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Research Article

Structural Interpretation and Tectonostratigraphy of High-Pressure Low-Temperature Blueschist Facies Rocks near Orhaneli, Bursa Province, Western Türkiye

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ABSTRACT

The Izmir-Ankara suture, a Neo-Tethyan collision zone between the Sakarya microcontinent (hanging wall) to the north and the Anatolide-Tauride block (footwall) to the south, including blueschist facies rocks near Dağgüney village, Orhaneli in Bursa, Türkiye, formed during the mid-Cretaceous. This study aims to better understand the tectonostratigraphy and the structural evolution of the high-pressure low-temperature (HP-LT) rocks and their surroundings by examining data obtained from detailed geological mapping near Dağgüney, Orhaneli, Bursa. There are three main tectonostratigraphic units including HP-LT rocks, mélange, and subophiolitic peridotites. Extensive exposures of lawsonite blueschist, graphitic mica schist, white mica schist, and marble there indicate HP-LT conditions of formation. In addition, the Tavşanlı Zone contains two other rock sequences of significance to subduction-related evolution. These are mélange, considered to have formed in an accretionary complex that includes metamorphosed radiolarian chert, greenstone, meta-volcanic-tuff, amphibolite, white-mica-schist, blueschist and serpentinite, peridotite which contains dunite, harzburgite, and gabbro, interpreted to have formed as the oceanic lithosphere. Metamorphic foliation, defined by compositional layering and schistosity, trends generally ENE and dips gently northerly. Metamorphic lineation, defined by elongate calcite and sodic amphibole grains, trends WSW and gently plunges. Mesoscopic isoclinal folds are common in the blueschist facies rocks. The majority of the folds trend NNE-SSW and plunge gently eastward in the HP-LT rocks. There are at least four major fault types based on age, cross-cutting relationships, and orientation. Blueschist facies mineral assemblages were preserved in the HP-LT rocks, thus a rapid exhumation mechanism of buoyancy-driven flow is interpreted to have taken place within the subduction channel. The presence of blueschist, amphibolite, and white mica schist within the mélange suggests that exhumation occurred during subduction.

Keywords: *Lawsonite blueschist, Structural Geology, Tavşanlı Zone, Tectonostratigraphy*

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Orhaneli, Bursa İli, Batı Türkiye Yakınlarındaki Yüksek Basınçlı Düşük Sıcaklıklı Mavişist Fasiyesli Kayaçların Yapısal Yorumlanması ve Tektonostratigrafisi

ÖZET

Kuzeyde Sakarya mikrokıtası (tavan bloğu) ile güneyde Anatolid-Torid bloğu (taban bloğu) arasında bir Neo-Tetis çarpışma bölgesi olan İzmir-Ankara sütur hattı, Bursa, Orhaneli, Dağgüney köyü yakınlarındaki mavişist fasiyes kayaları dahil, orta Kretase döneminde oluşmuştur. Bu çalışma, Bursa, Orhaneli, Dağgüney yakınlarındaki ayrıntılı jeolojik haritalamadan elde edilen verileri inceleyerek yüksek basınç düşük sıcaklık (HP-LT) kayaçlarının ve çevrelerinin tektonostratigrafisini ve yapısal evrimini daha iyi anlamayı amaçlamaktadır. Çalışma alanında (HP-LT) kayaçları, melanj ve subofiyolitik peridotitleri içeren üç ana tektonostratigrafik birim vardır. Lavsonit mavişist, grafitli mikaşist, beyaz mikaşist ve mermerin burada yoğun şekilde mostra vermesi, HP-LT oluşum koşullarına işaret etmektedir. Buna ek olarak, Tavşanlı Zonu dalma-batma-ilişkili etkileşim açısından önem taşıyan iki diğer kayaç birimini daha içermektedir. Bunlar, metamorizmaya uğramış radyolarit, greenstone, meta-volkanik-tüf, amfibolit, beyaz-mikaşist, mavişist ve serpantinit içeren melanj, ve okyanusal litosfer olarak oluştuğu düşünülen dünit, harzburjit ve gabro içeren peridotitlerdir. Bileşimsel katmanlanma ve şistozite ile tanımlanan metamorfik yapraklanma, genellikle DKD doğrultulu ve hafifçe kuzeye doğru eğimlidir. Yönlenmiş kalsit ve sodik amfibol mineralleri tarafından tanımlanan metamorfik lineasyon, BGB doğrultulu ve düşük açı ile dalım yapmaktadır. Mavişist fasiyes kayalarında mezoskopik izoklinal kıvrımlar yaygındır. Kıvrımların çoğu KKD-GGB doğrultulu ve doğuya doğru düşük açılarla dalmaktadır. Çalışma alanında yaşa, kesme ilişkisine ve doğrultu atımına bağlı olarak en az dört ana fay tipi tespit edilmiştir. HP-LT kayaçlarında mavişist fasiyes mineral topluluklarının kimyasal özellikleri korunmuştur, bu nedenle mavişistlerin yüzeylemesinin dalma-batma kanalı içinde kaldırma kuvveti kaynaklı v hızlı bir mekanizmayla gerçekleştiği yorumlanmıştır. Ayrıca melanj içinde mavişist, amfibolit ve beyaz mikaşist bulunması, yüzeylemenin dalma-batma sırasında meydana geldiğini açıklamaktadır.

Anahtar Kelimeler: *Lavsonit mavişist, Yapısal Jeoloji, Tavşanlı Zonu, Tektonostratigrafi*

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I. INTRODUCTION

The study area is located approximately 60 km south of Bursa in northwestern Anatolia, the Asian portion of Türkiye. It lies in the north wall of the Kocasu River adjacent to Dağgüney village, 13.6 km northwest of Orhaneli, Bursa, Türkiye (Figures 1 and 2), and is a part of the Tavşanlı tectonic zone. The east-trending Tavşanlı Zone extends across western and central Türkiye as one of the widest and best-preserved high-pressure (blueschist facies) belts in the world [1]. The zone, with a maximum width of 120 km in the west and an average width of 50-60 km elsewhere, extends for 280 km along the northern margin of the Anatolide-Tauride block. The Tavşanlı Zone, which consists of meta-sedimentary and meta-volcanic rocks, experienced subduction metamorphism which overprints these rocks with regional high-pressure low-temperature (HP-LT) blueschist facies metamorphism [2, 3, 4] in the Late Cretaceous (88-80 Ma) [5, 6, 7]. HP-LT metamorphism, also known as blueschist metamorphism, is a type of metamorphism that occurs under specific geologic conditions. It typically occurs in subduction zones. The name "blueschist" refers to the blue-colored minerals that are commonly found in rocks undergoing this type of metamorphism, such as glaucophane and lawsonite. These minerals form under the HP-LT conditions of blueschist metamorphism and are indicative of the specific conditions under which this type of metamorphism occurs. Sherlock et al. [6], reported the age of the blueschist metamorphism, based on Rb/Sr phengite dating, as Campanian (80Ma), and these rocks were buried to a depth of 80km [5]. Blueschists in the Sivrihisar, Eskişehir area, in the eastern Tavşanlı Zone, include Ar/Ar phengite dates that range from 88 to 81 Ma [7]. An upper age limit of 53 Ma was given for the high-pressure low-temperature (HP-LT) metamorphism for the Sivrihisar region [6] based on the age of granodiorite stocks that intrudes HP-LT rocks around Orhaneli region [8]. This would indicate that the HP-LT rocks around Orhaneli region reached upper crustal levels by the Early Eocene [1, 4].

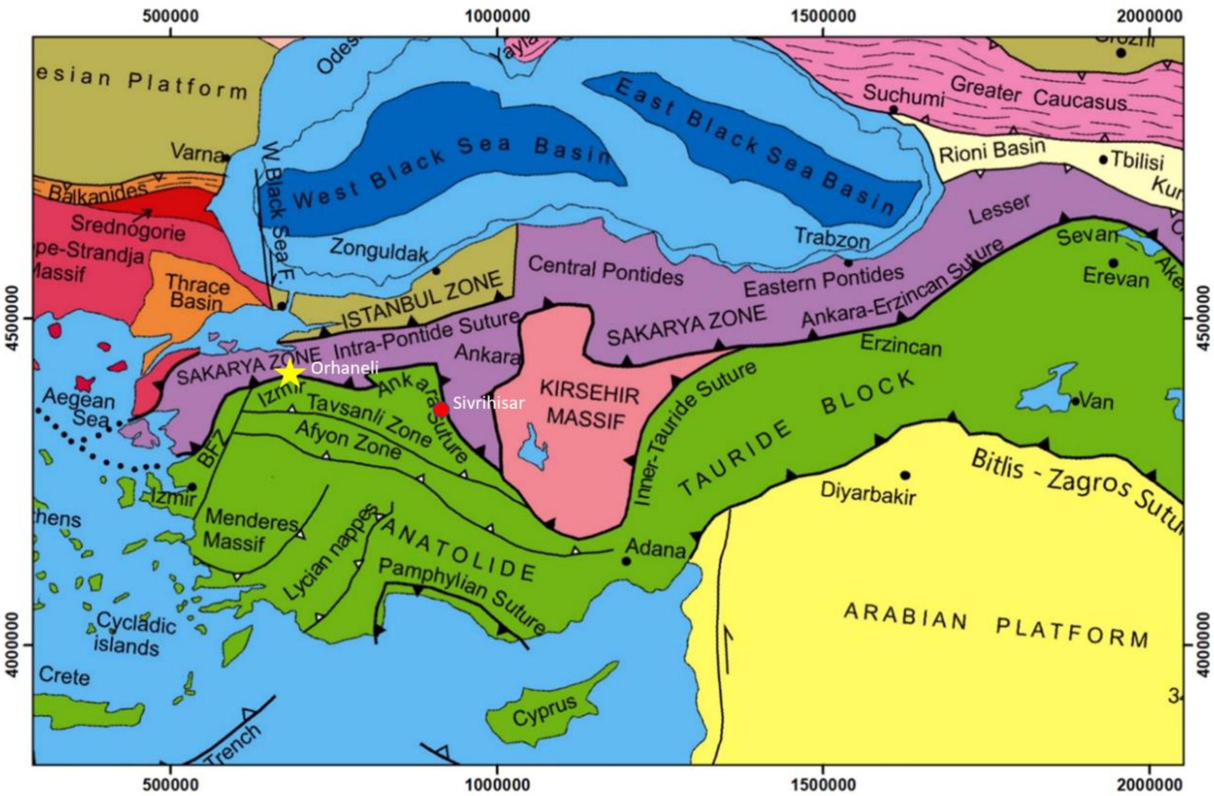

Figure 1. Tectonic Map of Türkiye and adjacent areas showing the major sutures and continental blocks [9]. The study area is marked by a yellow star (UTM Zone 35N, European Datum 1979).

