed to demonstrate ductile to brittle transition along with the Bursa Detachment in detail, available field observations presented above allow determination of the Uludağ Massif as an extensional metamorphic core complex.

In the north of UMMC, the spectacular outcrops of the Bursa detachment fault indicate top-to-the

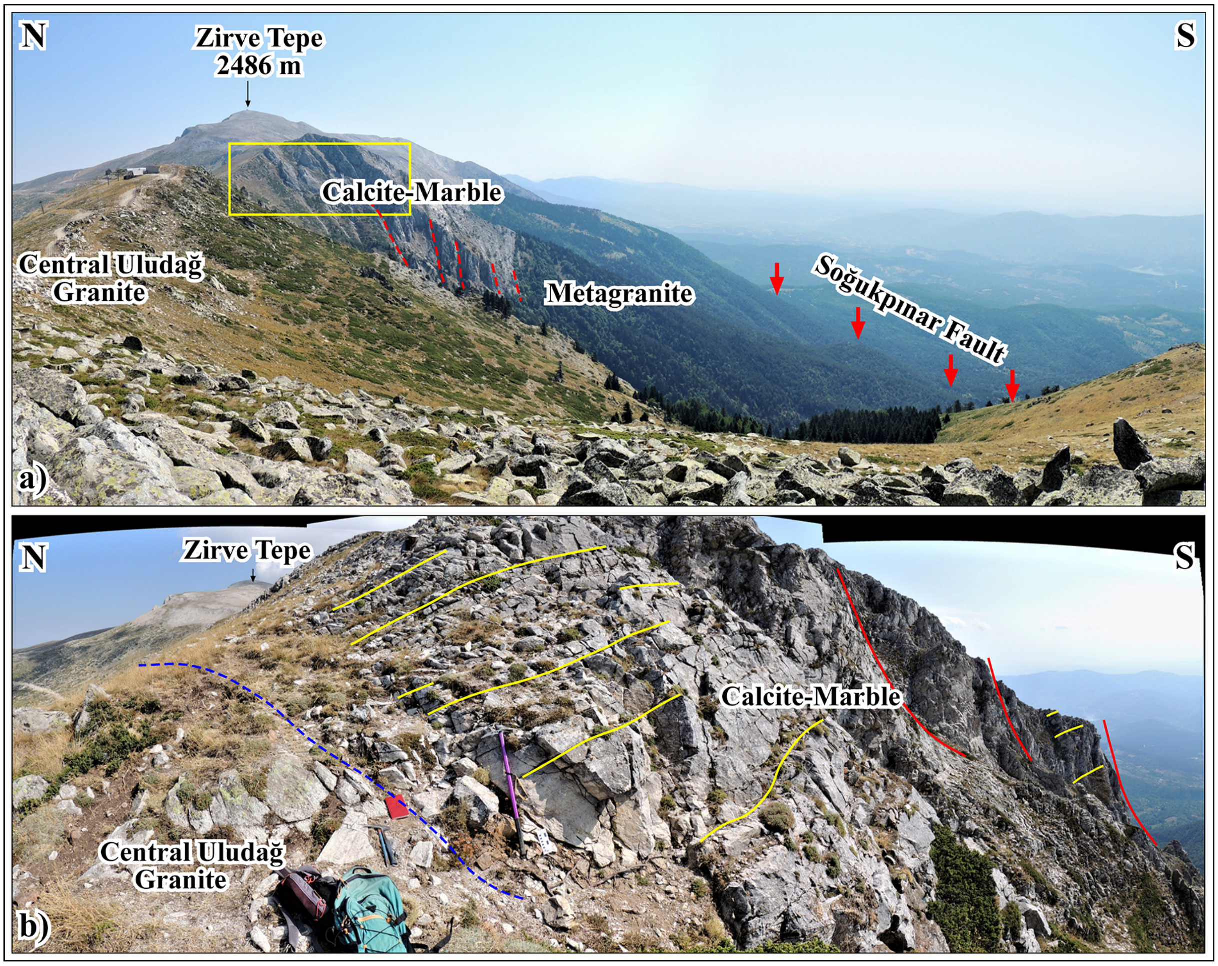

Figure 6- a) Southern margin of Uludağ and the position of Soğukpınar normal fault (red arrows). Broken red lines indicate synthetic fractures of the SF which creates a misperception of the vertical contact between calcite-marble and metagranite. Yellow rectangle shows the location of Figure 6b. For information about the location, see Figure 1b, b) a panoramic close-up view of calcite-marble indicating its schistosity slightly dipping to NE (yellow lines) and synthetic fractures of