BLUESCHISTS, ECLOGITES, OPHIOLITES AND SUTURE ZONES IN NORTHWEST TURKEY: A REVIEW AND A FIELD EXCURSION GUIDE

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Keywords: *blueschist, eclogite, subduction, suture. Tavşanlı Zone. Turkey.*

ABSTRACT

The Tavşanlı Zone in western and south-central Turkey constitutes one of the largest and best preserved high-pressure metamorphic belts in the world. Blueschists and scarce lawsonite-eclogites crop out in an east-west-rending zone, 50-60 km wide and about 250 km long, and are tectonically overlain by an oceanic accretionary complex and large ophiolite slabs. Undeformed Early to Middle Eocene granodiorites (ca. 50 Ma $^{40}Ar/^{39}Ar$ isochron ages), intrude the blueschists and the overlying ophiolite. The blueschists of the Tavşanlı Zone represent the subducted north-facing passive continental margin of the Anatolide-Tauride block. They were partly exposed by, or were at high crustal levels during the latest Cretaceous, prior to the Paleocene continent-continent collision. The blueschists of the Tavşanlı Zone comprise a variety of metasedimentary and metamagmatic lithologies. The metasedimentary sequence, originally deposited on continental crust, comprise a schist-marble series of Mesozoic age with peak pressure and temperatures of ~24 kbar and 430-500°C, respectively, and with Late Cretaceous (ca. 80 Ma) metamorphic ages. The oceanic lithologies are made up mainly of metabasites with metacherts, phyllites, which have undergone metamorphism from incipient blueschist facies to lawsonite-eclogite facies. The guide, prepared for a three-day field trip, provides information on the tectonic setting, tectonostratigraphy, petrology, and geological evolution of the Tavşanlı Zone blueschists and lawsonite-eclogites followed by detailed description of the field stops. It also includes data on the Triassic blueschists and eclogites from north of the Tavşanlı Zone.

INTRODUCTION

This paper comprises two sections. The first section gives the general background information on the tectonics of northwest Turkey with a review of the main features of the Tavşanlı Zone. The second part is a field trip guidebook.

Turkey, forming an east-west bridge between Europe and Asia, also straddles the geological boundary between Gondwana and Laurasia along a north-south transect. It was not a single entity until the Early Tertiary, when several continental fragments with independent Paleozoic and Mesozoic geological histories were assembled during a complex sequence of events leading to the collision of Gondwana and Laurasia.

Fig. 1 shows the sutures and major continental fragments in Turkey and the surrounding regions. There are six major lithospheric fragments or terranes in Turkey: the Strandja, the Istanbul and Sakarya Zones, the Anatolide-Tauride Block, the Central Anatolian Crystalline Complex (Kırşehir Massif) and the Arabian Platform (Şengör and Yılmaz, 1981; Şengör et al., 1982; Okay and Tüysüz, 1999). The first three terranes show Laurasian affinities and are classically referred to as the Pontides. They are separated by the İzmir-Ankara-Erzincan suture from the Anatolide-Tauride Block. The Intra-Pontide suture represents the former plate boundary between the Sakarya and Istanbul Zones. For the purposes of the field trip we will be chiefly interested in the Sakarya Zone and the Anatolide-Tauride Block, and will be crossing the Istanbul Zone. The major geological features of these terranes are summarized below.

THE ISTANBUL ZONE

The Istanbul Zone is a small continental fragment, about 400 km long and 70 km wide, located on the southwestern margin of the Black Sea (Fig. 1). It is made up of a late Proterozoic crystalline basement overlain by a continuous, well-developed transgressive sedimentary sequence extending from Ordovician to Carboniferous, and was mildly deformed during the Carboniferous Hercynian orogeny (e.g., Görür et al., 1997). The stratigraphy of the Istanbul Zone is shown in Fig. 2. The deformed but unmetamorphosed Paleozoic sequence of the Istanbul Zone is unconformably overlain by the earliest Triassic sedimentary rocks. The Triassic sequence is well developed in the Istanbul region and comprises an ~800 m thick sequence of Scythian to Norian age (e.g., Assereto, 1972). It ends with a flysch-like sequence of sandstones and shales marking the onset of the Late Triassic Cimmeride deformation, which is particularly strong in the Sakarya Zone to the south. In the Istanbul region the Triassic rocks are unconformably overlain by Late Cretaceous-Paleocene clastic, carbonate and andesitic volcanic rocks (e.g., Dizer and Meriç, 1983). Senonian andesitic lavas, dykes and small acidic intrusions, which are widespread in the northern part of the Istanbul Zone, were produced during the northward subduction of the Tethys Ocean.

The palaeomagnetic results from the Devonian and Triassic rocks of the Istanbul Zone indicate its affinity to Laurasia during these periods (Sarıbudak et al., 1989; Evans et al., 1991; Theveniaut, 1993). The Istanbul Zone shows a similar Paleozoic-Mesozoic stratigraphy similar to that of Moesian Platform. Prior to the Late Cretaceous opening of the West Black Sea Basin, the Istanbul Zone was situated south of the Odessa shelf (cf. Fig. 1). With the inception of back-arc spreading in the Black Sea, the Istanbul Zone was rifted off from the Odessa shelf and was translated southward, closing the Intra-Pontide Ocean in the south and eventually colliding with the Sakarya Zone during the Cretaceous (Okay et al., 1994).

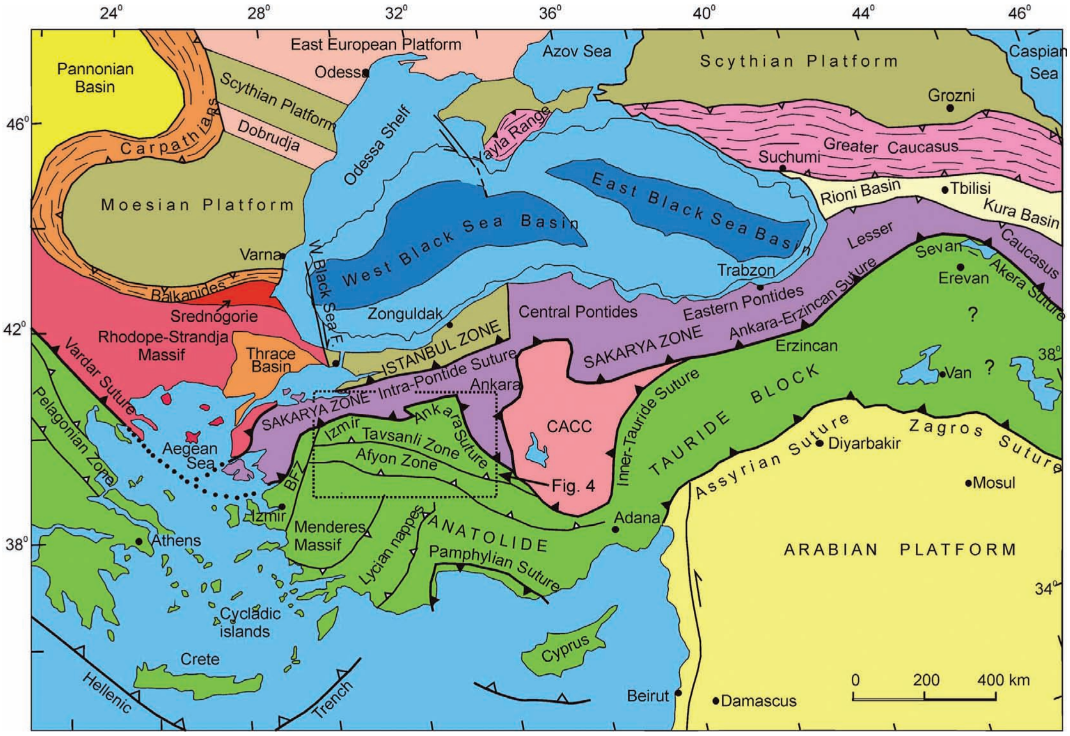


Fig. 1 - Tectonic map of the northeastern Mediterranean showing the major sutures and continental blocks. The high-pressure (HP) metamorphic rocks of the Tavşanlı and Afyon zones continue to the sotheast of the Kırşehir Massif. Sutures are shown by heavy lines with the polarity of the former subduction zones indicated by filled triangles. Heavy lines with open triangles represent active subduction zones. BFZ- Bornova Flysch Zone; CACC- Central Anatolian Crystalline Complex (Kırşehir Massif) (modified after Okay and Tüysüz, 1999).

THE SAKARYA ZONE

The Sakarya Zone is an east-west oriented continental fragment, about 1500 km long and 120 km wide, between the Anatolide-Tauride Block to the south and the Istanbul and Strandja Zones and the eastern Black Sea to the north (Fig. 1). A distinctive geological feature of the Sakarya Zone is the widespread presence of Triassic subduction-accretion complexes, which form a strongly deformed and partly metamorphosed basement to the overlying, unmetamorphosed Early Jurassic-Eocene sequence (Tekeli, 1981). The Triassic subduction-accretion units, called the Karakaya Complex, comprise a lower unit of Permian-Triassic metabasite-marble-phyllite series (the Nilüfer Formation or the Lower Karakaya Complex), over three kilometers in thickness, with exotic Triassic eclogite and blueschist lenses (Okay and Monie, 1997; Okay et al., 2002). The Nilüfer Formation is tectonically overlain by chaotically deformed, but largely unmetamorphosed, clastic and basic volcanic rocks of Triassic age with exotic blocks of Carboniferous and Permian neritic limestones, basalts, Carboniferous and Permian radiolarian cherts (Upper Karakaya Complex, Okay and Mostler, 1994; Kozur and Kaya, 1994; Leven and Okay, 1996; Okay and Göncüoğlu, 2004). The final phase of deformation and metamorphism of the subduction-accretion complexes occurred during the latest Triassic, and the various units of the Karakaya Complex are unconformably overlain by the Early Jurassic terrigeneous- to shallow-marine, clastic sedimentary rocks. The Sakarya Zone also includes upper Paleozoic granitoids and associated metamorphic rocks, which are in tectonic contact with the Karakaya Complex, and represent Variscan basement fragments of the Laurasian margin (Fig. 3, Yılmaz et al., 1994; Okay et al., 1996). As we will be seeing some of the tectonostratigraphic units of the Sakarya Zone during the fieldtrip, they are described below in more detail.

Paleozoic Continental Rocks of the Sakarya Zone

The continental basement of the Sakarya Zone is represented by a high-grade Variscan metamorphic sequence of Paleozoic gneiss, amphibolites and marbles. The metamorphism is in amphibolite to granulite facies and is dated to the Carboniferous (330-310 Ma) by zircon and monazite ages from the Pulur, Kazdağ, Devrekani and Gümüşhane massifs (Topuz et al., 2004; 2007; Okay et al., 2006; Nzegge et al., 2006). The Variscan basement is intruded by Carboniferous granitoids (Delaloye and Bingöl, 2000; Okay et al., 2002; 2006; Topuz et al., 2007) and was probably overlain by Late Carboniferous molasse, which is only preserved in the Pulur region in the easternmost part of the Sakarya Zone (Okay and Leven, 1996).

Paleo-Tethyan active margin units - the Karakaya Complex

The Karakaya Complex represents Triassic subduction-accretion units including possible fragments of a Triassic oceanic plateau (Tekeli, 1981; Okay et al., 1996; Okay, 2000). It extends from the Biga Peninsula eastwards for over 1000 km in the Sakarya Zone, and northward to the southern Crimea (e.g., Kotanski, 1978; Tekeli, 1981; Tüysüz, 1990; Ustaömer and Robertson, 1994; Topuz et al., 2004). Studies in northwest Turkey have led to the subdivision of the Karakaya Complex into two major tectonostratigraphic units (Fig. 3, Okay and Göncüoğlu, 2004) as described below.

Lower Karakaya Complex (The Nilüfer Formation): remnant of a Triassic oceanic plateau?