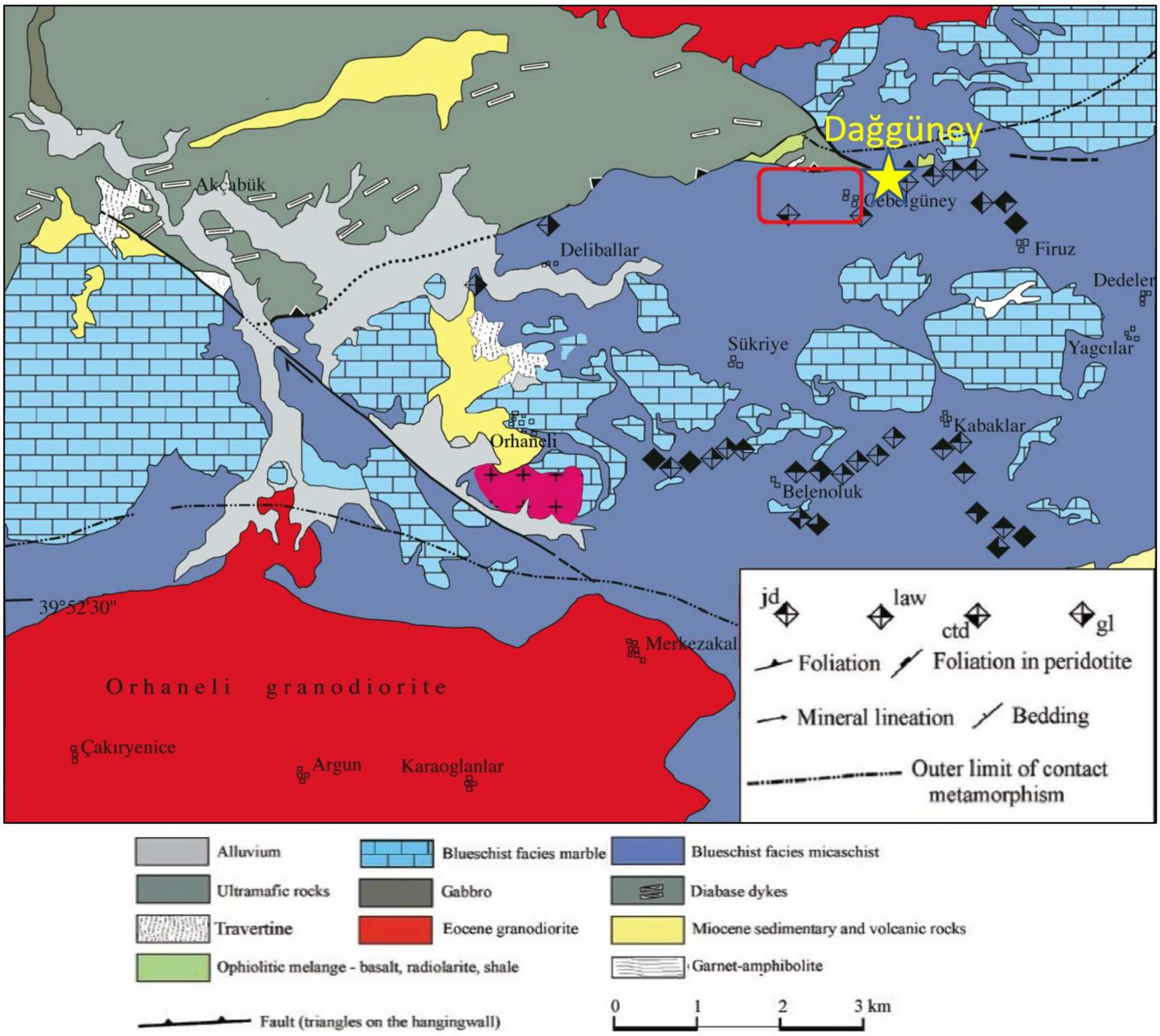

Figure 2. *Geologic map of the Dağgüney, Orhaneli area [2]. The study area is marked by the red box.*

Micaschists (white mica schist and graphitic mica schist) of the Dağgüney area, have a mineral assemblage of jadeite + chloritoid + lawsonite + glaucophane + quartz + phengite + graphite, and based on this mineral assemblage, pressure-temperature (P-T) conditions of meta-sedimentary rocks (micaschists) of the Orhaneli area was 24±3 kbar and 430±30°C [2,10]. P-T conditions of metamorphism varied along the strike of the western Tavşanlı Zone. In the western portion, they are reported as 15-16 kbar and 520°C [2], in Sivrihisar region as 22-24 kb and 520°C [11], and as 9-11 kbar and 375-400°C in the Konya-Altintekin region (southeastern Tavşanlı Zone) [12].

High-pressure low-temperature (HP-LT) rocks of the Tavşanlı Zone were partly exposed by the latest Cretaceous, Maastrichtian [4] before the Paleocene continent-continent collision, as demonstrated by blueschist debris in the latest Cretaceous clastic strata in the Sakarya Zone, which is on the north of the Tavşanlı Zone. According to Okay [4], the Lower Eocene marine deposits in the Tavşanlı Zone show that by the end of the Paleocene, the Orhaneli Group (which is present in the study area) was on the surface or very close to the surface.

Subduction and exhumation mechanisms of HP-LT blueschist facies rocks have been studied for years, but the exhumation mechanism of the HP-LT rocks is still controversial. The Tavşanlı Zone provides a spectacularly well-exposed blueschist belt that is similar to HP-LT metamorphic belts in Oman [13, 14, 15], in the Cyclades of the Aegean Sea [16, 17], in terms of stratigraphy, petrology, and geochronology.

This field-based study aims to better understand the tectonostratigraphy, the structural evolution, and the exhumation mechanisms of the HP-LT rocks and their surroundings by examining data obtained from detailed geological mapping and tectonostratigraphic field measurements from a unique study area that clearly reveals the tectonic relationships between the accretionary complex and the HP-LT blueschist facies rocks.

II. GEOLOGICAL SETTING

During the Alpine orogeny in the Early Paleogene, continental fragments were juxtaposed by continent-to-continent collision after Tethyan oceanic lithospheres in between were eliminated by east-west trending and northward-dipping subduction zones [18, 19]. The study area lies at the northern margin of the Anatolide-Tauride micro-continent along the Late Cretaceous-Paleocene suture with the Sakarya micro-continent. The area is part of the Tavşanlı zone of high-pressure metamorphism. The Tavşanlı zone is the northern margin of the Anatolide/Tauride block. On the north it is separated from the Sakarya Microcontinent by the Izmir-Ankara suture (Figure 1) that also separates Laurasia and Gondwana mega-continents: on the south is in tectonic contact with the underlying Afyon zone: on the west is in tectonic contact with Bornava Flysc. The Izmir-Ankara suture, including blueschist facies rocks near Orhaneli in Bursa Province, Türkiye, formed during the mid-Cretaceous [2]. Extensive exposures of lawsonite blueschist, graphitic mica schist, white mica schist, and marble there indicate high-pressure and low-temperature conditions of formation [3, 4, 20] in the Late Cretaceous (88-80 Ma) [5, 6, 7].

In addition to the high-pressure low-temperature (HP-LT) blueschist facies rocks, a mélange of accretionary complex crops out in multiple locations within the study area and across the region and tectonically overlies the blueschist facies rocks. The mélange consists of metamorphosed basalt, metamorphosed radiolarian chert (quartzite), metamorphosed tuff (phyllite), greenstone, knockers of amphibolites, blueschist, serpentinite, and metamorphosed lapilli tuff; possible pillow lavas are also present. Studies show that the mélange of the accretionary complex has undergone low-grade metamorphism of $T < 200°C$ and $P \sim 4\text{-}7$ kb [21]. The age of the metamorphism is unknown.

In the Orhaneli region, a large slab of peridotite (the Burhan peridotite) tectonically overlies mélange, or the blueschist facies rocks, and is Albian in age [5]. Within the study area, peridotite consists mainly of dunite, harzburgite, and strongly sheared and weathered serpentinite. Hydrothermal silicic alteration of peridotite formed listvenite along the fault zones and the serpentinite margins, but the peridotite shows no sign of regional metamorphism. The peridotite slab is cut by diabase dikes which generally trend E-W also present within the study area.

Low-grade meta-limestone, which is part of the mélange, conformably overlies meta-basalt within the accretionary complex. Low-grade meta-limestones are interbedded with cherts and are adjacent to jasper-silica or jasperoid. Jaspereoid silica is part of the meta-limestone as it is the possible hydrothermal replacement product of the low-grade meta-limestone.

In the northeast portion of the study area, along the high-angle fault zone, a series of granodioritic intrusions, which generally strike NW-SE, are present. These Early-Middle Eocene plutons [5] intrude blueschist facies rocks, mélange, and the peridotite within the study area.

III. METHODS

A. GEOLOGIC MAPPING and FIELDWORK

Two detailed geological maps were produced. The first map, at a scale of 1:6,250, represents the geology of the entire study area. The second map, at a scale of 1:500, was prepared for the rare contact exposure between the high-pressure low-temperature (HP-LT) blueschist facies rocks and the mélange of an accretionary complex (Figure 3). In addition to the geological maps, two tectonostratigraphic columns were prepared. The first column represents the tectonostratigraphic relationships between the HP-LT rocks and the mélange of an accretionary complex. The second column represents the interbedded tectonostratigraphic relationship between the low-grade meta-limestones and cherts.