the Soğukpınar normal fault (red lines) in the footwall. The blue dashed line is the contact between Central Uludağ Granite and calcite-marble. For the location, see Figure 6a.

Figure 7- In the south of Uludağ, NE dipping schistosity of the calcite-marble (yellow lines) and the contact with the metagranite which is nearly parallel to the schistosity (blue and white dashed lines); a) a view from the Aras Dere valley to Zirve Tepe and b) a view from Kalemlik to Kuşaklıkaya Tepe. For locations, see Figure 1b.

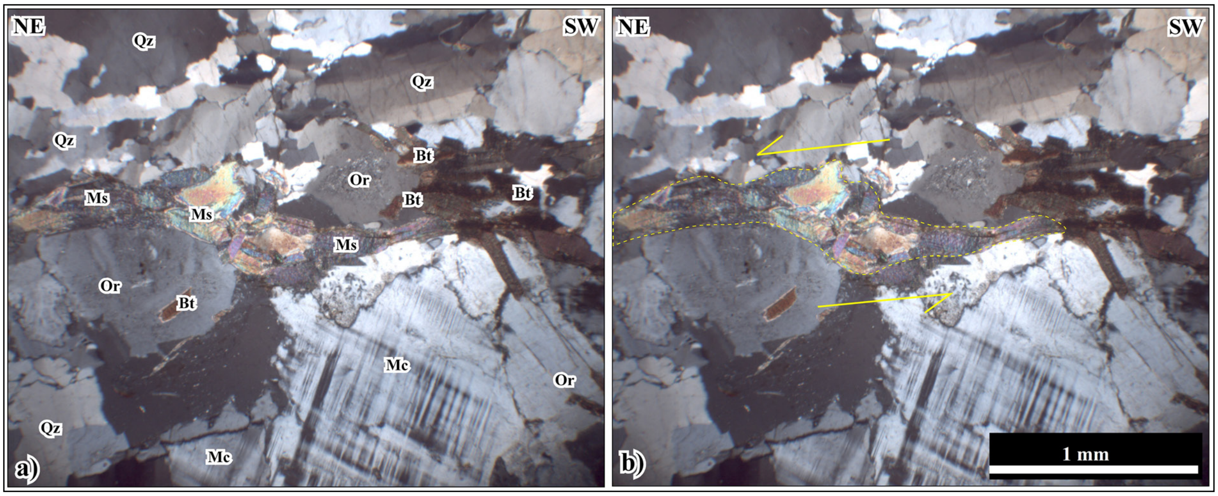

Figure 8- Oriented thin section photos from the meta-granite viewed on crossed polars; a) main minerals are quartz (Qz), orthoclase (Or), muscovite (Ms), biotite (Bi), and microcline (Mc) and b) muscovites indicate top-to-the NE sense of shear. For the location of the sample, see Figure 1b.