This is an over 3-km-thick, semi-coherent sequence of mafic tuffs, pyroclastic rocks, and pillow lavas that are interstratified with up to 50-m-thick carbonate and shale bands (Fig. 3). The stratigraphic base of the Nilüfer Formation is not known. In the Kazdağ and Uludağ ranges it rests with a tectonic contact over the high-grade gneisses, amphibolites and marbles.

The Nilüfer Formation is overlain generally through tectonic contacts by the Triassic clastic sequences of the Upper Karakaya Complex.

The Nilüfer Formation has undergone a high-pressure greenschist facies metamorphism with the development of albite + chlorite + epidote + actinolite + sphene in the fine-grained mafic tuffs. Sodic amphibole occurs rarely in iron-rich tuffs, while the massive coarse-grained pyroclastic flows retain most of their igneous texture and the igneous clinopyroxene. The greenschist facies metabasites of the Nilüfer Formation include very rare, generally a few ten meters large tectonic lenses of ultramafic rock. A 40-m-large lens of glaucophane-eclogite has been described in the Nilüfer Formation east of Bandırma (Okay and Monie, 1997), as well as a large blueschist-eclogite thrust sheet north of Eskişehir (Okay et al., 2002).

The deformation in the Nilüfer Formation is characterized by the development of cleavage in the phyllites and fine-grained metatuffs, and mesoscopic isoclinal folds. The more massive marble bands have boudinaged, giving a "broken formation" character to the Nilüfer Formation. Early and Middle Triassic conodonts are described from the carbonates interstratified with the metabasites from the Nilüfer Formation south of Bursa (Kozur et al., 2000) and in the Kozak Range (Kaya and Möstler, 1992), indicating a Middle Triassic and earlier depositional age for the sequence. Ar-Ar phengite and amphibole ages are latest Triassic (Okay and Monie, 1997; Okay et al., 2002). This, together with the unconformably-overlying Early Jurassic clastic rocks, indicate a latest Triassic age for the regional metamorphism in the Nilüfer Formation.

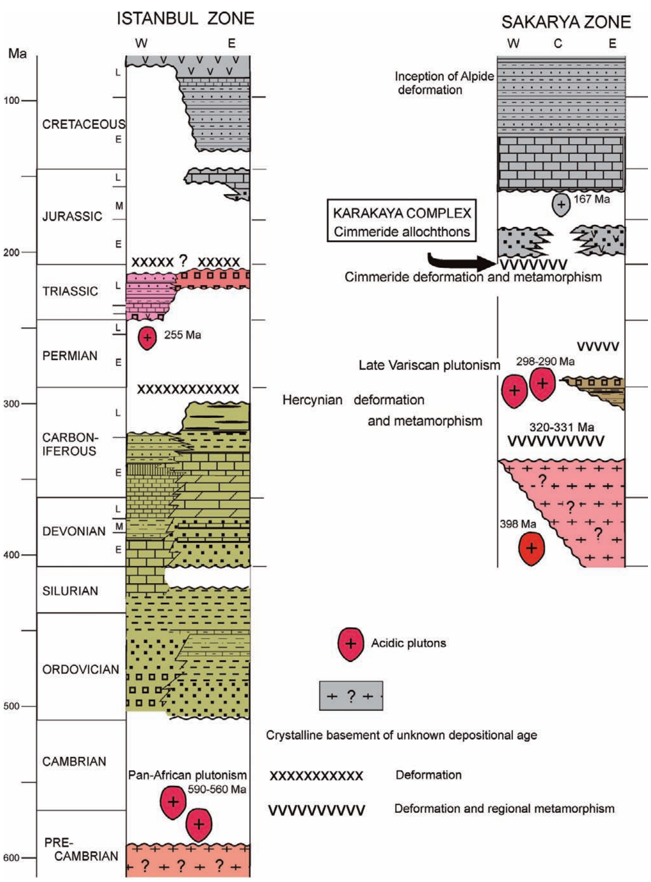


Fig. 2 - Stratigraphy of the Istanbul and Sakarya zones. (modified from Okay and Tüysüz, 1999).

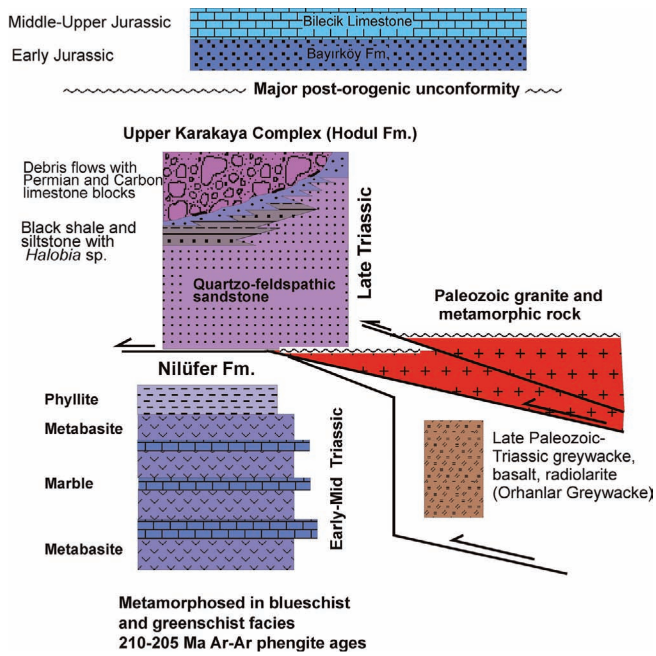


Fig. 3 - Generalized tectono-stratigraphy of the Karakaya Complex in northwest Turkey (modified from Okay, 2000).

Various tectonic settings have been proposed for the Nilüfer Formation. These include an accreted oceanic plateau (Okay, 2000), an oceanic seamount (Pickett and Robertson, 1996) and an ensimatic fore arc (Göncüoglu et al., 2000). For more extensive discussions of the tectonic setting of the Nilüfer Formation see Picket and Robertson (1996; 2004), Okay (2000), Göncüoğlu et al. (2000), and Okay and Göncüoğlu (2004).

Upper Karakaya Complex (Hodul Formation and the Orhanlar Greywacke): trench clastics

The basaltic rocks of the Nilüfer Formation are overlain by several-km-thick, highly disrupted, turbiditic clastic sequences representing Triassic accretionary complexes. The contacts between the two are almost always tectonic. The coherence of the clastic sequences is largely destroyed; they range from broken formation to mélange, and locally show a dynamo-thermal metamorphism and cleavage development (Federici et al., 2010). Two major types of clastic sequences can be distinguished. One is a quartzo-feldspathic sandstone-shale sequence (Hodul Formation) with a continental granitic source; the other is a greywacke-shale sequence (Orhanlar Greywacke) (Fig. 3; Okay et al., 1991).

The quartzo-feldspathic clastic sequence (the Hodul Formation) ranges from proximal to distal turbidites and, in regions near the İzmir-Ankara suture, passes up to extensive Late Triassic debris flows with exotic Carboniferous-Permian limestone blocks in a greywacke matrix. This olistostromal belt can be traced from the mainland to the Island of Lesbos in the Aegean. The neritic Carboniferous and Permian limestone blocks, that may reach up to several kilometers in size, make up over 95% of the olistoliths and are characterised by rich fusulinid faunas (Leven and Okay, 1996). Rarer blocks of fine-grained aphyric mafic volcanics and pelagic sedimentary rocks also occur in the olistostromes.

The Orhanlar Greywacke consists of homogeneous greywackes with poorly sorted, angular quartz, plagioclase, opaque, lydite, radiolarian cherts, mafic volcanic rocks and phyllite fragments in an argillaceous matrix. The sandstones contain small blocks of Early Carboniferous dark limestones, rich in corals, brachiopods and foraminifera (Leven and Okay, 1996). The pelagic limestones and radiolarian chert blocks in the Upper Karakaya Complex have yielded Devonian, Middle Carboniferous (Bashkirian) and Late Permian conodont and radiolaria ages (Okay and Mostler, 1994; Kozur and Kaya, 1994; Okay et al., 2011) pointing to the existence of a late Paleozoic ocean.

Jurassic and younger cover rocks of the Sakarya Zone

Following the latest Triassic Karakaya orogeny, molasse-type continental- to shallow-marine Early Jurassic clastic rocks were deposited over the entire Sakarya Zone (e.g., Altıner et al., 1991). They lie unconformably over various Karakaya Complex units, as well as on the Paleozoic granitic rocks. The Early Jurassic clastic rocks are disconformably succeeded by the Middle Jurassic to Early Cretaceous neritic carbonates, which are in turn unconformably overlain by the Albian-Cenomanian pelagic limestones and clastic rocks. In northwest Turkey the rest of the Cretaceous and Paleocene sedimentary sequence is missing, and Middle Eocene neritic limestones unconformably overlie units as old as the Karakaya Complex (Siyako et al., 1989). However, farther east, in the region east of Bursa, the Middle Cretaceous pelagic limestones are succeeded by an over 1000-m-thick Late Cretaceous tuffaceous flysch sequence with serpentinite, blueschist and Jurassic limestone olistoliths, which passes up into the continental to fluviatile Paleocene clastic rocks (Saner, 1980). The first contractional movements were in the Paleocene, when Jurassic limestones were thrust south over the Paleocene terrigeneous sandstones (Yılmaz, 1981). The passage from flysch to molasse sedimentation, and subsequent thrusting, reflect the Paleocene continent-continent collision between the Sakarya Zone and the Anatolide-Tauride Block.

THE ANATOLIDE-TAURIDE BLOCK

The Anatolide-Tauride Block forms the bulk of southern Turkey and, in contrast to the Pontide continental fragments, shows a Paleozoic-Mesozoic stratigraphy similar to the Arabian Platform, and hence to that of Gondwana (Şengör and Yılmaz, 1981). During the obduction, subduction and continental collision episodes in the Late Cretaceous-Paleocene, the Anatolide-Tauride Block was in the footwall position, and underwent much stronger deformation and higher grade regional metamorphism than that observed in the Pontide zones. During the early part of the Late Cretaceous, a massive body of ophiolite and accretionary complex was emplaced over the Anatolide-Tauride Block. The northern margin of the Anatolide-Tauride Block underwent high pressure-low temperature (HP/LT) metamorphism at depths of over 70 km. Erosional remnants of this ophiolite thrust sheet occur throughout the Anatolide-Tauride Block. With the inception of continental collision in the Paleocene the Anatolide-Tauride Block was internally sliced, and formed a south to southeast vergent thrust pile. The compression continued until the Early to Middle Miocene in western Turkey, and is still continuing in eastern Anatolia. The lower parts of the thrust pile in the north were regionally metamorphosed, while the upper parts in the south form large cover nappes. This leads to subdivision of the Anatolide-Tauride Block into zones with different metamorphic and structural features, in a similar manner to the subdivision of the Western Alps into Helvetics and Penninics albeit with a different polarity. In western Turkey there are three main regional metamorphic complexes: a Cretaceous blueschist belt (the Tavşanlı Zone in the north), a Paleocene HP metamorphic belt (the Afyon Zone in the centre, Candan et al., 2005; Pourteau et al., 2010), and an Eocene Barrovian-type metamorphic zone (the Menderes Massif, in the south, Bozkurt and Oberhansli, 2001, Figs. 1 and 4). To the northwest of the Menderes Massif there is a belt of chaotically-deformed latest Cretaceous-Paleocene flysch with Triassic to Cretaceous limestone blocks (Bornova Flysch Zone). The Taurides, which lie south of the metamorphic regions, consist of a stack of thrust sheets of Mesozoic sedimentary rocks (e.g., Gutnic et al., 1979; Özgül, 1984).

Although the Anatolide-Tauride Block shows a variety of metamorphic, structural and stratigraphic features, there are some elements of stratigraphy common to all of these zones, and which distinguish the Anatolide-Tauride Block as a single tectonic entity. These are a Pan-African crystalline basement, a discontinuous Cambrian to Devonian succession dominated by siliciclastic rocks, a Permian-Carboniferous sequence of intercalated limestones, shales and quartzites, and a thick Late Triassic to Late Cretaceous carbonate sequence. Hercynian deformation or metamorphism, and Triassic subduction-accretion units, characteristic features of the Sakarya Zone, are not observed in the Anatolide-Tauride Block.