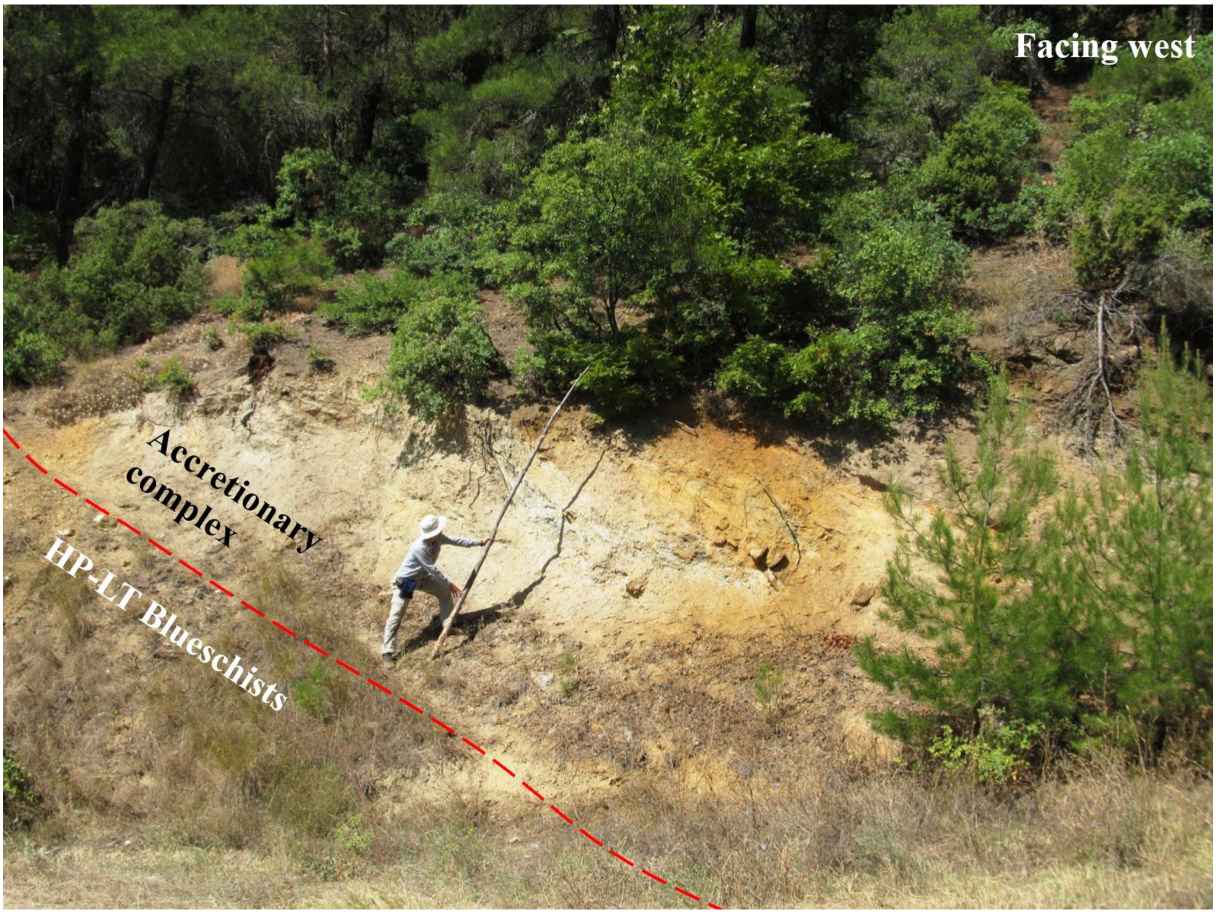

Figure 3*. The photograph showing the contact between the HP blueschist rocks and a zone of highly sheared serpentinite forming the base of a section of mélange of accretionary complex. Red dashes for the contact (Stick length = 5 m). UTM Location: 4423837N – 674130E.*

Geologic contacts were drawn on a topographic map and precise locations were obtained by a handheld Garmin GPS unit in European-Datum-1979, UTM-Zone-35N. In certain areas, where vegetation, steep terrain, or inaccessible private land make mapping difficult, geology and structures were approximated and/or inferred based on the surrounding geological evidence. In addition, numerous structural data, which include metamorphic foliation, mineral lineation, fold axis, and fault planes, were measured by right-hand rule using a Brunton compass and later plotted on Allmendinger’s stereonet program. Finally, geological maps and tectonostratigraphic columns were digitized in ESRI’s ArcMap 10.0 [22] with the representative UTM coordinate system and datum. Additionally, two cross-sections were drawn and digitized in ArcMap 10.0 based on the geological map and the data observed from the structural measurements. Section A-A’ trends N-S and section B-B’ trends NW-SE.

IV. RESULTS

A. GEOLOGICAL MAPS

A detailed geologic map at a scale of 1:6,250 shows the tectonic relationship and the contacts between the oceanic lithosphere (Burhan peridotite), the accretionary complex (mélange), and the underlying high-pressure low-temperature (HP-LT) metamorphic rocks near the village of Dağgüney (Figure 4).

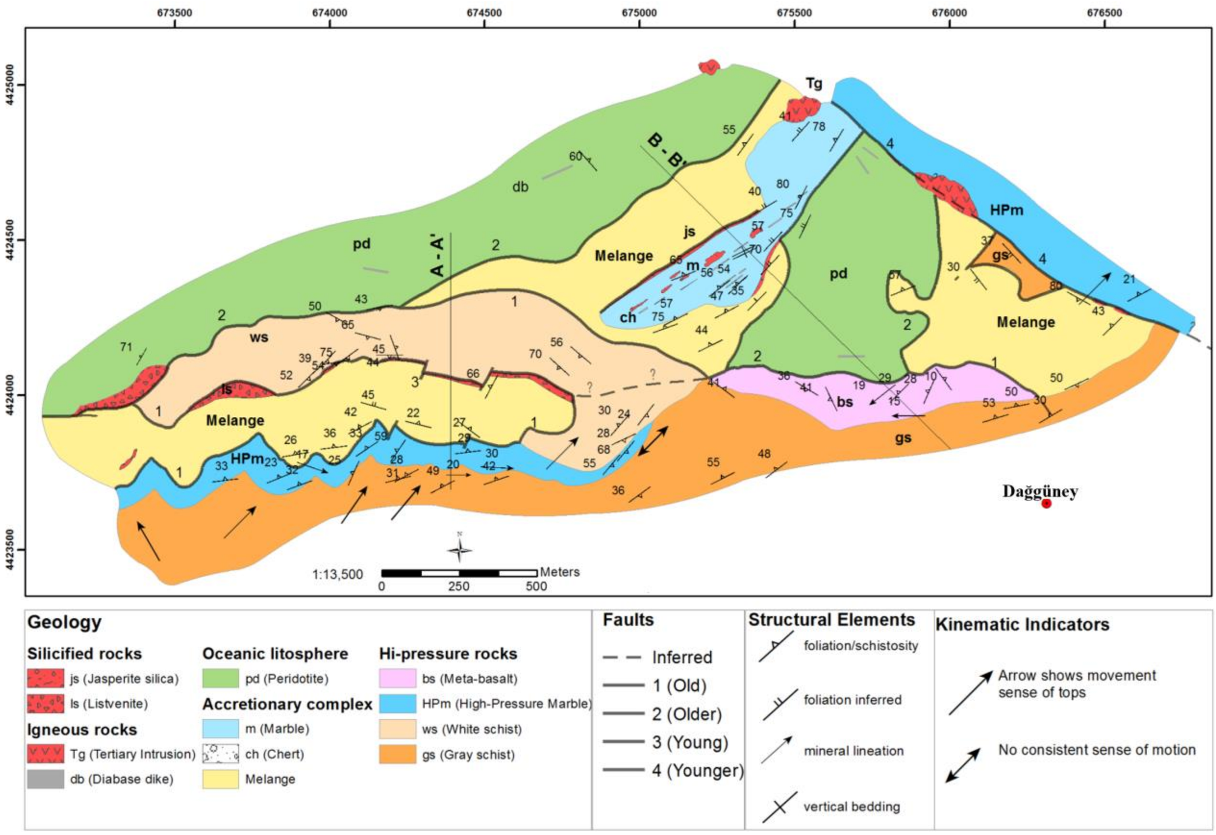

***Figure 4**. Geologic map of Dağgüney showing the tectonic relationship and the contacts between the oceanic lithosphere, accretionary complex and the HP/LT blueschist facies rocks.*

The peridotite unit tectonically overlies both the accretionary complex and the HP-LT blueschist facies rocks and consists of dunite, harzburgite, and minor serpentinite. Orange-colored listvenite, a silicified hydrothermal alteration product of peridotite, occurs locally along the contact with the underlying units. East-west trending diabase dikes cut the peridotite units. Northwest-southeast trending Tertiary plutons mapped as granodiorite, intrude the peridotites and the HP-LT blueschist rocks. The thickness of the peridotite was reported as 2 kilometers [5, 23].

Another detailed geological map was prepared at a 1:500 scale that illustrates the tectonic relationships at the significant contact between the accretionary complex and the HP-LT blueschist facies rocks (Figure 5). This is the only location within the study area where one can observe an actual contact between the accretionary complex and the HP-LT blueschist facies rocks (UTM Location: 4423837N – 674130E).