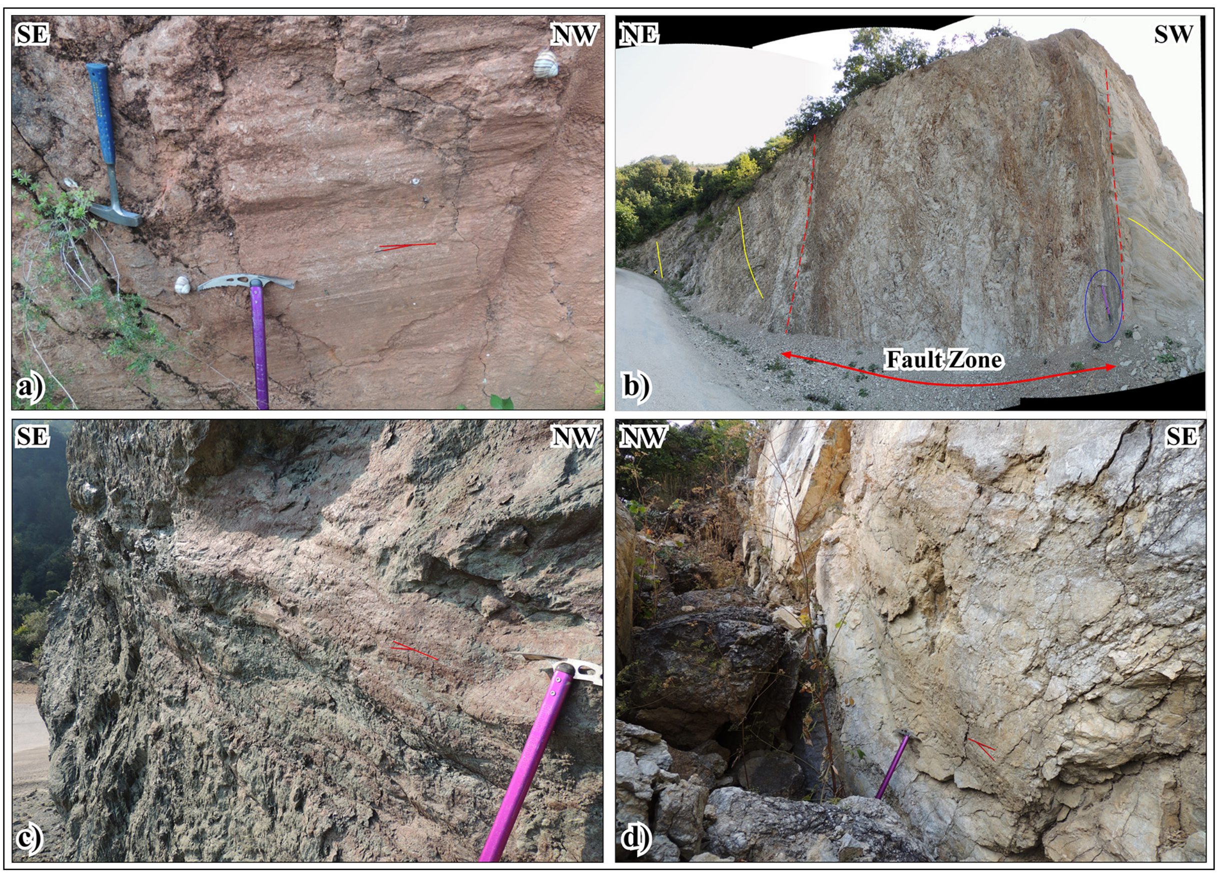

Figure 9- a) The close-up view of the fault surface having slicken-lines in the Oylat-1 segment of Eskişehir Fault Zone near the entrance of Oylat cave, b) panoramic view of the Doğanyurdu segment of Eskişehir Fault Zone. The Doğanyurdu segment is an NW- SE trending right-lateral strike-slip fault that clearly cuts the Neogene İnegöl basin. Yellow lines are the bedding of sedimentary unit, c) nearly pure right-lateral strike-slip data obtained from the fault surface in the NW-SE trending Cerrah-1 segment of Eskişehir Fault Zone at the SW of Cerrah village and d) close-up view of the fault surface indicating right-lateral strike-slip movement in the northwestern edge of the Eskişehir Fault Zone, the Babasultan segment at the NE of Sayfiye village. See Figure 1b for locations.

north/northeast normal sense of shear which were previously evaluated as thrust (Ketin, 1984; Şengör and Cin, 1988). Except for one sample, the AFT ages of Okay et al. (2008) are getting younger towards the detachment surface that supports the extensional nature of the Bursa Detachment Fault.