The geology of the Tavşanlı Zone, the Anatolide-Tauride Zone, is described below.

TAVŞANLI ZONE - A SUBDUCTED PASSIVE CONTINENTAL MARGIN

The Tavşanlı Zone is a 50-60-km-wide and about 250-km-long east-west trending belt of regional blueschists tectonically overlain by an oceanic accretionary complex and large peridotite slabs (Figs. 1 and 4). Undeformed Early to Middle Eocene granodiorites (ca. 50 Ma $^{40}Ar/^{39}Ar$ isochron ages), intrude the blueschists and the overlying peridotites. The blueschists of the Tavşanlı Zone represent the subducted north-facing passive continental margin of the Anatolide-Tauride Block, and show a similar tectonic evolution to those from Oman (e.g., Goffe et al., 1988; Searle et al., 1994). They were partly exposed by, or were at high crustal levels during the latest Cretaceous, prior to the Paleocene continent-continent collision, as evidenced by blueschist detritus in the latest Cretaceous clastic sequences in the Sakarya Zone north of the Tavşanlı Zone.

The four tectonostratigraphic units of the Tavşanlı Zone, namely the regional blueschists, the Cretaceous accretionary complex, the ophiolite, and the Eocene granodiorites, are described below.

The coherent continental blueschist sequence - Orhaneli Group

The Orhaneli Group constitutes a coherent stratigraphic series made up predominantly of metasedimentary rocks (Okay, 1985). In the western part of the Tavşanlı Zone it is

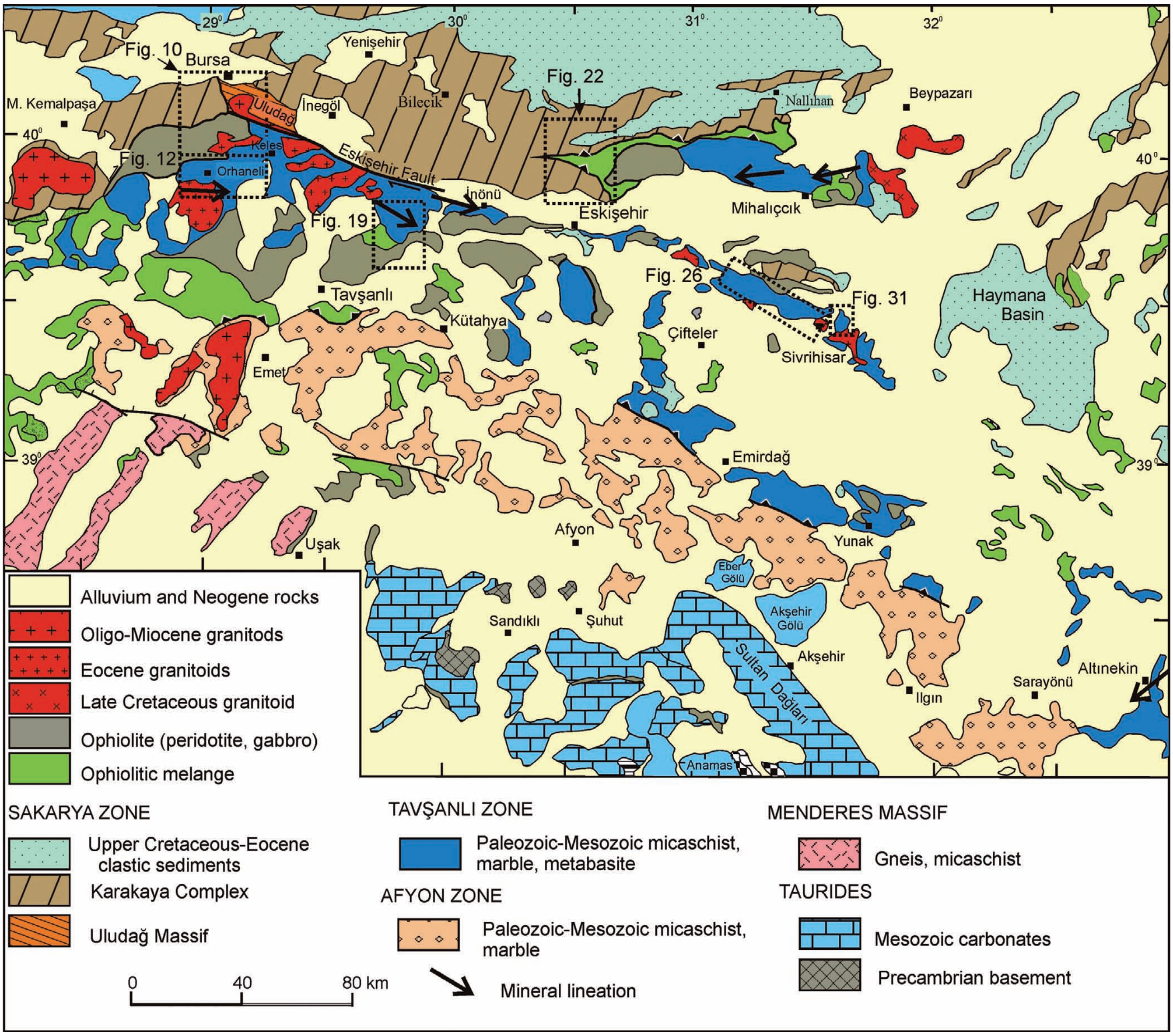


Fig. 4 - Geological map of the Tavşanlı Zone. The Figure numbers (e.g., Fig. 19) refer to the detailed maps in the paper.

subdivided into three formations. These are from base upwards the Kocasu Formation, the İnönü Marble and the Devlez Formation (Figs. 5 and 6). In the eastern part of the Tavşanlı Zone, the intercalated micaschists and marbles, which crop out at around Sivrihisar, are known as the Sivrihisar Formation. The stratigraphic base of the Orhaneli Group is not observed. An Ordovician metagranitoid only crops out in a small area around Orhaneli, which may represent a tectonic slice from the basement. The age of the blueschist metamorphism, based on Rb/Sr phengite dating, is Campanian (ca. 80 Ma, Sherlock et al., 1999). Ar/Ar phengite plateau ages from blueschists in the Sivrihisar region are 88-81 Ma (Seaton et al., 2009; Whitney et al., unpublished data).

The Kocasu Formation

The Kocasu Formation is a coherent sequence of quartz-micaschists, with a minimum thickness of 800 meters, at the base of the Orhaneli Group (Okay, 2004). Micaschists form medium-grained, hard, finely banded, grey to light grey rocks. Quartz-rich micaschist bands with a gneissic texture, 0.1 to 2 m in thickness, alternate with finer grained and more mica-rich micaschists (Okay and Kelley, 1994; Okay, 2002). Metaconglomerates with quartz clasts occur rarely within the micaschists. The percentage of mica increases upwards in the metamorphic sequence. Southeast of the town of M. Kemalpaşa there are metaaplitic sills and dykes, 0.5 to 3 m in thickness, within the micaschists, now consisting of jadeite, quartz and secondary albite (Okay and Kelley, 1994).

The lithological characteristics of the Kocasu Formation indicate that before the metamorphism the sequence consisted of an alternation of sandstones and shales, however, the rocks are now completely recrystallized and have lost their primary lithological features. The Kocasu Formation passes upwards gradually to the İnönü Marble. The transition zone consists of micaschists intercalated with marble layers.

The Kocasu Formation crops out over a large area between Mt. Kemalpaşa in the west and southeast of Uludağ in the east. It also crops out northwest of Mihaliçcık under the İnönü Marble. In this latter region, the metaclastic

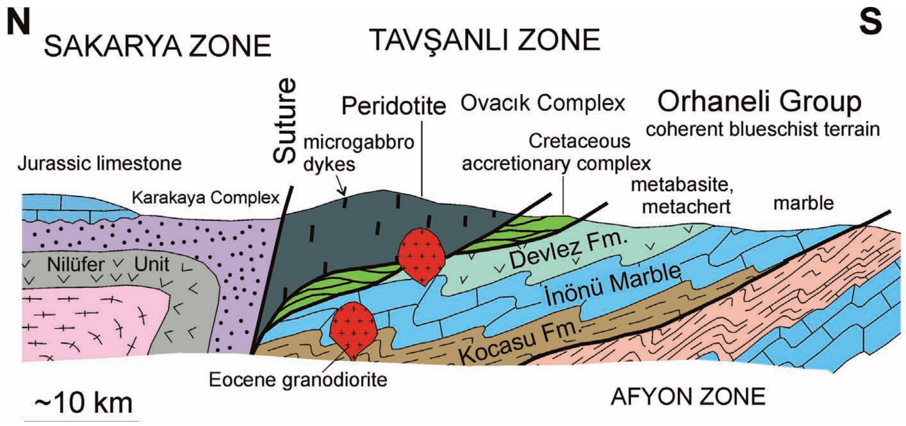


Fig. 5 - Simplified schematic cross-section across the Tavşanlı Zone showing the gross-scale structure and the tectonostratigraphic units.

sequence has been called the Göktepe metamorphics by Göncüoğlu et al. (2000). The stratigraphic base of the Kocasu Formation is not exposed; however, it is probably underlain by a lower Paleozoic granitic basement. The clastic zircon ages from the Kocasu Formation in the Orhaneli and Keles regions are Ordovician and Permian-Carboniferous (Okay et al., 2008a) and indicate a post-Carboniferous depositional age. A comparison with the general stratigraphy of the Taurides (e.g., Gutnic et al., 1979; Özgül, 1976) suggests a Permian-Triassic, and probably Early to Middle Triassic age for the Kocasu Formation.

The micaschists of the Kocasu Formation consist essentially of quartz and phengite. South of Bursa, these minerals are accompanied by chlorite, jadeite, chloritoid, lawsonite and albite. The critical HP/LT mineral paragenesis in the micaschists is quartz + phengite + jadeite + chloritoid + glaucophane + lawsonite. Jadeite, locally pseudomorphed by sericite and albite, is common in the Orhaneli region, which possibly is the most jadeite-rich area in the world. The mineral assemblages in the metaclastic rocks tightly constrain the P-T (pressure-temperature) conditions in the Orhaneli Group to a pressure of about 24 kbar and a temperature of about 430°C (Okay and Kelley, 1994; Okay, 2002).

İnönü Marble

The micaschists of the Kocasu Formation are stratigraphically overlain by a thick sequence of carbonates, called the İnönü Marble (Figs. 5 and 6; Servais, 1982). The İnönü Marble crops out over large areas in the western part of the Tavşanlı Zone (Konak, 2002). It is made up of white and light grey, massive, locally banded marbles with occasional chert bands. A characteristic microstructural feature of the İnönü Marble is a strong mineral lineation defined by the parallel alignment of elongate calcite grains, common throughout the Tavşanlı Zone including the Sivrihisar area. The İnönü Marble consists of calcite, although it must have been made up of aragonite during the metamorphism.

The İnönü Marble represents the metamorphosed equivalent of the Tauride Mesozoic carbonate platform. This is supported by the description of Late Triassic (late Norian) conodonts from the lower parts of the İnönü Marble from east of Orhaneli (Kaya et al., 2001). The upper parts of the İnönü Marble probably extend into the Early Cretaceous.