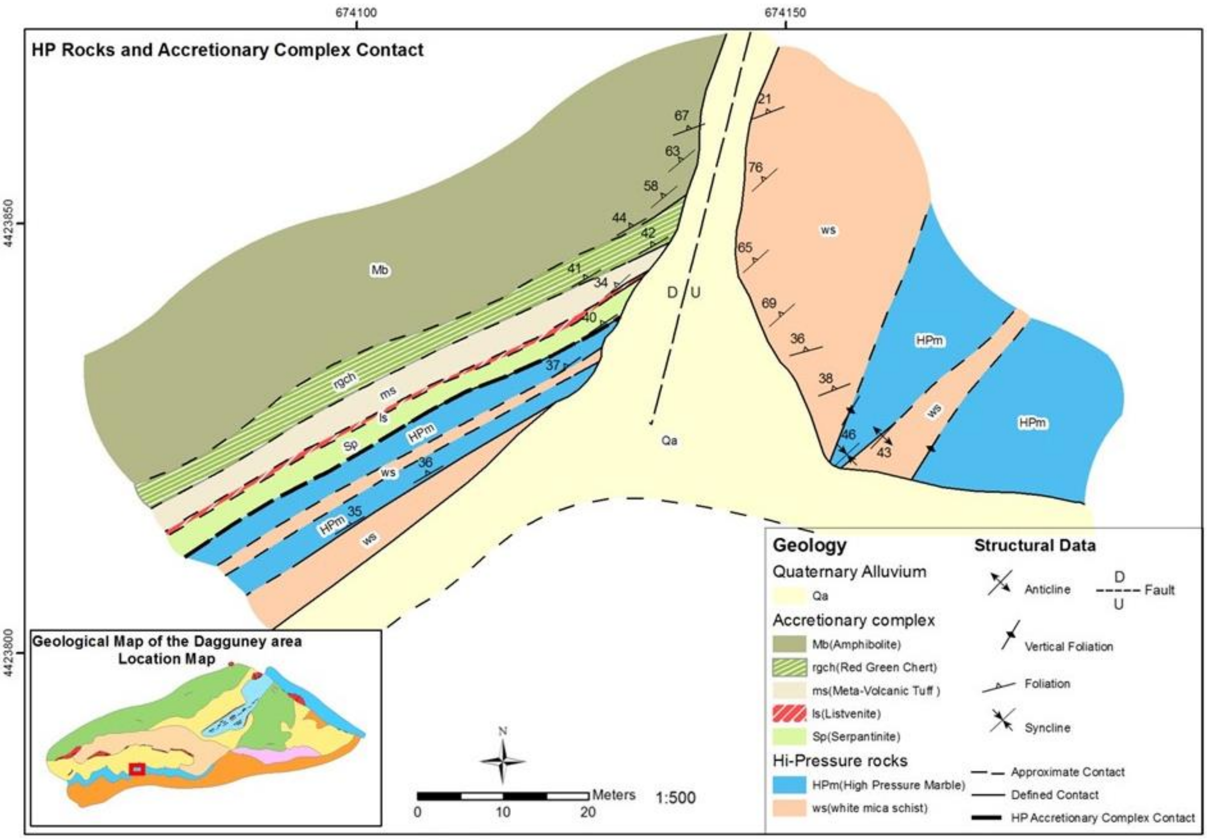

***Figure 5**. Geologic map showing the tectonic relationship and the contacts between the accretionary complex and the HP-LT blueschist facies rocks.*

The accretionary complex is in tectonic contact with both the overlying peridotite and the underlying HP-LT blueschist facies rocks. This unit consists of mélange which is mainly composed of metamorphosed basalt, metamorphosed radiolarian chert (quartzite), greenstone, metamorphosed volcanic tuff (phyllite), serpentinite with listvenite, marble with chert interlayers and jasper-silica which probably is a replacement product of marble. A single amphibolite block is also present in the accretionary complex.

High-pressure low-temperature (HP-LT) blueschist facies rocks are tectonically overlain by accretionary complex and peridotites. The base of HP-LT rocks is not exposed within the study area. Blueschist facies rocks consist of lawsonite blueschist, HP marble, white mica schist, and graphitic mica schist. The parallel alignment of mineral grains shows a mineral lineation that generally trends east-west. Measured metamorphic foliations within these rocks dip generally northwards. A local garnet-bearing blueschist is also present. HP marble is massive in many outcrops, and elsewhere is interbedded with thin layers of white mica schist, graphitic mica schist, and lawsonite blueschist at the transition zones. White mica schist and graphitic mica schist crop out over a large area around Dağgüney. According to Okay [24], the minimum thickness of micaschists is about 800 meters. Metaconglomerates with quartz clasts and calcite pebbles are also present within the white mica schist. Lawsonite blueschist crops out in several locations in the study area. Okay [25] describes these rocks as classic blueschists and Lisenbee [23] mapped this unit as basic schist. Lawsonite blueschist shows a strong foliation which generally trends northeast, and a strong mineral lineation defined by the parallel alignment of the sodic amphibole grains, which generally trends east-west.

B. TECTONOSTRATIGRAPHY

A tectonostratigraphic column was prepared based on the field measurements of different units within the mélange found at the significant outcrop (UTM Location: 4423837N – 674130E). This column shows the tectonostratigraphic relationships of the mélange units and their underlying contact with the HP-LT rocks (Figure 5). In addition, another tectonostratigraphic column was drawn based on the field measurements of the low-grade meta-limestones and interbedded cherts, which are all underlain by a phyllite unit within the melange (Figure 6).

B.1. Tertiary Plutons (Granodiorite)

In the northeastern portion of the study area (Figure 4), along the high-angle, NW-trending fault zone, a series of granodioritic igneous plutons are present. The trend of the intrusions is consistent and is NW-SE which is similar to the high-angle NW trending strike-slip fault in the northeastern portion of the study area. This would suggest that igneous intrusions tend to follow the strike of the major fault. Granodioritic intrusions have a mineral assemblage of plagioclase (35%), potassium feldspar (10%), quartz (45%), hornblende (5%), and biotite (5%). Undeformed Early to Middle Eocene granodiorite bodies (50 Ma 40Ar/39Ar isochron ages), intrude the blueschists and the overlying peridotites [4].

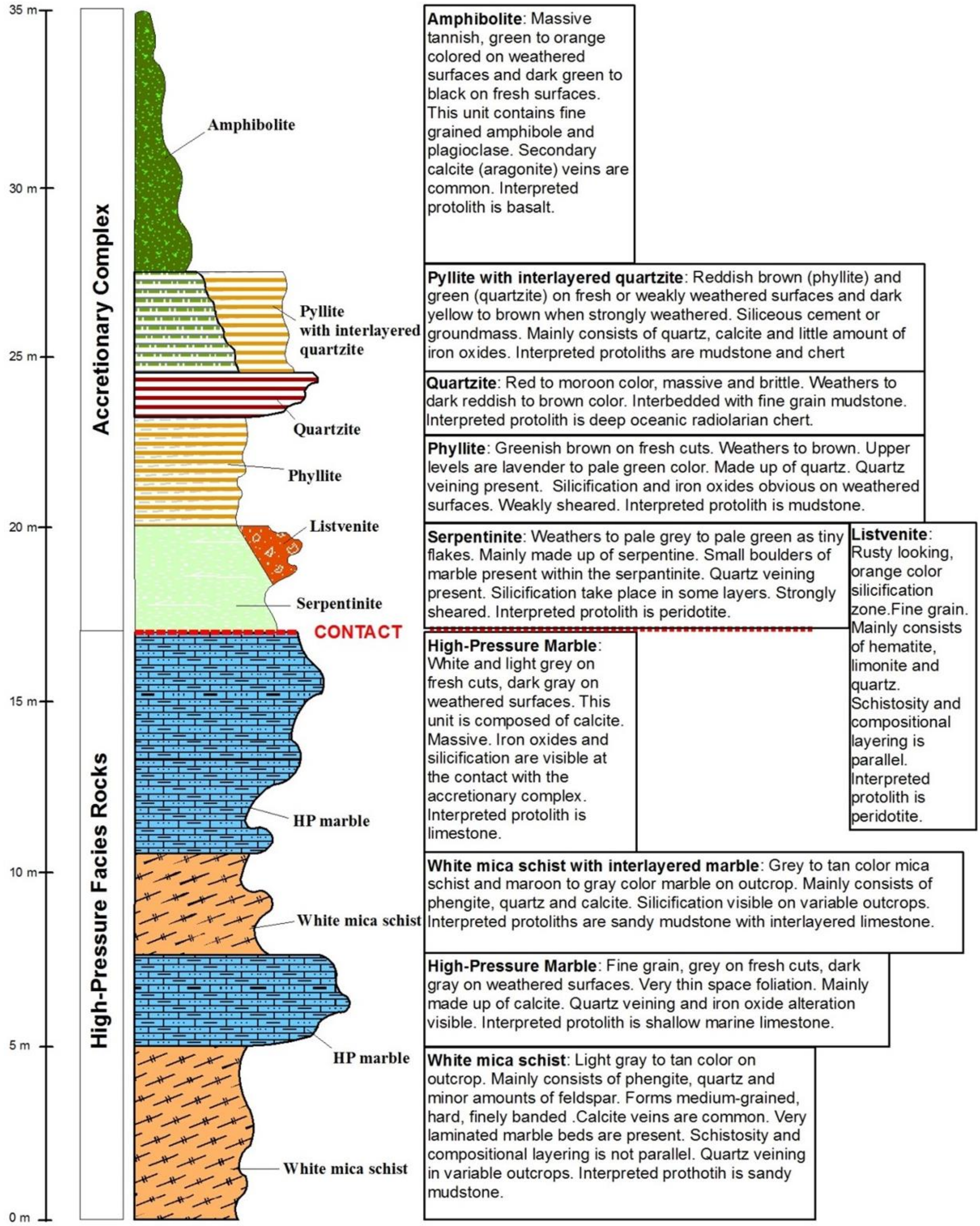

***Figure 6**. Tectonostratigraphic section illustrating the relation between the HP-LT rocks and the mélange of the accretionary complex.*