In the south of UMMC, the SF and its western counterparts are normal faults and there is no fault attributable to the right-lateral strike-slip EFZ. Moreover, the near-vertical contact between calcite-marbles and underlying metagranite is a misperception (Okay et al., 2008; Topuz and Okay, 2017) due to the well-developed synthetic faults and fractures in the footwall of a normal fault SF, thus the claim of an Oligocene ductile shear zone exhumation related to the right-lateral EFZ (Okay et al., 2008) is doubtful. Instead, a granitic intrusion might have intruded the extensional ductile shear zone creating the metagranite of the UMCC while the upper crust was under brittle conditions when the Bursa Detachment was active between the rocks of Series-A and Series-B. Available isotopic dating provided by Okay et al. (2008) indicates that extensional ductile shear must be around 38-27 Ma and this should be ceased around 27 Ma as demonstrated by the age of post-kinematic Central Uludağ Granite. It is not clear, however, whether the movement on the Bursa Detachment Fault is continuing after 27 Ma. The published AFT ages (Okay et al., 2008) indicate that Uludağ continues to uplift until 9 Ma, but this could be related to the other younger tectonic events around UMCC. Further systematic sampling and isotopic dating are necessary to clarify the uplift history of UMCC. In this stage, under the light of our field observations, it can be said that the extensional exhumation model proposed in this paper is a more convincing explanation compared to the model of Okay et al. (2008) since other extensional core complexes exist around the UMCC (see Seyitoğlu and Işık, 2015; Figure 5). One of them is the Kazdağ Core Complex which was first exhumed along with the Şelale Detachment with a top-to-the-north sense of shear and followed by top-to-the-south movements of Yeşilyurt Detachment controlling the accumulation of the Neogene sediments (Kurt et al., 2010). Another example is the Çataldağ Core Complex (Kamacı and Altunkaynak, 2019) exhumed along with the Çataldağ Detachment with a top-to-the-north sense of shear. All these features and close isotopic ages indicate that the asymmetric Menderes Core Complex (Seyitoğlu et al., 2004; Seyitoğlu and Işık, 2015), as well as the other core complexes in NW Anatolia (the Kazdağ, Çataldağ, and Uludağ), are genetically linked. This allows for further speculation that the NW continuation of the Bursa Detachment can be seen the north of Marmara Island (Aksoy, 1996) where a low-angle detachment is visible in seismic reflection sections under the Marmara Sea (Okay et al., 1999; Figure 10). If this assumption is correct, then the Thrace basin could be classified as a supra-detachment basin.

4. Results

The Bursa Fault is a low-angle normal fault and shows a detachment character developed on the dolomite-marble which is the uppermost rock unit of the Series-A (Uludağ Group). The upper plate rocks of the Bursa Detachment are composed of mica schist, phyllite, calcite-marble, epidote and glaucophane schist, serpentinite, and greenschist of the Series-B (Karakaya Complex). Spectacular outcrops of the Bursa Detachment located on the northern margin of the UMCC occur south of Alaçam village and Saitabad. They provide kinematic data of the top-to-the north/northeast sense of shear. The deeper sections are represented by the Oligocene metagranite at the southern UMCC interpreted as a syntectonic granite entering a ductile shear zone which is slightly dipping to the north below the calcite-marble at the Uludağ peak. All these features indicate that the UMCC is a typical metamorphic core complex similar to the Menderes, Kazdağ, and Çataldağ core complexes. The deeper sections of the UMCC are exposed due to the younger high-angle normal fault to the south of the UMCC. The normal SF cannot be attributed to the right-lateral EFZ because all segments of the EFZ to the east of the UMCC show a strike-slip character and run towards the north of the UMCC. Therefore, the interpretation of Okay et al. (2008) explaining the exhumation of the UMCC along the ductile shear zone of the EFZ should be re-examined. This paper presents an interpretation based on field observations regarding the nature of UMCC, further studies are necessary to clarify conflicting arguments.

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