Devlez Formation

The sequence of metabasites, metacherts and phyllites, which overlie the İnönü Marble, is called the Devlez Formation (Okay, 1981; 2004). Metabasites constitute the bulk (>80%) of the Devlez Formation. They are represented by submarine lavas, pyroclastic rocks and tuffs, which are, however, completely recrystallized with the development of a penetrative metamorphic fabric and new minerals. The metabasites are characterized by sodic amphibole and lawsonite with minor sodic pyroxene, chlorite, leucoxene and phengite (Okay, 1980a). These are the classical "blue" blueschists. The metacherts include quartz, spessartine-rich garnet, hematite, lawsonite and sodic pyroxene (Okay, 1980a). The structural thickness of the Devlez Formation in the region northeast of Tavşanlı is one kilometer. Metabasites and metacherts of the Devlez Formation show a strong foliation and a strong mineral lineation defined by the parallel alignment of the sodic amphibole grains. The Devlez Formation shares a common metamorphic and deformational history with the underlying İnönü Marble.

Sivrihisar and Halilbağı Formations

In the eastern part of the Tavşanlı Zone, especially in the region of Sivrihisar, the Orhaneli Group is represented by an intercalation of marble and micaschist. These metasedimentary rocks, called the Sivrihisar Formation, have a structural thickness of over three kilometers (Kulaksız, 1981; Gautier, 1984; Monod et al., 1991). Marbles form bands within the micaschists, whose thickness ranges from a few meters to several hundred meters. There are approximately equal amounts of marbles and micaschists in the Sivrihisar Formation. Apart from these two dominant rock types, there are rare metabasite layers within the micaschists. The Sivrihisar Formation probably represents a lateral facies variation of the Kocasu Formation and İnönü Marble.

Unlike the western part of the Tavşanlı Zone, HP/LT mineral paragenesis is not well preserved in the Sivrihisar Formation. The common mineral assemblage in the micaschists is quartz + albite + chlorite + phengite, and in the metabasites albite + chlorite + actinolite + epidote (Gautier, 1984; Davis and Whitney, 2006). However, the presence of lawsonite in the metabasites and in calcium-rich micaschists and relict sodic amphibole in the metabasites indicates that the Sivrihisar Formation has undergone a regional HP/LT metamorphism (Monod et al., 1991; Davis and Whitney, 2006), which was subsequently overprinted by a greenschist facies metamorphism.

South of the village of Halilbağı, the Sivrihisar Formation is overlain by metabasites, metacherts and marbles, called the Halilbağı Formation. The HP/LT mineral paragenesis, including lawsonite-eclogites, is well preserved in the Halilbağı region, which has been the subject of several detailed petrological studies (Kulaksız, 1978; Monod et al., 1991; Davis and Whitney, 2006; 2008; Whitney and Davis,

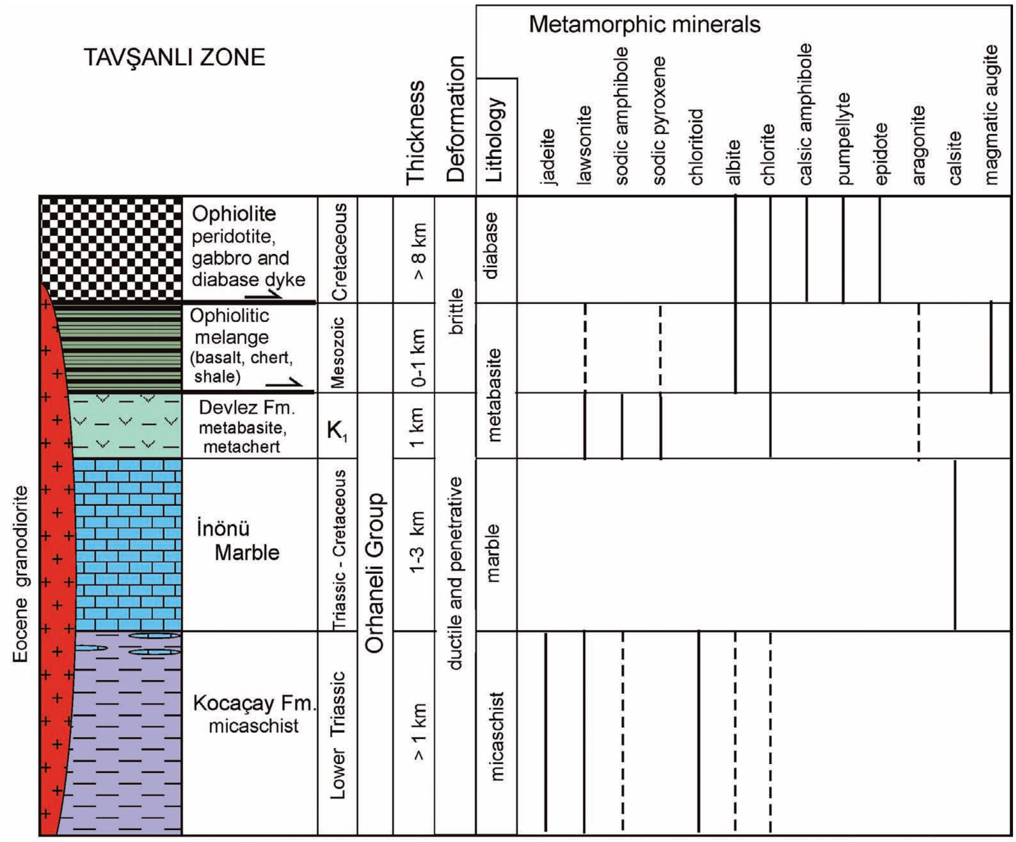


Fig. 6 - Stratigraphy, lithology, structural features and mineral parageneses in the western part of the Tavşanlı Zone (modified from Okay, 1986). ab- albite; co- coesite; grt.- garnet; jd- jadeite; ky- kyanite; law- lawsonite; pa- paragonite; q- quartz; sp.- spinel; v- H_2O; zo- zoisite.

2006; Çetinkaplan et al., 2008). In the Halilbağı region, the metabasic rocks consist of an interesting intercalation of blueschists, garnet-blueschists and lawsonite-eclogites. The Halilbağı Formation is underlain possibly tectonically by the Sivrihisar Formation. The nature of the contact between the two formations is difficult to characterize, as petrologically uninformative marbles crop out along the contact zone. Nevertheless, all marbles in the region are characterized by elongate calcite (pseudomorphs after aragonite), indicating that all units experienced HP/LT metamorphism. The Halilbağı Formation can be correlated with the Devlez Formation from the western part of the Tavşanlı Zone.

Structure of the blueschists

The metasedimentary rocks of the Orhaneli Group show penetrative foliation and isoclinal folding, and have lost all traces of their primary sedimentary protolith. The foliation is gently dipping except at some fault zones. A mineral stretching lineation has developed in marbles, metacherts and metabasites defined mainly by calcite and sodic amphibole (Monod et al., 1991; Okay et al., 1998; Masuda et al., 2004). The mineral lineation trends approximately east-west in the Orhaneli, Tavşanlı and Mihaliççık regions subparallel to the İzmir-Ankara suture (Fig. 4), and north-south and northeast-southwest in the Sivrihisar (Monod et al., 1991) and Konya-Altınekin regions (Eren, 2000), respectively. The axes of the isoclinals folds are subparallel to the mineral lineation. These observations indicate a strong stretching subparallel to the present trend of the İzmir-Ankara suture. The shapes of the clasts in the metaconglomerates of the Orhaneli Group also indicate that the finite strain ellipsoid is of constrictional type. An analysis of the crystallographic orientation of the quartz crystals in the blueschists of the Halilbağı Formation also produced a finite strain ellipsoid that falls in the field of apparent constriction ($0.2 < k < 0.8$, Monod et al., 1991). This deformation is coeval with the HP/LT metamorphism. A possible model explaining this unusual trend of the mineral lineation, as well as an exhumation mechanism for the blueschists, is given in Okay et al. (1998).

The Cretaceous accretionary complex (The Ovacık Complex)

In many regions in the Tavşanlı Zone a tectonic unit of basalts, radiolarian cherts, pelagic shales, pelagic limestones and serpentinites, often referred to as ophiolitic mélange, lies above the Orhaneli Group. Most of this Ovacık Complex is constituted by basaltic agglomerates and pyroclastics with lesser amounts of red radiolarian cherts and pelagic shales. Serpentinites, pelagic limestones and greywackes make up less than 10%. Basaltic agglomerates commonly contain blocks of recrystallized limestones up to several hundred meters wide.

Although the Ovacık Complex is generally known as a mélange, it lacks an easily definable matrix and instead consists of strongly deformed rock types juxtaposed along tectonic contacts. Stratigraphic relation between the different rock types are generally not preserved and it is difficult to follow bedding for more than ten meters without encountering a fault or shear zone. With its lithological features, internal structure and its incipient HP metamorphism, the Ovacık Complex represents a Tethyan subduction-accretion complex. The Ovacık Complex differs from the Franciscan or Makran type accretionary complexes in the scarcity of clastic rocks.

Apart from local foliation along the shear zones, the rocks of the Ovacık Complex are generally free of penetrative deformation and generally appear unmetamorphosed, except for the ubiquitous spilitization, which imparts a green color to the basalts. However, this is deceptive, as almost all the Ovacık Complex has undergone an incipient blueschist facies metamorphism (see later).

The Ovacık Complex and equivalent ophiolitic mélanges crop out widely outside the Tavşanlı Zone within the Afyon Zone, in the Bornova Flysch Zone, in the Menderes Massif and in the Taurides. Radiolaria from the cherts within the Ovacık Complex from the Tavşanlı and Bornova Flysch Zones have given Late Triassic (late Carnian, late Norian), Jurassic, Early Cretaceous (Berriasian-Hauterivian) and Late Cretaceous (Cenomanian, Turonian) ages (Bragin and Tekin, 1996; Tekin et al., 2002; Göncüoğlu et al., 2006). These radiolarian ages indicate that the Neo-Tethyan oceanic crust north of the Anatolide-Tauride Block had a minimum age range from Late Triassic to Cretaceous. A 179±15 Ma zircon U-Pb age from a plagiogranite from an ophiolitic mélange near Ankara also indicates the presence of an Early Jurassic oceanic crust in the northern Neo-Tethys (Dilek and Thy, 2006). The geochemistry of the basaltic rocks in the Ovacık Complex shows the presence of several magma types with a dominance of oceanic island and mid-ocean ridge type basalts (Tankut et al., 1998; Rojay et al., 2004; Göncüoğlu et al., 2006; Gökten and Floyd, 2007).

Anatolian Ophiolites

Large ophiolite massifs lie tectonically over the Ovacık Complex or directly on the blueschists of the Orhaneli Group. Over 90% of the ophiolitic masses in the Tavşanlı Zone are made up of peridotites; the rest is represented by pyroxenites, gabbros, chromites and diabase dykes. Sub-ophiolitic metamorphic rocks are described from the base of the ophiolites. It is probable that the various ultramafic fragments in the Tavşanlı Zone (Fig. 4) initially formed part of a very large ophiolite.

The peridotites consist of harzburgites and dunites; lenticular chromite deposits occur within the dunites. The best studied ophiolite is the Burhan ophiolite north of Orhaneli; it consists predominantly (>90%) of harzburgites and dunites, the rest is made up of gabbros, pyroxenites, chromites and diabase dykes (Lisenbee, 1971; 1972; Tankut, 1980). The harzburgites and dunites form bands, ~2 km thick, intercalated with thinner bands of gabbro and pyroxenite. The bands are transitional over a width of 50 m. The peridotites show a tectonic foliation subparallel to the lithological layering. The thickness of the Burhan ophiolite, measured perpendicular to lithological layering, is over 13 kilometers. The lithological and structural features of the Burhan ophiolite show it to be a deformed cumulate sequence. Locally, such as in the Sivrihisar region, the peridotites are intensely serpentinized.

The mineral paragenesis in the peridotites of the Tavşanlı Zone is olivine + orthopyroxene + clinopyroxene + chrome-spinel (Lisenbee, 1971; Okay, 1985; Lünel, 1986; Asutay et al., 1989; Önen, 2003). This mineral assemblage is stable at pressures of less than 14 kbar; garnets start to form at higher pressures (Perkins et al., 1981). The paragenesis in the gabbros is plagioclase (An_{89-100}) + clinopyroxene + orthopyroxene + spinel (Önen, 2003). Based on the petrography and geochemistry of the ophiolitic rocks around Kütahya, Önen (2003) argues that they are similar to those formed in the oceans and in the back-arc basins.