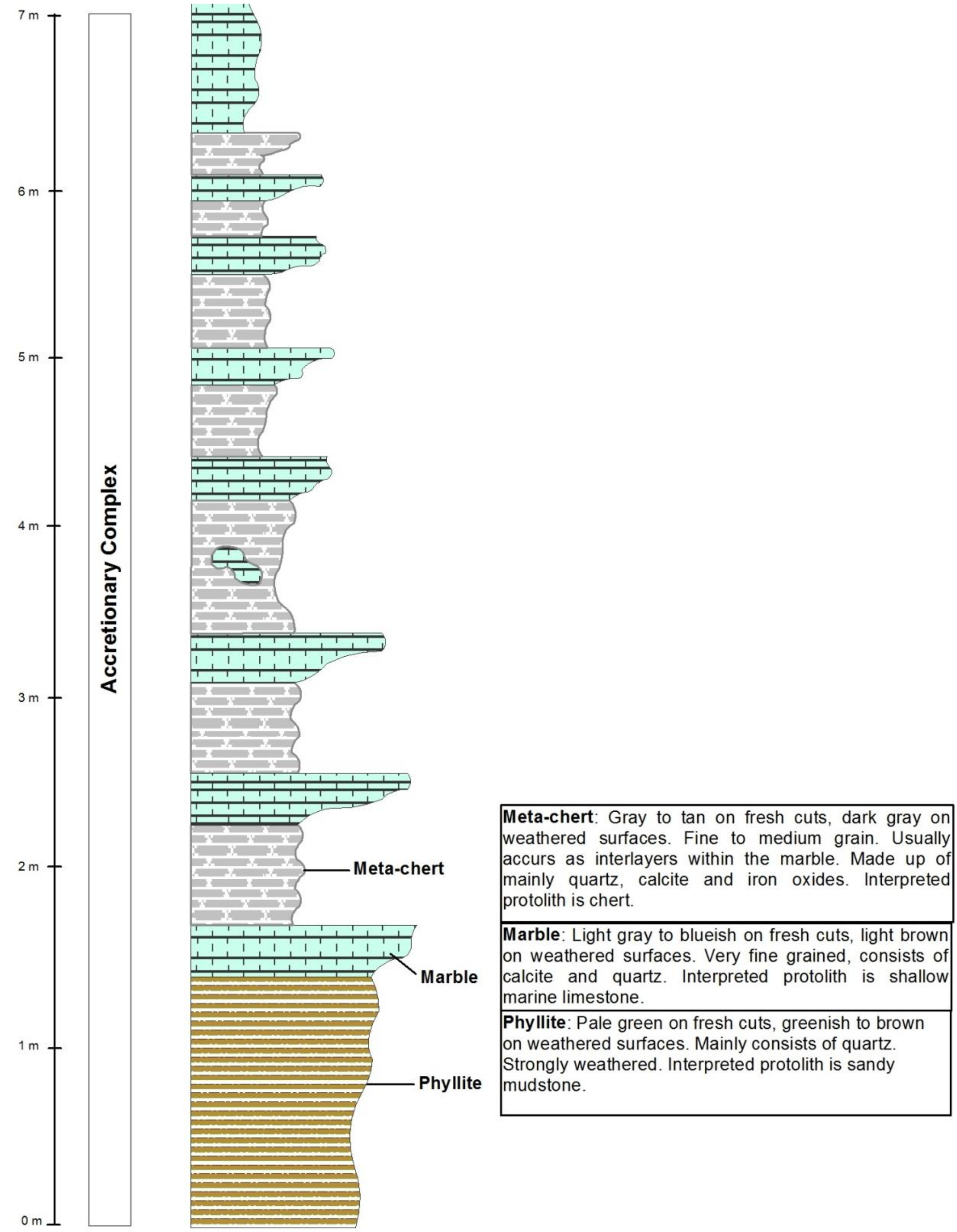

Figure 7. *Tectonostratigraphic section showing the low-grade meta-limestone with chert interlayers within the accretionary complex.*

B.2. Oceanic Lithosphere (Burhan Peridotite)

The Burhan peridotite slab consists of dunite, harzburgite and minor serpentinite and listvenite. This unit is part of Anatolian ophiolite and is of Albian age [5]. This slab is interpreted to have formed as the oceanic lithosphere and occurs as locally large tectonic sheets, which tectonically overlies the accretionary complex and the HP-LT blueschist facies rocks [23]. The Burhan peridotite obducted over the Anatolide-Touride block during the Late Cretaceous [26]. The mineral assemblage for peridotite is olivine + orthopyroxene + clinopyroxene + chrome-spinel. The peridotite shows no sign of regional metamorphism as magmatic mineral assemblage of plagioclase + pyroxene is well preserved [26]. In the study area, dunite weathers to serpentinite and makes up most of the peridotite slab. The dunite is fine to medium-grained, composed of yellowish-dark green olivine and tiny black grains of chromite; the rock weathers to orange to light brown at local outcrops. Serpentinite occurs mainly at the base of the peridotite and the shear zones. Strongly sheared and weathered serpentinite is pale green in color, and breaks into tiny flakes. 2 to 3 centimeters bands of chromite deposits are also present within the dunite. Listvenite occurs as a hydrothermal alteration product of the peridotites. Silicification (listvenite) is a late, post-tectonic feature, due to fluid circulation along the fault contacts [1]. Kaya et al. [27] also reported that smaller amounts of silicified listvenite and magnesite are present within the peridotite tectonic slab within the study area. East-west trending diabase dikes crops out within the peridotite units. Diabase dikes consist of mainly hornblende and plagioclase, and as a result, this rock has a salt and paper texture. The rock is gray to pale blue on fresh surfaces, and dark gray to light brown on weathered surfaces. Based on the mineral assemblage and the texture this rock has not gone under HP-LT metamorphism. Diabase dike thickness ranges from 2 to 8 meters within the study area. Dike-peridotite contacts are generally faulted due to later brittle deformation. In some outcrops, however, the original intrusive contacts are preserved, and the dikes can be seen to have narrow chilled margins. This observation indicates that the dikes intruded into cold peridotite [20]. Ar-Ar dating for the diabase dikes was determined by Okay [4] as approximately 90 Ma. Okay and Whitney [1] reported that magmatic hornblende replaced the pyroxene (augite) and that plagioclase is commonly altered into very fine-grained aggregates of pumpellyite and albite. These indicate that the diabase dikes have undergone low-grade metamorphism. The thickness of the peridotite was measured based on field mapping and cross-sections by Okay [5] and on detailed gravity profiles by Lisenbee [23], and is as about 2 kilometers.

B.3. Mélange (Accretionary Complex)

The mélange consists of low-grade metamorphosed basalt, metamorphosed radiolarian chert (quartzite), metamorphosed tuff (phyllite), and metamorphosed basalt (greenstone). Additionally, amphibolite, blueschist, low-grade marble, white mica schist, serpentinite, metamorphosed volcanic lapilli tuff, jasperoid, and listvenite are present within the mélange, Stratigraphic relationships between the different rock types are typically not preserved, except in one outcrop in the study area (Figure 3). Elsewhere, it is difficult to follow bedding without encountering a fault or shear zone. A typical mélange either has a greywacke or serpentinite matrix. The mélange near Dağgüney village has a serpentinite matrix. Metamorphosed basalts within the accretionary complex may have several types of magmatic protoliths [4]. The alkali basalts in the mélange are chemically comparable to Pacific Ocean seamounts, however, the close connection of red radiolarites and cherts suggests that several varieties of basalt represent the edges of such structures rather than the main seamount architecture [28]. Another possible type is the mid-oceanic ridge type. Regardless of their type, these basalts were formed on the oceanic floor and preserved within the mélange of an accretionary complex during the subduction. The mélange within the study area underwent low-grade metamorphism of T<200ºC and P~ 4-7 kbar [21, 29]. The age of metamorphism is still undefined. Possible pillow lavas are also present in the western portion of the study area. Several basalt outcrops show no deformation and original mineral assemblages were preserved. With its lithological features, internal structure, and its incipient HP metamorphism, the mélange of an accretionary complex represents a Tethyan subduction-accretion complex. According to Okay and Whitney [1], the Ovacık Complex (which includes the mélange in the study area) differs from the Franciscan or Makran-type accretionary complexes in the scarcity of clastic rocks.

Metamorphosed radiolarian chert (quartzite) crops out in several locations in the field area. Meta-radiolarian cherts are maroon to red in color. Radiolaria from cherts within the Ovacik complex from the Tavşanlı and Bornova Flysch zones yield Late Triassic (late Carnian, late Norian), Jurassic and Early Cretaceous (Cenomanian-Hauterivian) ages [30, 31, 32]. These ages indicate that the Neo-Tethyan oceanic crust north of the Anatolide-Touride Block has a minimum age of Late Cretaceous

[4]. Lisenbee [23] reported that Late Cretaceous-Paleocene pollens from tuffaceous rocks are present within the mélange near Dağgüney village. This would indicate that the Neo-Tethyan oceanic crust within the study area has an age between Late Triassic to Paleocene. Greenstone, phyllitic in texture, is also present within the accretionary complex. Local outcrops range from a couple of meters to 50 meters in length. Several outcrops of greenstone occur as interlayers with meta-radiolarian chert (quartzite). The interpreted protolith is basalt. A metamorphosed lapilli tuff outcrop was noted within the mélange unit in the northeastern side of the study field. It is very fine-grained and of a greenish color. Light gray clasts range from 3 to 15 millimeters in diameter. Weathered surfaces are dark brown to light tan. The interpreted protolith is volcanic tuff. Additionally, HP-LT blueschist rocks such as blueschist, marble, and white mica schist knockers are present within the accretionary complex. Metamorphic mineral textures and grain sizes are characteristics of these blueschist facies knockers. An amphibolite knocker is present in the accretionary complex. This rock consists mainly of hornblende, plagioclase, and garnet cut by calcite veinlets and iron oxides and is a typical metamorphic sole. The possible protolith based on the mineral assemblage and the texture is basalt. A marble unit contained within the accretionary complex differs from the high-pressure marble by its grain size and the metamorphic texture. This unit crops out on a ridge crest (locally called Söğütoğlukırı Tepesi) with chert interlayers. The northern margin of the marble chert interlayers is the jasperite-silica unit. Based on the texture, the marble shows no sign of high-pressure metamorphism. This unit is light gray to light blue on fresh surfaces, and light brown to dark gray on weathered surfaces. The marble consists of calcite, quartz grains, and minor amounts of iron oxide and is interbedded with discontinuous meta-chert layers. Field observations indicate that the chert is deformed, this suggests the chert was already within the limestone before the metamorphism and deformation has taken place. The interpreted protolith is shallow marine limestone. Metamorphosed chert in the marble is tan to pale pink on fresh surfaces, and light brown to tan on weathered surfaces. This unit consists of quartz with minor amounts of iron oxide staining. The trend of the meta-chert strikes consistently NE-SW and steeply dips to the NW within the marble. The interpreted protolith is chert. Jasperite-silica crops out also on the same ridge crest in the northern portion of the mapping area. This rock consists of silica that has formed largely by epigenetic replacement [33]. This unit is composed of mainly quartz and minor amounts of hematite and other iron oxides. Jasper-silica occurs as pink to tan on fresh surfaces and reddish pink on weathered surfaces. This unit is very fine-grained. Individual bodies of jasperite-silica range in size from little pods to masses more than half a kilometer in their greatest dimension. The trend of this unit strikes NE-SW and dips steeply to the NW. Jasperite-silica outcrops within the marble indicate that calcite was replaced by silica epigenetically.

B.4. High-Pressure Low-Temperature Blueschist Facies Rocks

High-pressure low-temperature (HP-LT) blueschist facies rocks are tectonically overlain by the peridotite and the mélange. HP-LT rocks consist of four major units. These are lawsonite blueschist, high-pressure (HP) marble, white mica schist, and graphitic mica schist.