The ophiolites in the western Anatolia show many common lithological and structural features: (a) they are generally made up of harzburgites and dunites, (b) the peridotites are cut by diabase dykes, (c) all of the isotopically dated sub-ophiolite metamorphic rocks in Anatolia are Albian in age, (d) the sub-ophiolite metamorphic rocks show a low-grade HP/LT metamorphism that overprints the earlier HT (high-temperature) metamorphism (Dilek and Whitney, 1997; Okay et al., 1998; Önen and Hall, 2000). These common features suggest that these ophiolitic massifs formed part of a very large ophiolite obducted over the Anatolide-Tauride Block during the Late Cretaceous (Dilek et al., 1999; Önen 2003). In terms of its size and its association with the HP/LT metamorphic rocks this Anatolian ophiolite nappe can be compared with the Semail Ophiolite in Oman.

Sub-ophiolite metamorphic rocks

Most ophiolites have a metamorphic sole produced during the intra-oceanic thrusting stage (e.g., Williams and Smyth, 1973; Woodcock and Robertson, 1977). The sub-ophiolite metamorphism forms during intra-oceanic thrusting through frictional heating and through the downward convection of heat from the overlying ophiolite body. As the heat is conducted downward, the sub-ophiolite metamorphic rocks show an inverted metamorphic zonation with the metamorphic grade increasing upwards in the sequence. As the sub-ophiolite metamorphism occurs in the oceanic lithosphere, the metamorphic rocks are naturally of oceanic crustal origin.

Sub-ophiolite metamorphic rocks are described from several localities in the Tavşanlı Zone, including the Sivrihisar, Kütahya and Orhaneli areas (Gautier, 1984; Monod et al., 1991; Önen and Hall, 1993; 2000; Okay et al., 1998). The garnet-amphibolites at the base of the Burhan ophiolite have peak P-T values of 8.5±30 kbar and ~700°C (Okay et al., 1998). The pressure values indicate an initial ophiolite thickness of 25±10 km. The amphibolites at the base of the Burhan ophiolite also exhibit a second phase of low-grade HP/LT metamorphism marked by the development of sodic amphibole and very fine-grained aggregates of lawsonite. A similar case has been described from the sub-ophiolite metamorphic rocks in the Central Taurides (Dilek and Whitney, 1997). Hornblende Ar-Ar cooling ages of the sub-ophiolite metamorphic rocks at the base of the Burhan ophiolite are 101±4 Ma (Harris et al., 1994), and those from the Kütahya region 93±2 Ma (Önen, 2003). These ages are similar to the 95-90 Ma Ar-Ar hornblende and mica ages from the sub-ophiolite metamorphic rocks of the Lycian, Beyşehir, Aladağ, Kızıltepe and Mersin ophiolites in the Taurides (Dilek et al., 1999; Parlak and Delaloye, 1999; Çelik et al., 2006).

Diabase dykes

The ophiolites in the Tavşanlı Zone are cut by generally east-west trending diabase dykes. The diabase dykes, which have an average thickness of 1-2 meters, cannot generally be followed along strike for more than 100 meters. The dyke frequency is quite variable and ranges from a single dyke within a stretch of several hundred meters of peridotite to 10 dykes within 30 m of peridotite. The dyke-peridotite contacts are generally faulted due to later brittle deformation, however, in some localities the original intrusive contact are preserved and the dykes can be seen to have narrow chilled margins. This observation indicates that the dykes intruded into cold peridotite (Okay, 1981). The mineral assemblage in the diabase dykes is augite, partly replaced by magmatic hornblende, and altered plagioclase. Plagioclase has commonly altered into very fine grained aggregates of pumpellyite and albite. The mineral assemblage in the diabase dykes indicates that they, and by implication the ophiolitic rocks, have not undergone the HP/LT metamorphism observed in the underlying Orhaneli Group.

Diabase dykes very similar to those described above occur in the peridotites of the Lycian nappes (Whitechurch et al., 1984) and of the Central Taurides (Lytwyn and Casey, 1995; Parlak, 2000). Whole rock Ar-Ar ages of the diabase dykes cutting the Mersin ophiolite and the sub-ophiolitic metamorphic rocks of the Mersin ophiolite range between 90 Ma and 64 Ma (Parlak and Delaloye, 1996). Considering the large errors associated with whole rock Ar-Ar dating, and that the emplacement of the ophiolite over the Anatolide-Tauride Block occurred during the Campanian, the crystallization ages of the diabase dykes are expected to be at around 90 Ma.

Early Eocene Sedimentary Rocks

In the eastern part of the Tavşanlı Zone, ophiolitic rocks, ophiolitic mélange and the blueschists of the Orhaneli Group are unconformably overlain by Early Eocene marine sedimentary rocks (Fig. 4). The westernmost exposure of the Eocene sediments is found north of Tavşanlı, where the peridotites are unconformably overlain by a 60-m-thick shallow marine sequence of Early Eocene (Cuisian) sandy and pebbly limestones (Baş, 1986). Farther east, south of Eskişehir and southwest of Çifteler an Early Eocene (Cuisian) marine sequence of conglomerates, sandstones, shales and shaley limestones with abundant nummulites, ~300 m thick, lies unconformably over the ophiolitic gabbros and the metamorphic rocks (Gözler et al., 1985; Göncüoğlu et al., 1992; Özgen-Erdem et al., 2007). The stratigraphic data indicate that the Tavşanlı Zone was covered by a shallow sea at the beginning of the Early Eocene (50 Ma).

Eocene Plutons

Apart from the marine Eocene sedimentation, a series of plutons have intruded into the Tavşanlı Zone during the Eocene. These intrusions form a WNW-ESE trending linear belt between Sivrihisar and Bursa (Fig. 4, Okay and Satır, 2006). The plutons have generally a granodioritic composition and comprise hornblende and biotite; their ages range from 53 Ma and 45 Ma (Early-Middle Eocene). The 48 Ma old Topuk pluton farthest west cuts the blueschists of the Orhaneli Group as well as the overlying peridotites, indicating that the tectonic contact between these units is pre-Eocene in age (Okay et al., 1998).

The Eocene plutons in the Tavşanlı Zone have a metaaluminous composition and the amount of SiO_2 varies between 63 and 69%. Enrichment in the large ion lithosphere elements in the granodiorites indicates a calc-alkaline magma. Relatively low yttrium and heavy rare earth ratios suggest that garnet was not an important restite phase in the region of magma generation and hence the magma was generated at depths of less than 30 kilometers (10 kbar). The Eocene granodiorites have formed by fractionation of mantle-derived magmas in shallow magma chambers and through crustal melting induced by mantle derived basic magmas (Harris et al., 1994; Altunkaynak, 2007; Karacık et al., 2008; Kibici et al., 2008).

Metamorphism and metamorphic ages in the Tavşanlı Zone

The three tectonostratigraphic units of the Tavşanlı Zone show different metamorphic characteristics. The Orhaneli Group has undergone a regional blueschist facies metamorphism (Çoğulu, 1965; 1967; van der Kaaden, 1966; Lünel, 1967; Okay, 1980a; 1980b; 1981; 1984; 2002; Servais, 1981; Kaya, 1981; Gautier, 1984; Monod et al., 1991; Davis and Whitney, 2006; 2008; Çetinkaplan et al., 2008). The minerals of the blueschist metamorphism are particularly well preserved in the western part of the Tavşanlı Zone and in the Sivrihisar region near the Halilbağı village. The characteristic HP/LT mineral paragenesis in the metabasites is sodic amphibole + lawsonite + chlorite ± sodic pyroxene + phengite + sphene (Çoğulu, 1967; Okay, 1980a). Apart from these minerals some metabasites contain garnet. In the metabasites the sodic amphibole is generally of glaucophane and crossite composition and the sodic pyroxene is chloromelanite. In the Sivrihisar-Halilbağı region where metamorphic temperatures were slightly higher, rutile substitutes for sphene and omphacite for chloromelanite. The common mineral paragenesis is the metacherts is quartz + garnet + sodic amphibole + lawsonite + phengite + hematite In the metacherts the garnet is rich in spessartine and sodic amphibole is magnesio-riebeckite and crossite in composition.

An important feature of the blueschists in the western part of the Tavşanlı Zone is that they commonly preserve prograde mineral assemblages. This is most apparent in the metabasites of the Devlez Formation (Okay, 1980b). The initial metabasite assemblage consisted of sodic pyroxene + lawsonite + chlorite + quartz, where sodic pyroxene typically pseudomorphs the igneous augite. Sodic pyroxene in these metabasites is of an aegirine-jadeite composition with high aegirine content. At this metamorphic stage, called the lawsonite zone, there is no penetrative deformation, and the original igneous texture of the basalt is discernable (Okay, 1980b). In the second stage associated, with the inception of penetrative deformation, sodic amphibole forms at the expense of sodic pyroxene, chlorite and quartz. The metamorphic reaction can be written as:

Sodic pyroxene + chlorite + quartz =
sodic amphibole + lawsonite

The characteristic HP/LT mineral paragenesis in the micaschists of the Kocasu Formation and of the Kapanca metagranitoid is: jadeite + chloritoid + lawsonite + glaucophane + quartz + phengite (Okay and Kelley, 1994; Okay, 2002; Okay and Satır, 2006; Okay et al., 2008a). This mineral assemblage in the metapelitic rocks shows that the peak pressure and temperature values of the metamorphism in the western part of the Tavşanlı Zone is 24±3 kbar and 430±30°C (Okay, 2002).

In the Halilbağı region, where the temperature during the metamorphism was slightly higher, the metabasic rocks contain the mineral assemblages characteristic for the lawsonite-eclogite: sodic pyroxene + garnet + sodic amphibole + lawsonite (Kulaksız, 1981; Monod et al., 1991; Davis and Whitney, 2006; 2008; Whitney and Davis, 2006; Çetinkaplan et al., 2008). The lawsonite eclogites in the Halilbağı region are intercalated with lawsonite ± garnet-bearing blueschists. The peak P-T conditions of eclogite in the Halilbağı region have been estimated as 22-24 kbar pressure and 520°C temperature (Davis and Whitney, 2008). Lawsonite blueschist records similar P-T conditions to other parts of the Devlez Formation to the west, some at lower pressures (15-16 kbar) (Davis and Whitney, 2006).

The P-T conditions of the HP/LT metamorphism in the Sivrihisar Formation is not well constrained because of the strong overprint by the greenschist facies metamorphism. In the southeastern part of the Tavşanlı Zone, in the Konya-Altınekin region, the peak P-T conditions of the blueschist facies metamorphism have been estimated as 9-11 kbar pressure and 375-400°C temperature (Droop et al., 2005).

Metamorphism, in terms of recrystallization and associated deformation, is not apparent in the field in the rocks of the Ovacık Complex. However, close petrographic examination of the basalts usually reveals HP minerals such as lawsonite, sodic pyroxene and aragonite in the veins and amygdales of the rock (Okay, 1982). The magmatic clinopyroxene in the basalts has commonly been partly or totally pseudomorphed by aegirine-rich sodic pyroxene. Associated with the incipient metamorphism, there has been sodium metasomatism producing basalts with up to 8wt% Na_2O. Another interesting feature of the Ovacık Complex is the replacement of primary micrite in the pelagic limestones by several centimeters long aragonite crystals (Topuz et al., 2006). This case of prograde aragonitization from northeast of Tavşanlı, unique in the world, points to the very low temperature and relatively high pressure values in the subduction-accretion complex. The Ovacık Complex is made up of numerous tectonic slices buried to different depths; therefore it is not possible to give a single peak P-T value for the unit. The general absence of recrystallization indicates that the temperatures were below 200°C. The HP minerals in the basalts and their composition suggest that the pressure was in the range of 4 to 7 kbar (Okay, 1982; Topuz et al., 2006). In rare cases, the Ovacık Complex has undergone a stronger deformation and metamorphism, producing a sequence similar to the Devlez Formation.

In some parts of the Ovacık Complex, metamorphism is more apparent, foliation has started to develop in finer grained rocks and the color of the red cherts has become pale as a result of recrystallization. In such basaltic rocks the magmatic texture is still largely preserved, however the magmatic mineral assemblage is replaced by sodic pyroxene + lawsonite + chlorite + sphene. With an increase in penetrative deformation and in the intensity of foliation, sodic amphibole forms at the rims of the sodic pyroxenes through the reaction: sodic pyroxene + chlorite + quartz = sodic amphibole + lawsonite (Okay, 1980b).

The Anatolian Ophiolite does not show any regional metamorphism. The magmatic mineral assemblage of plagioclase and pyroxene is well preserved in the ophiolitic gabbros (Önen, 2003). The diabase dykes in the peridotites consists of magmatic hornblende, which has partly or totally replaced augite, and plagioclase, which has been replaced by fine grained aggregates of pumpellyite in albite. The secondary mineral assemblage in the diabase dykes is indicative of very low-grade metamorphism and shows that the Anatolian Ophiolite has not been affected by the HP/LT metamorphism observed in the Orhaneli Group.

The tectonic contact between the Orhaneli Group and the overlying ophiolitic mélange-ophiolite represents a major jump in the metamorphic grade. Rocks below the contact have undergone metamorphism at pressures of ca. 24 kbar and those above at pressures below 8 kbar; this difference in metamorphic pressures indicates that a rock column of 50 km in thickness has been excised along the contact.

Some regions in the Tavşanlı Zone show an Eocene high temperature - low pressure metamorphism associated with the Eocene granitic magmatism. The metamorphic rocks southeast of Uludağ (Fig. 4) are characterized by andalusite + cordierite + biotite + muscovite + K-feldspar + plagioclase mineral assemblage in the micaschists of the Kocasu Formation (Okay and Satır, 2006), and are intruded by Eocene plutons. In this region the development of a new foliation defined by biotite, cordierite and muscovite shows that the metamorphism is not just static contact metamorphism. The peak P-T conditions of this metamorphism overprinting the blueschist facies metamorphism is estimated as 2±1 kbar and 575±50°C. Rb-Sr muscovite and biotite isotopic analyses from a single specimen gave cooling ages of 46±3 Ma and 39±1 Ma, respectively (Okay and Satır, 2006).

A Barrovian metamorphism in the Orhaneli Group has been described from southeast of Sivrihisar. The metamorphic belt extending southeastward from Sivrihisar is made up of metabasites with partially overprinted lawsonite blueschists and eclogites and some metacherts, underlain by a thick pure marble series, which passes down into a mixed schist-marble unit with a dominance of schists (Fig. 4, Türkay and Kuşçu, 1992, Whitney et al., 2010). Whitney (2002) has described from this region micaschists and quartzites with andalusite, kyanite, sillimanite, staurolite and garnet. The Barrovian metamorphism southeast of Sivrihisar overprints the blueschist metamorphism and is of Eocene age (Whitney et al., 2010). The metamorphism predates intrusion of the Eocene plutons, as shown by the 58-63 Ma muscovite Ar/Ar cooling ages, which are older than the nearby pluton (53 Ma). In southeast Sivrihisar, the Barrovian rocks show a strong fabric in which the metamorphic index minerals define a regional lineation in L-tectonites developed under constriction.

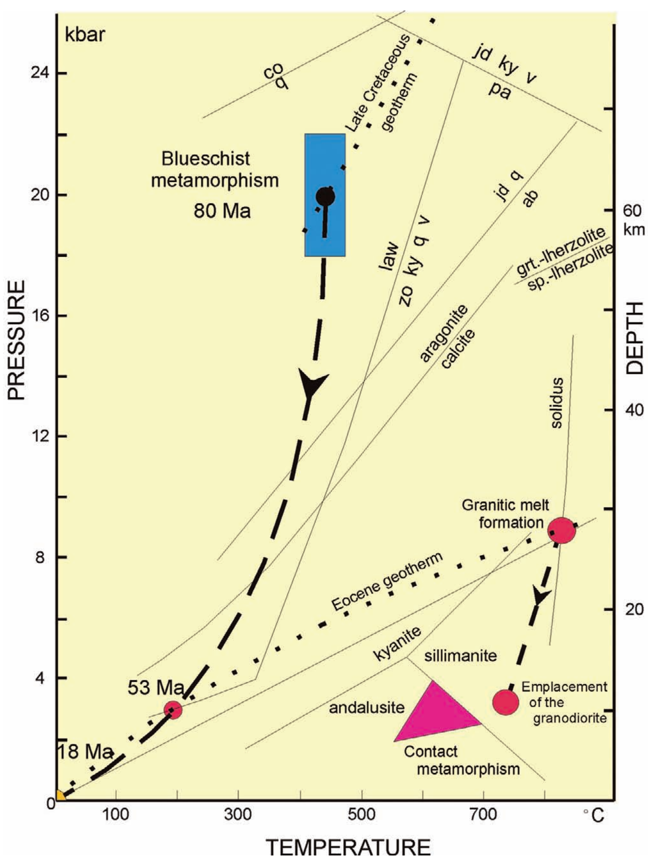


Fig. 7 - Exhumation pressure-temperature path of the Orhaneli Group blueschists.

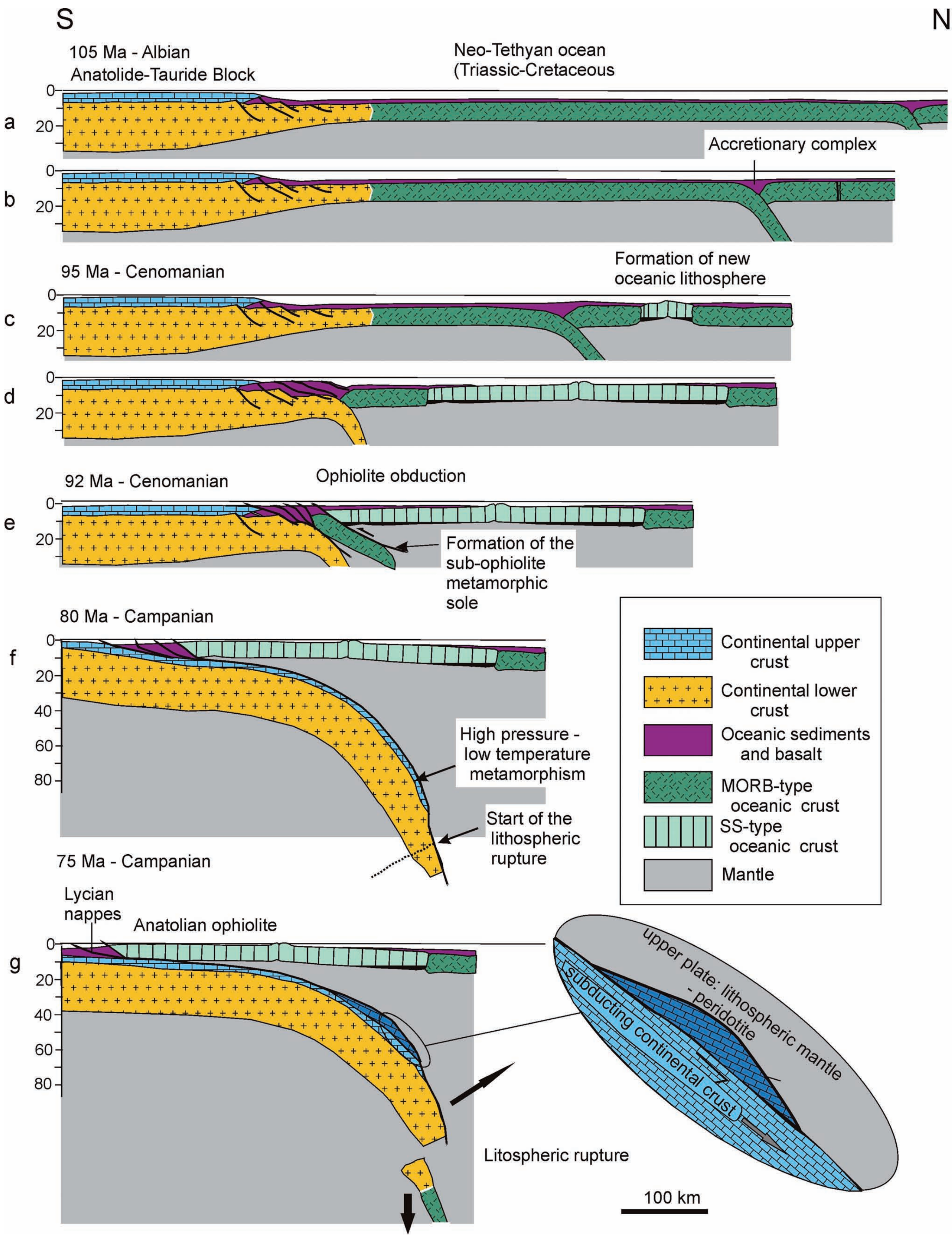


Fig. 8 - Geological evolution of the Tavşanlı Zone. For explanation see the text. The Figure is inspired from Lippard et al. (1986).

Age constraints on metamorphism

K-Ar and Ar-Ar isotopic determinations in HP/LT metamorphic rocks commonly give incompatible and contradicting ages due to excess argon and incomplete equilibration at these low temperatures (e.g., Arnaud and Kelley, 1995; Scaillet, 1996; Sherlock and Kelley, 2001; Warren et al., 2005). The K-Ar and Ar-Ar ages from the blueschists of the Tavşanlı Zone range between 175 Ma and 60 Ma (Çoğulu and Krummenacher, 1967; Okay and Kelley, 1994; Harris et al., 1994; Sherlock et al., 1999; Seaton et al., 2009). A detailed study by Sherlock (1998) on this topic has shown that this spread in Ar-Ar ages is largely due to excess argon. In contrast Rb-Sr phengite ages from four blueschists sampled between Tavşanlı and Sivrihisar are coherent and range between 78.5±15 Ma and 82.8±16 Ma (Sherlock et al., 1999). The relatively low peak metamorphic temperatures in the Orhaneli Group (430-450°C) imply that the Rb-Sr ages reflect the age of the HP/LT metamorphism. Similar Rb-Sr phengite ages from the blueschists of the Tavşanlı and Sivrihisar regions, separated by a distance of 130 km, indicate that the Orhaneli Group has undergone the HP/LT metamorphism during the Campanian (80±2 my). The isotopic ages from the blueschists of the Konya-Altıntekin region also correspond to Campanian (Giles Droop, 2000, personal communication).

A firm upper age limit for the HP/LT metamorphism is given by the 53 Ma Sivrihisar (Sherlock et al., 1999) and Orhaneli granodiorites (Harris et al., 1994), which are intrusive in the blueschists and show that the Orhaneli Group has reached upper crustal levels during the Early Eocene (Fig. 7). The Ar/Ar muscovite ages for Barrovian rocks intruded by the Sivrihisar granite are also 58-63 Ma.

The Ovacık Complex has undergone a low-grade HP/LT metamorphism. The age of this metamorphism is not known. Furthermore, as the Ovacık Complex represents an accretionary complex, one is not dealing with a single age of metamorphism. Considering that the northward subduction of the Neo-Tethys has started in the Albian, the metamorphism in the Ovacık Complex could have encompassed the whole of the Late Cretaceous.

GEOLOGICAL EVOLUTION

Early Cretaceous – Subduction and formation of the back-arc oceanic crust

In the beginning of the Cretaceous, the northern part of the Anatolide-Tauride Block was a passive margin facing north to the İzmir-Ankara Neo-Tethyan Ocean (Fig. 8). The Pontides, consisting of the Sakarya and İstanbul Zones, lay north of the İzmir-Ankara Neo-Tethyan Ocean. Paleontological data from the radiolarian cherts from the ophiolitic mélange show that the age of the İzmir-Ankara Neo-Tethyan Ocean extends from Middle Triassic to Cretaceous (Bragin and Tekin, 1996; Tekin et al., 2002).