B.4.1. Lawsonite Blueschist

Lawsonite blueschist is blue, green, and lavender on fresh cuts and darker gray to blueish green on weathered surfaces. This unit only crops outs in the southeastern portion of the study area, where it overlies HP marble and is overlain by the accretionary complex. Lawsonite blueschist consists of glaucophane, lawsonite, chlorite, phengite, and quartz, minor amounts of calcite and iron oxides are also present. A strong foliation and strong mineral lineation are defined not only through the parallel alignment of the sodic amphibole (glaucophane) grains but also through white mica (phengite) grains. Quartz and calcite veinlets are present at local outcrops. The interpreted protoliths are basalt, volcanic tuff, and pyroclastic rocks. On several outcrops, lawsonite blueschist forms very thin bands within the massive HP marble layers. Based upon the cross sections drawn, the structural thickness of the lawsonite blueschist is about 200 meters. According to Okay [25], the structural thickness of the lawsonite blueschist unit is about one kilometer in the Tavşanlı Zone. Lawsonite blueschist shares a common metamorphic and deformational history with the underlying HP marble [1]. Studies indicate that the peak pressure and temperature values of the metamorphism for these rocks (lawsonite blueschist, HP marble, white mica schist, graphitic mica schist) around Dağgüney area is 24±3 kbar and 430±30ºC [2, 4, 10].

B.4.2. HP Marble

High-pressure (HP) marble crops out over large areas within the study area. Outcrops range from a couple of meters to hundreds of meters. Okay [4], reported that HP marble has a structural thickness of several kilometers in the Tavşanlı Zone. This unit is gray to white on fresh surfaces and dark gray on weathered surfaces. Usually, HP marble is fine-grained, consists of calcite and minor quartz, and is locally banded. Calcite minerals possibly transform to arogonite and revert to calcite after exhumation. The marble contains a strong mineral lineation defined by the parallel alignment of elongated calcite grains. This unit provides easy measurements of compositional layering, mineral lineation, fold axes, and schistosity. Quartz veining is also present. HP marble is massive in outcrop scale and is interbedded with thin layers of white mica schist, graphitic mica schist, and lawsonite blueschist at the transition zones. Additionally, a metaconglomerate unit is present in the HP marble unit. The interpreted protolith is Mesozoic shallow marine limestone [4].

B.4.3. White Mica Schist

White mica schist crops out over a large area around Dağgüney. The rock is light gray, pale pink, and tan in color on fresh surfaces, and light brown, dark tan to gray on weathered surfaces. White mica schist unit consists mainly of phengite, quartz, calcite, and minor amounts of iron oxides. Jadeite is alos present. Mesoscopic folds and microscopic boudins within the white mica schists are good kinematic indicators. White mica schists crop out within HP marble at several locations. Well-developed metamorphic foliation and strong mineral lineation are defined by the phengite bands. White mica schist contains quartz in the study area, indicating that the protolith is possibly sandy mudstone. A rare metaconglomerate is present within the white mica schist near Dağgüney village, which is composed mainly of phengite, calcite, and quartz; calcite and quartz clasts are elongated and range from a couple of centimeters to 10 centimeters in diameter. Based upon the presence of jadeite, chloritoid, and quartz, micaschists within the study area were metamorphosed at 80 kilometers of depth. According to Okay (2011), the Orhaneli region is possibly the most jadeite-rich area in the world. The structural thickness of the micaschist was measured by Okay [4] as about 800 meters within the Tavşanlı Zone. Okay et al. [34], reported Ordovician and Permo-Carboniferious zircon ages for micaschists within the Tavşanlı Zone. White mica schist shares the same peak metamorphic conditions as the overlying HP marble and lawsonite blueschist.

B.4.4. Graphitic Mica Schist

Graphitic mica schist crops out over a very large area in the southern portion of the study area. This unit is dark gray to dark tan color on fresh surfaces and very dark gray color on weathered surfaces. This unit has a waxy luster and consists of graphite, quartz, calcite, and phengite. Quartz veining is present on local outcrops. Metaconglomerate, similar to those layers within the HP marble and white mica schist, is also present within the graphitic mica schist. Isoclinal and chevron folds are common within this unit. The interpreted protoliths are sandy mudstone with limestone interlayers. Graphitic mica schist shares the same peak metamorphic conditions as the overlying white mica schist, HP marble, and lawsonite blueschist.

C. STRUCTURAL GEOLOGY

C.1. Structural Relations Among the Rock Units

There are three major rock units within the study area. The mutual relations are as shown on the two geological maps, two tectonostratigraphic sections, and two cross-sections which were made based on the detailed field study (Figures 4, 5, 6, and 7). Based on the observed field relationships, the peridotite unit overlies both the mélange of the accretionary complex and the high-pressure blueschist rocks. The accretionary complex overlies the high-pressure blueschist rocks. These relationships are present in the northeastern portion of the study area (Figure 4). Listvenite and serpentinite occur as the basal portions of the ultramafic complex and separate mélange and HP-LT rocks from the peridotite (ultramafic complex). The orientation of foliation and compositional layering, which generally strike northeast-southwest and dip gently northwards in the HP-LT rocks, also indicate that the peridotite unit structurally overlays the mélange and the HP-LT rock units.

C.2. Metamorphic Foliations

All three major tectonostratigraphic units including the ultramafic complex, accretionary complex, and HP-LT rock units have a metamorphic foliation. The dunite and harzburgite units in the ultramafic complex contain a distinct tectonic foliation defined by the preferred orientation of olivine and elongated grains of enstatite and chromite. The metamorphic foliation generally parallels the compositional layering within the study area. The foliation generally strikes northeast and dips northwest (Figure 8).

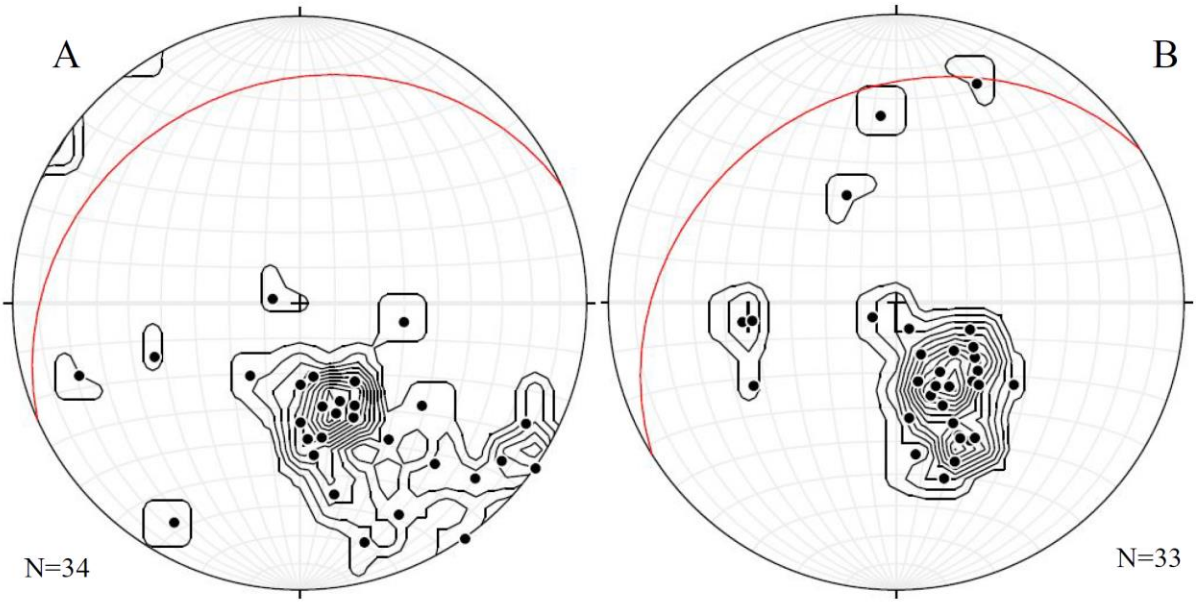

***Figure 8**. (**A**)- Equal-area stereonet projection showing 1% area contours of poles to foliation in the accretionary complex. (**B**)- Equal-area projection showing 1% area contours of poles to foliation in the HP-LT blueschist facies rocks. The contour interval (CI) = 2%.*

Attitudes of foliation and compositional layering are the same in the large mass of the Burhan peridotite body to the north and in the smaller isolated mass near Dağgüney. Such a foliation is believed to form during recrystallization in mantle conditions [23]. Foliation generally parallels the compositional layering in the meta-sedimentary and the meta-basalt units (meta-radiolarian chert, meta-volcanic tuff, and greenstone) within the accretionary complex. Figure 8 (A) shows that the foliation defined by compositional layering in the accretionary complex generally strikes at 246° and dips 24º northwesterly. The HP-LT rocks foliation is defined by tabular mica grains and generally strikes at 238º and dips 28º northwesterly as illustrated in Figure 8 (B). The compositional layering within the HP-LT rocks is usually sub-parallel to the metamorphic foliation. Foliation is present in all of the units (HP marble, white mica schist, graphitic mica schist, and lawsonite blueschist).

C.3 Metamorphic Lineations

High-pressure low-temperature (HP-LT) blueschists of the Tavşanlı Zone contain a strong mineral lineation defined by elongated calcite and sodic amphibole grains. These are interpreted to represent a stretching lineation by Okay et al. [5], Monod et al. [35], and Masuda et al. [36]. Similar lineations, which are defined by the parallel alignment of calcite and glaucophane grains, are present within the study area. Elongated quartz and marble pebbles also display long axes oriented east-west within the study area. Figure 9 (A) shows that mineral lineations on lawsonite blueschist generally trend east-west and plunge on average 19º near Dağgüney village. These measurements are local to a single outcrop. Similar mineral lineation data were reported by Lisenbee [23] for a larger study area near Dağgüney, Orhaneli area. Mineral lineation data trend approximately east-west in the Tavşanlı and Mihalıççık regions, north-south in Sivrihisar [35], and northeast-southwest in the Konya-Altınekin regions [37]. Figure 9 (B) illustrates mineral lineation data obtained from HP-LT rock units at seven different locations (white mica schist, graphitic mica schist, and HP marble), however, shows a slightly different direction. These metamorphic lineation measurements are defined by the parallel alignment of tabular mica grains, and trend generally 252º and plunge 19º. These measurements are consistent with the metamorphic foliation data obtained from the HP-LT rock units.