Data on the age of the initiation of northward subduction of the İzmir-Ankara Neo-Tethyan Ocean are not clear. The arc magmatism in the Pontides started in the Turonian, however, isotopic ages of the Elekdağ blueschists and eclogites in the Central Pontides indicate ongoing subduction during the Albian (~105 Ma, Okay et al., 2006). During the Late Cretaceous there might have been two subduction zones; one giving rise to the development of an oceanic back-arc basin (Fig. 8c) and the other farther north (not shown in Fig. 8) producing the Pontide arc-magmatism. The Anatolian Ophiolite represents not the İzmir-Ankara Neo-Tethyan Ocean but rather the back-arc oceanic lithosphere formed during the Cretaceous. There is no isotopic or paleontological data on the age of this back-arc type Anatolian Ophiolite. However, studies in the ophiolites worldwide have shown that the age of the sub-ophiolite metamorphism is close to the age of the ophiolite (e.g., Spray et al., 1984; Hacker et al., 1996). The 95-90 Ma ages from the sole of the Anatolian Ophiolite (Dilek et al., 1999; Parlak and Delaloye, 1999; Çelik et al., 2006) suggest that the Anatolian Ophiolite is of Cenomanian age.

Late Cretaceous (Campanian) – Continental subduction and metamorphism

Following the complete subduction of the İzmir-Ankara Neo-Tethyan oceanic lithosphere, the northern margin of the Anatolide-Tauride Block entered in an intra-oceanic subduction zone and was metamorphosed at HP/LT conditions (Fig. 8e-f). The Rb-Sr ages from the Orhaneli Group blueschists indicate that the continental crust was subducted to a depth of 80 km by 80 Ma (Campanian). The obduction of the ophiolite over the continental crust must have started with an intra-oceanic slicing (Fig. 8e). The 90-95 Ma isotopic ages from the sub-ophiolite metamorphic rocks show that the intra-oceanic thrusting began in the Cenomanian-Turonian. Biostratigraphic data from the blocks of the Bornova Flysch Zone also indicate that the foundering of the Anatolide-Tauride carbonate platform as a result of compression started in the late Cenomanian (Okay and Altıner, 2007).

The lithostratigraphic features of the Orhaneli Group imply that these rocks were not deposited on a continental margin but rather on a shelf or on a shallow-marine platform. This suggests that during the continental subduction the continental margin deposits were detached from their substratum and thrust southward (Fig. 8f-g). These continental margin sequences are probably represented by the Lycian Nappes in the Taurides, basal parts of which show HP/LT metamorphism (Rimmele et al., 2003). The Mesozoic carbonate stratigraphy within the blocks of the Bornova Flysch Zone shows great similarity to some of the units in the Lycian Nappes (Okay and Altıner, 2007).

Late Cretaceous (Maastrichtian) – Paleocene exhumation

The Early Eocene marine deposits in the Tavşanlı Zone show that by the end of the Paleocene the Orhaneli Group was at the surface or very close to the surface. The marine character of the Early Eocene sediments indicates that the crust was of normal thickness in the Tavşanlı Zone at this time. The post-tectonic Eocene granodiorites, which intrude the Orhaneli Group, the ophiolitic mélange and the ophiolite in the Tavşanlı Zone also indicate that the main tectonism in the Tavşanlı Zone was completed by the end of the Paleocene.

Stratigraphic and sedimentological data from the Sakarya Zone indicate that the blueschists of the Orhaneli Group were locally on the surface by the Maastrichtian. In the southern part of the Sakarya Zone and in the Haymana basin the Maastrichtian deposits are represented by thick flysch-type clastics. In contrast, in the northern parts of the Sakarya Zone and in the İstanbul Zone, the Maastrichtian-Paleocene interval is represented by deposition of marine limestones and marls. This shows that the source of the Maastrichtian clastics lay south of the Sakarya Zone. Although continental collision between the Sakarya Zone and the Anatolide-Tauride Platform had not started by the Maastrichtian, the two terranes must have been in close proximity. During the Maastrichtian the Sakarya Zone was receiving detritus from the uplifted and eroding Tavşanlı Zone. Late Campanian-early Maastrichtian debris flows with glaucophane-lawsonite pebbles have been described within the 5000 m thick flysch sequence of the Haymana basin (Batman, 1978), furthermore, serpentinite and blueschist clasts are common in the Paleocene-Eocene sandstones and conglomerates (Norman and Rad, 1971).

Two coeval tectonic processes were responsible for the exhumation of the Orhaneli Group blueschists that were buried to 80 km depth (Okay et al., 1998). The first one is the detachment of the Orhaneli Group from its crystalline basement and its exhumation within the subduction channel bounded by a thrust at the base and a normal fault at the top (Fig. 8g). The other process is the rupture of the subducting oceanic lithosphere from the continental one. Additional information about exhumation processes as interpreted from kinematic analysis of HP rocks is described later in the field guide.

Paleocene – Continental collision

The continental crust thickens in the region of continental collision and undergoes uplift and erosion. Consequently an upward coarsening and regressive clastic sedimentation is observed in such regions, which are followed by uplift and erosion. The first clastic sedimentation on top of pelagic carbonates in the southern parts of the Sakarya Zone starts in the middle to late Albian, and the siliciclastic turbidites intercalated with pelagic carbonates continue into the Campanian and Maastrichtian. In the late Maastrichtian the flysch deposition gives way to sedimentation of shallow marine sandstones, and in the Paleocene fluviatile sandstones and conglomerates are deposited (Tansel, 1980; Yılmaz, 2008). The sedimentary data suggests that the collision between the Tavşanlı and Sakarya Zones started in the Paleocene. A transition from the deep sea Maastrichtian turbidites to Paleocene continental clastics is also observed in the Haymana basin (Ünalan et al., 1976).

Sedimentary sequences on both sides of a suture are expected to show features of deposition on continental margins. However, such sequences are not recognized north and south of the İzmir-Ankara suture in northwest Turkey. Shallow marine Jurassic limestones crop out within 14 km of the İzmir-Ankara suture south of Bursa (Fig. 10). In contrast in the Eastern Pontides the Jurassic-Cretaceous sediments show an increasingly deeper marine character towards the İzmir-Ankara-Erzincan suture. The absence of such deep marine Jurassic-Cretaceous sequences in the western part of the Sakarya Zone suggests major strike-slip faulting following continental collision (e.g., Okay et al., 2008b).

Eocene – Calk-alkaline magmatism and low-pressure metamorphism

Rocks of the Tavşanlı Zone are unconformably overlain by the Early Eocene shallow marine limestones. This provides an upper age limit for the deformation related to continental collision in the Tavşanlı Zone. Furthermore, several Early to Middle Eocene calc-alkaline plutons have intruded the Tavşanlı Zone between 53 and 45 Ma. These Eocene plutons are of post-tectonic character and intrude the Orhaneli Group, ophiolitic mélange and the ophiolite and cut the tectonic contacts between these units. In most regions, the contact effects of the granitoids are limited within ~100 m of the pluton. However, a low pressure dynamothermal metamorphism has developed around the Eocene plutons south of Uludağ characterized by the andalusite + cordierite + biotite + muscovite + K-feldspar + plagioclase paragenesis in the metapelitic rocks (Okay and Satır, 2006).

Two hypotheses have been suggested for the genesis of Eocene magmatism: slab-break off (Altunkaynak, 2007; Karacık et al., 2008) and arc magmatism (Okay and Satır, 2006). In the slab-break off hypothesis, asthenospheric mantle intrudes into the rupture between the oceanic and continental lithosphere and the additional heat brought by the asthenospheric mantle leads to partial melting and magmatism. Both hypotheses result in the generation of magmas with similar geochemical and petrographic features. Nevertheless, the extension of the Eocene plutonic belt 140 km northwest of the İzmir-Ankara suture to Marmara Island and Karabiga makes the magmatic arc hypothesis more probable. Furthermore, as discussed above, the rupture between the oceanic and continental lithosphere most probably occurred during the Maastrichtian and not in the Eocene.

FIELD TRIP ITINERARY

This guidebook has been prepared for the field excursion to northwest Turkey preceding the Geological Society of America Tectonic Crossroads meeting in Ankara in 4-8 October 2010. The aim is to show the well-preserved and widespread high pressure - low temperature metamorphic rocks of northwest Turkey in their regional tectonic context. The field trip guidebook summarizes geological data of a large region where we have been working for a number of years. We tried to make it a self-contained independent guidebook by giving precise information on the locations of the key outcrops. Independent geologists with this guidebook at hand should be able to visit all the sites mentioned in the text. Most stops described in the guidebook can be reached by a normal car. In terms of the preservation of the high-pressure mineral assemblages, the blueschists of the Tavşanlı Zone are among the best in the world and are highly suitable as samples for metamorphic petrography classes.

The itinerary of the field trip is summarized below and the route of the field trip is shown in Fig. 9. For the location of the field stops we provided geographic coordinates in UTM European 1950 or 1979 grid, which is closely compatible with the 1: 25 000 scale topographic maps of Turkey.

1st day. An early morning drive from Istanbul to Bursa. Bursa-Orhaneli road section: Triassic metabasites with high-pressure greenschist-facies metamorphism and the overlying Triassic greywackes, Jurassic sandstones and limestones, İzmir-Ankara suture fault, peridotites, banded gabbros, diabase dykes in peridotites, peridotites and the underlying and Cretaceous blueschists, blueschist metapelites with jadeite, lawsonite, glaucophane and chloritoid; Ordovician jadeite-metagranite. Night in Tavşanlı.

2nd day. Tavşanlı-Bozüyük-Eskişehir. Aragonitized limestones in the accretionary complex; lawsonite-zone blueschists; glaucophane-lawsonite blueschist facies metabasites and marbles. Triassic blueschists and eclogites north of Eskişehir. Night in Eskişehir.

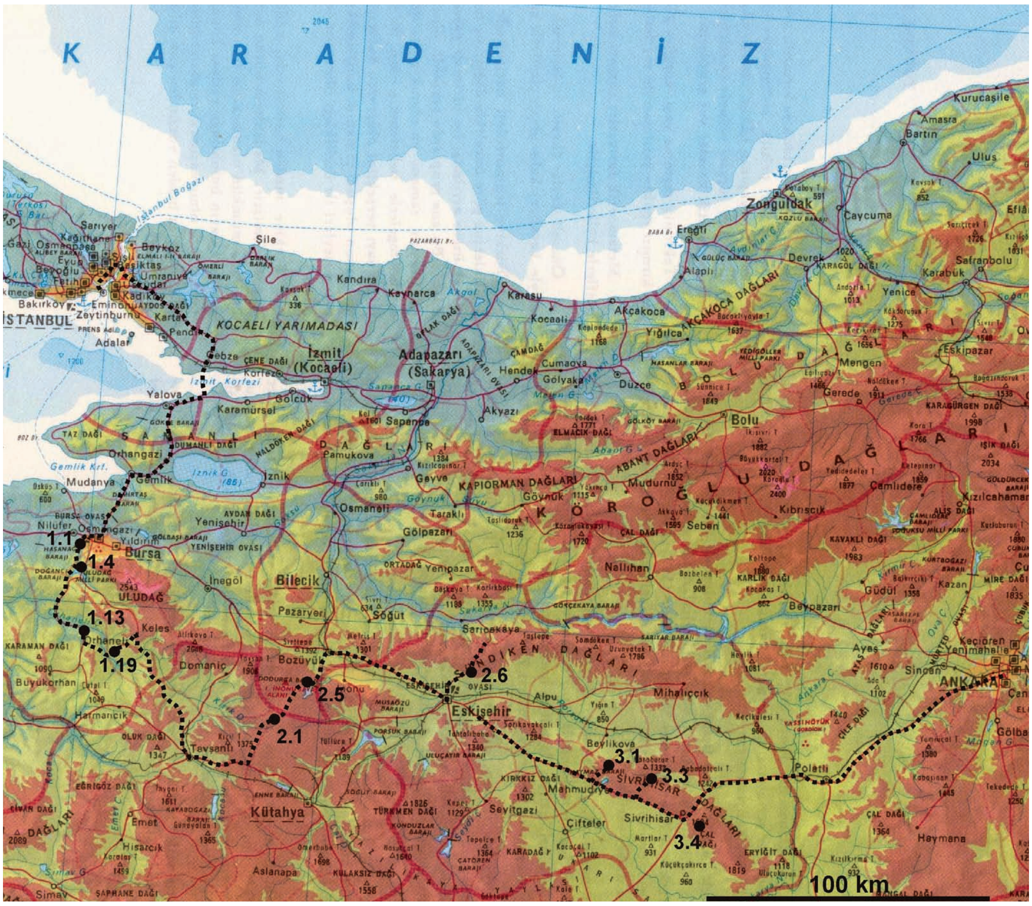


Fig. 9 - Map of northwest Turkey showing the field trip route and the location of some of the field stops.