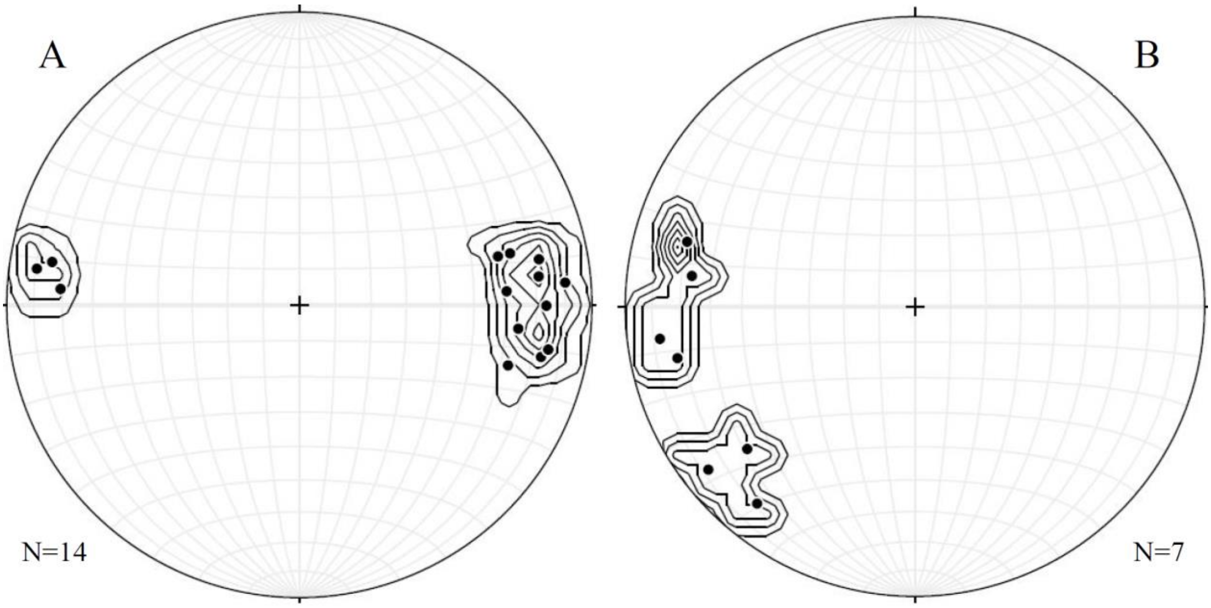

***Figure 9**. **(A)**- Equal-area lower hemisphere stereonet projection showing 1% area contours of lineation defined by elongated mineral grains in the lawsonite blueschist unit. (**B)**- Equal-area lower hemisphere stereonet projection showing 1% area contours of lineation defined by elongated mineral grains in the HP-LT rock units. Contour interval (CI) = 4%.*

C.4. Folds

Mesoscopic isoclinal folds are common in the blueschist facies rocks within the study area. Fold axes plunge gently eastward, sub-parallel to the mineral lineation of muscovite, calcite, and glaucophane mineral grains. Both isoclinals recumbent and chevron-type folds are present in the HP-LT rocks within the study area. This suggests at least two different deformation events occurred. The majority of the folds trend ENE-WSW and plunge gently eastward as shown in Figure 10 (A). Mesoscopic isoclinal folds are also present within the mélange. Figure 10 (B) shows the structural data obtained from the mélange indicating that the fold axes trend N-S and plunge gently to the east.

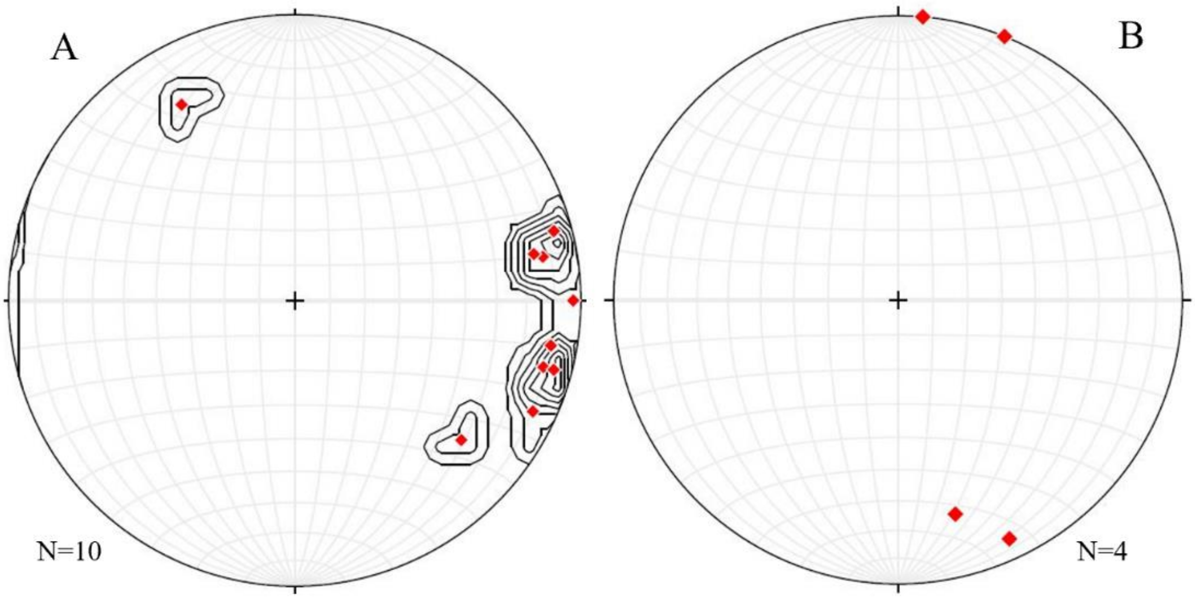

***Figure 10**. **(A)**- Equal-area stereonet projection showing fold plunges in the HP-LT blueschist facies rocks. **(B)**- Equal-area stereonet projection showing fold plunges in the mélange unit. Red diamonds for fold plunges.*

C.5. Faults

Most of the mapped contacts within the study area are tectonic in nature and indicative of a sequence of deformational events. At least four major types of faulting, based on age, cross-cutting relationships, and orientation, are recognized (Figures 4, 11, and 12).

C.5.1. Type 1 Faults

Low-angle fault contacts occur between the mélange and the HP-LT blueschist facies rocks. This fault type places mélange onto the blueschist facies rocks and fault planes generally strike east-west and dip to the north. Type-1 faults juxtapose HP-LT rocks in the footwall against the mélange in the hanging wall (Figure 11). Strong shearing and extremely fine-grained, mylonitized serpentinite are good indicators of type-1 faults. During field mapping, a spectacular outcrop has been recognized by a road cut that provides the ductile fault (type 1) contact between the accretionary complex and the HP-LT rock units (UTM: 4423837N – 674130E). At this location, the fault plane strikes E-W and dips 34ºN. Small amounts of silicification (listvenite) occur along the faulted contacts. Knockers of HP marble within the serpentinite are present at this significant outcrop. There is a major jump in the metamorphic grade at this outcrop. Peak metamorphic pressure of 24 kbar for the HP-LT rocks and 7 kbar for the accretionary complex were previously reported by Okay [4]. Based on the 2.7 gr/cm^3 average continental crust bulk density, a 46 km thick rock section is missing.

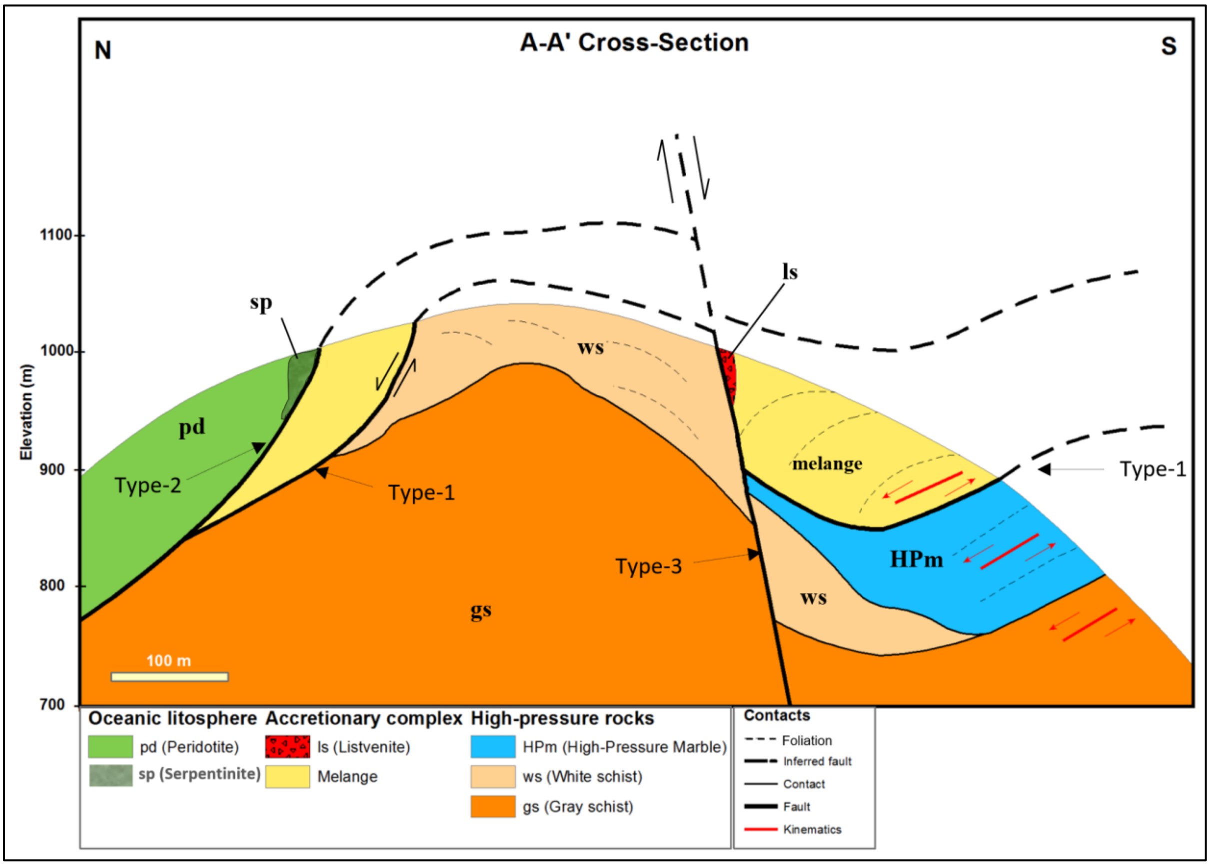

***Figure 11**. Geologic cross-section A-A' showing the structural relations among the rock units.*

C.5.2. Type 2 Faults

Low-angle faults at the base of peridotite sheets. In the klippe of the Burhan peridotite, located approximately one-kilometer northwest of Dağgüney, these faults place peridotite onto the mélange of the accretionary complex. The larger mass of the Burhan peridotite also overlies the HP-LT blueschist facies rocks (Figure 12). Based upon the structural data, these faults behave as reverse on the northern massive masses and thrust on the smaller masses near Dağgüney village. Strong shearing, serpentinization, and silicification (listvenite) are good indicators of these types of faults.

C.5.3. Type 3 Faults

High-angle, south side down, normal faults (Figures 11 and 12). This fault generally strikes northeast-southwest and dips steeply to the south. The relative motion of the footwall on the north compared to the hanging wall on the south which indicates these are high-angle normal faults with a dip-slip separation of 100 m (Figure 11).

C.5.4. Type 4 Faults

Steeply dipping, northwest-southeast trending strike-slip fault. This fault occurred possibly as a result of the youngest deformation event and juxtaposes peridotite and mélange against the HP-LT marble in the northeastern portion of the study area. The fault well extends outside the study area. Whether or not the fault crosscuts the Tertiary igneous intrusions is unknown, but it is possible that Tertiary intrusions were emplaced along the trend of the NW striking fault within the study area (Figure 4).

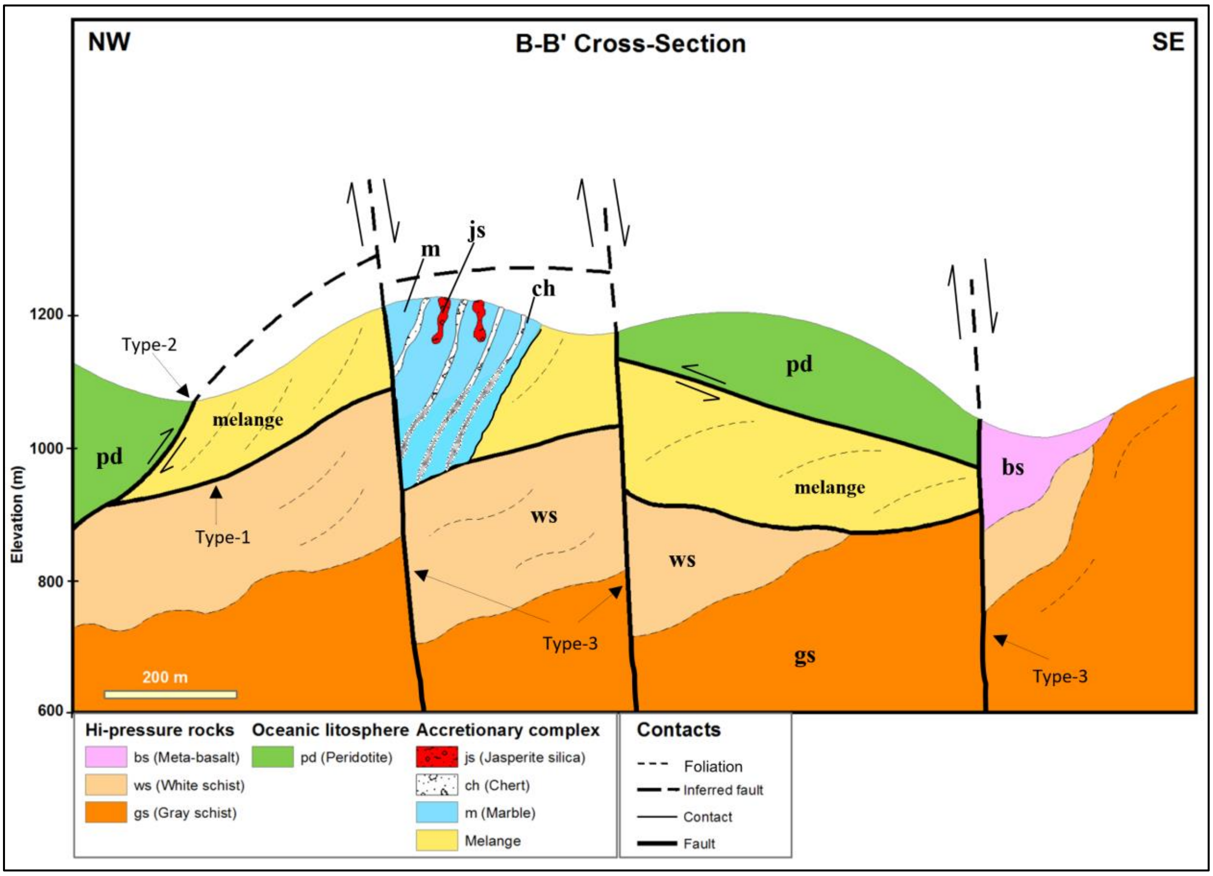

Figure 12. *Geologic cross-section B-B' showing the structural relations among the rock units.*

V. DISCUSSIONS

Based on the structural data obtained in the field, the structural evolution appears to be as followed (from oldest to youngest): Continental subduction occurred as the Gondwana microcontinent was subducted northward under the Laurasian microcontinent. Gondwanan continental margin rocks (white mica schist, graphitic mica schist, and marble) and oceanic floor rocks (lawsonite blueschist) experienced blueschist facies metamorphism at a depth of 80 km during the Late Cretaceous. Exhumation of the HP-LT rocks, the metamorphic sole, and the mélange occurred within the same subduction channel. Subsequently, the peridotite slab was obducted over the mélange and the HP-LT rocks.

The axes of the isoclinal folds are sub-parallel to the mineral lineation. These observations indicate a strong stretching sub-parallel to the present trend of the İzmir-Ankara suture. The shapes of the clasts in the meta-conglomerates of the Orhaneli Group also indicate that the finite strain ellipsoid is of a constructional type (Okay and Whitney, 2010). E-W-trending mineral lineation within the study area is related to N-S-directed compressional fabrics. The accretionary complex and the blueschist facies rocks are characterized by penetrative metamorphic foliation and strong stretching mineral lineation which have been folded. The tectonic contact between the HP-LT blueschist rocks and the overlying accretionary complex represents a major jump in the metamorphic grade. Rocks below the contact have undergone metamorphism at pressures of 24 kbar and those above at pressures of ~7 kbar [5]; this may suggest a 46 km-thick missing section based on the average 2.7 gr/cm^3 continental crust bulk density. The mélange contains a mylonitic serpentine at the base. Such a serpentine mass may have behaved as a lubricant between the mélange and HP-LT rocks. The mélange contains low-grade and medium-grade units as well as high-grade blocks which may suggest that it has undergone metamorphism at the same time as blueschist rocks. The mélange also contains both undeformed and strongly deformed basalt units. The strongly deformed basalt contains macroscopic faults and talc-filled joints. The mélange shows silicification along the basal contact and secondary mica and quartz veins within the meta-basalt units.

Deformed chert layers are present as interlayers with the low-grade meta-limestone unit within the mélange suggesting that chert formed in the limestone before metamorphism and deformation took place. The chert and meta-limestone unit is interbedded with the phyllite (meta-volcanic tuff) at the base. This indicates that this is a depositional contact and that the limestone protolith formed in the same ocean and at the same time as the volcanic rocks. Jaspereoid silica within the mélange unit adjacent to the meta-limestone is a hydrothermal replacement product of the low-grade meta-limestone. The peridotite does not show any sign of regional metamorphism. Chromite mineralization occurs within peridotite and magnesite veins fill some fractures and faults within the dunite. Serpentinization occurs at the base of peridotite slabs, and it may be due to hydrothermal fluids rising along the fault zones. Listvenite crops out along the high-angle fault zones with or without serpentinite. This indicates that the ultramafic protolith was influenced by hydrothermal fluids. Recognition of an amphibolite unit within the accretionary complex is a discovery for the area and suggests that a metamorphic sole has been exhumed with the accretionary complex. In addition, the presence of blueschist and white mica schist blocks within the accretionary complex suggests that exhumation occurred during subduction. Based on the cross-cutting relationships and type, there are at least four major fault types. The relative ages (youngest to oldest) are as follow:

1. Steeply dipping, NW-trending sinistral strike-slip fault.
2. High-angle, south side down, normal faults.
3. Low-angle faults at the base of peridotite sheets.
4. Low-angle ductile fault contacts between the mélange and the HP-LT blueschist facies rocks.

The presence of amphibolite knockers (metamorphic sole), white mica schist, and lawsonite-mica schist (HP-LT blueschist rocks) within the accretionary complex not only suggests that exhumation occurred during subduction, but also indicates that the metamorphic sole, the accretionary complex, and the HP-LT blueschist facies rocks converged and were exhumed along the same subduction channel. In an exhumation model for the study area proposed by [5], according to this model, a metamorphic sole is interpreted to have formed at the base of the Burhan peridotite slab. Okay's model relies on isobaric cooling of the sole, which is not consistent with the recent data. The sole display a very different metamorphic foliation and degree compared to that of the peridotite, suggesting that the metamorphism of the sole was independent of that of the peridotite.

VI. CONCLUSIONS

The Tavşanlı zone of northwestern Türkiye is a great example of continental crust subducted to a greater depth of 80 km and exhumed to the surface. Blueschist facies mineral assemblages of the HP/LT rocks were well preserved, therefore, the exhumation rate must be rapid enough, that HP/LT blueschist facies rocks would not be overprinted by other facies such as amphibolite and greenschist. HP-LT blueschist rocks have both oceanic and continental protoliths. White mica and graphitic mica schists are continental in origin, whereas lawsonite-blueschist has an oceanic protolith. The mélange of the accretionary complex shows different metamorphic grades including very low-grade to greenschist facies, amphibolites facies, and blueschist facies. The accretionary complex also has both oceanic protoliths (meta-basalts, meta-radiolarian chert) and continental protoliths (low-grade meta-limestone, phyllite). The accretionary complex and the HP-LT blueschist rocks are concordant, they converged and exhumed within the same subduction channel. Perdidotites, which contain chromite mineralization, show no sign of regional metamorphism and were later trusted southward, and tectonically overlie the accretionary complex and the HP-LT blueschist facies rocks.

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