3rd day. Eskişehir - Sivrihisar - Ankara. Lawsonite-eclogite, blueschists and serpentinites at around Sivrihisar, micaschists-calcschists, quartzites and marbles with high-pressure (HP) mineral assemblages, Barrovian metamorphic overprint of the HP metamorphic sequence southeast of Sivrihisar.

DAY 1

Road description between Istanbul and Bursa

We leave Istanbul early in the morning, passing to Asia using the Fatih Bridge built in 1988. The first Bosphorus Bridge, built in 1973, can be seen farther south. We take the new motorway to Ankara. The hills around the motorway are made up of Ordovician quartzites of the Istanbul Zone. We leave the motorway near Gebze and head for the ferry station in Eskihisar, a small village on İzmit Bay. The crossing by ferry saves a detour around İzmit Bay. The white cliffs around the ferry station are made up of Late Cretaceous marly limestones, similar in age to those in northwest Europe. In the east, above the village, is a ruined castle, which gives its name to the village (Eskihisar literally means "old castle"). The castle rests on the Middle Triassic carbonates of the Istanbul Zone. One of the substages of the Triassic (Bithynian Substage of the Anisian Stage) was named from this region (Assereto, 1974). The ferry across İzmit Bay takes about 45 minutes. İzmit Bay, as well as the Marmara Sea, exist because of the North Anatolian Fault, a 1500 km long right-lateral strike-slip fault forming the boundary between the Anatolian and Eurasian plates. The post-Early Miocene North Anatolian Fault consists essentially of a single fault zone along most of its 1500 km long course; however, as it nears the Marmara Sea it splits into several branches. The main branch is responsible for the formation of the Marmara Sea. Despite its small size, the Marmara Sea is deep; 20 km west of the route of the ferry the sea is more than 1200 m deep The main branch of the Anatolian Fault passes through the centre of İzmit Bay, a subparallel fault with a major normal fault component bounds the southern side of the Bay. As the ferry approaches Topçular on the south side of the Bay, you will be able to see the sharp breaks in the steep slopes of the east-west aligned hills, which mark the location of this normal fault. The hills are made up of red continental sandstones of earliest Triassic age.

We drive from Topçular to Yalova along the alluvial coastal strip. The low-lying hills south of the road consist of Neogene sediments. We will not enter the town of Yalova, famous for its hot springs, but instead take the road to Bursa. The road climbs up hills amidst heavy traffic and passes through the unremarkable town of Orhangazi. A few kilometers after Orhangazi we will see İznik Lake and the mountains rising along its southern margin. A branch of the North Anatolian Fault follows the southern margin of Iznik Lake. On the way to Gemlik, the road cuts expose white marbles intercalated with greenish grey metabasites, and grey phyllites. They form part of the Nilüfer Unit of the Karakaya Complex and indicate that we have entered the Sakarya Zone. There is a small diabase quarry on the roadside, which works a thick dolerite flow with a striking ophitic texture. Next we come to Gemlik, a small port on the Marmara Sea. The olive trees line both sides of the road towards Bursa The flat-lying sediments on the left (east) as the road climbs up from Gemlik are Oligocene-

Miocene deposits. Farther on we pass south-dipping, thickly-bedded red sandstone conglomerates; these are fluvial deposits of Early to Middle Eocene age. Then the road descends into the Bursa plain. If the sky is clear we will see in front of us the mighty mountain Uludağ, the ancient Bithynian Olympus, rising to 2500 metres from the Bursa plain.

We will not enter the city of Bursa but will take the bypass to Çanakkale/İzmir and then follow the road to Orhaneli. This road skirts the western margin of the Uludağ and follows the Nilüfer Valley. The Uludağ forms a major topographic and geological dome; the core of this dome is made up of ?Paleozoic high-grade metamorphic rocks (gneiss, amphibolites and marbles) with Eocene and Oligocene mica cooling ages. During the Oligocene it formed part of major ductile right-lateral strike-slip shear zone with over 100 km of cumulative displacement (Okay et al., 2008b). A subvertical sheet of a syntectonic two-mica granite has intruded and has been deformed by this Eskişehir shear zone. The mantle of the dome consists of the metabasite-phyllite-marble sequence of the Nilüfer Formation of the Karakaya Complex. The road to Orhaneli is a reference section for the Nilüfer Formation (Okay et al., 1991). The first stop will be in this unit.

The meter is set to zero at the Bursa-Orhaneli-Çanakkale junction.

Stop 1.1 Triassic metabasite-marble-phyllite of the Nilüfer Formation of the Karakaya Complex

Locality: opposite the Misi (Gümüştepe) village on the Bursa-Orhaneli road, 4.6 km from the junction, UTM 35T 06 68 037, 44 49 361, Fig. 10.

The road to Orhaneli follows the Nilüfer Valley, the type locality of the Nilüfer Formation, which is also known as the Lower Karakaya Complex. Here, on the east side of the road, opposite the village of Misi, there are outcrops of intercalated metabasites, marbles and calcschists of the Nilüfer Formation. The metabasites are mostly fine-grained tuffs. Lamination in some marbles and calcschists suggests a pelagic environment of deposition. Conodonts from the marbles in the Nilüfer Valley have been dated as earliest Triassic (Kozur et al., 2000). The metamorphic sequence dips steeply northwest and is folded with the fold axis showing variable plunge but generally trending 60-70°. On the tectonic discrimination diagrams involving Ti, Y, Zr, Nb and, Cr, the metabasites from this area (as well as from other areas of the Nilüfer Formation) plot in the "within plate basalt" field (Pickett, 1994).

The metamorphism in the Nilüfer Unit in this valley is in high-pressure greenschist facies. The mineral assemblage in the metabasites is actinolite/barroisite + epidote + chlorite + albite + leucoxene. Within the green metabasites there is a blue siliceous band repeated by folding. It is an epidote-blueschist with the mineral assemblage of quartz + sodic amphibole + epidote + albite. Sodic amphibole is a Fe^{3+}-rich-crossite with blue to lavender-blue pleochroism. As there is no evidence for poly-metamorphism in these rocks, here we have a clear case of cogenetic blueschists and greenschists, which is to be expected in the transition region between the greenschist and blueschist facies. Sodic amphibole also occurs in some coarse metabasites as rims around relict igneous augite or kaersutite. Phengites from these type of blueschists and greenschists a few kilometers farther east have given latest Triassic Ar/Ar ages (Okay, unpublished data).

Stop 1.2 Deformational features of the Nilüfer Formation

Locality: Bursa-Orhaneli road, 11 km after the Orhaneli junction, before the Doğancılar Dam, UTM 35T 06 67 772, 44 43 768, Fig. 10.

On the quarry face on the opposite side of the Nilüfer valley we can observe an upright isoclinal antiform, well characterized by a marble bed. The core of the fold is made up of marble flanked by metabasites. Through such folding the structural thickness of the Nilüfer Formation exceeds 7 km.

Stop 1.3 Deformational features of the Nilüfer Formation

Locality: Bursa-Orhaneli road, ~12 km after the Orhaneli junction, before the Doğancılar dam, UTM 35T 06 67 380, 44 43 312, Fig. 10.

On the opposite side of the Nilüfer Valley we can see a succession of pyroclastic flow, marble, pyroclastic flow and tuff. The more massive marble band has boudinaged

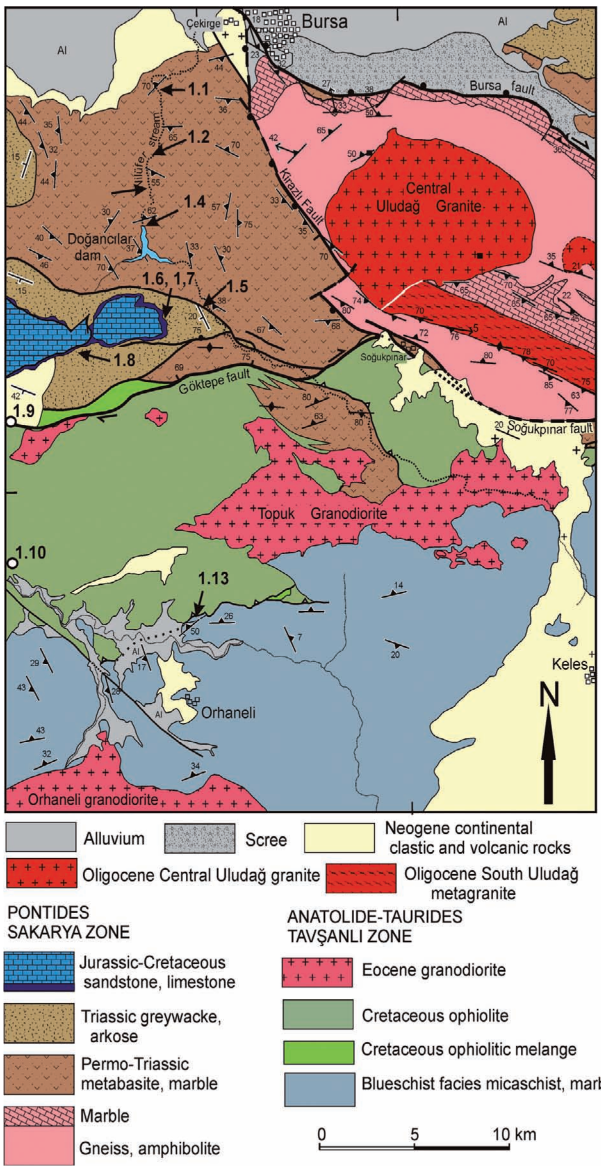


Fig. 10 - Simplified geological map of the Bursa-Orhaneli region showing the field stop locations. For location see Fig. 4 (modified from Okay and Tüysüz, 1999).

and has partly lost its continuity. This commonly gives a "broken-formation" character to the Nilüfer Formation. The normal faulting observed in the marble band suggests an earlier episode of brittle stretching, prior to isoclinal folding. There is as yet no detailed study of the structure of the Nilüfer Formation.

Stop 1.4 Metabasites of the Nilüfer Formation and the panorama to the south

Locality: on the Bursa-Orhaneli road above the axis of the Doğancılar Dam, 13 km after the Orhaneli junction, at the Orhaneli-Keles road junction, UTM 35T 06 67 375, 44 42 490, Figs. 10 and 11.

On the well-exposed road cut one can see the metabasites of the Nilüfer Formation. Over 80% of the metabasites in the Nilüfer Formation have a pyroclastic origin, and pillow lavas are rare. On the road cut the pyroclastic character of the mafic rocks is apparent in the fresh surfaces. In this locality there is also a tectonic slice of deformed pillow lavas. Pillow lavas are identifiable by their amygdaloidal rims. The pillow lava sequence forms an ~35 m thick section and is bounded by two faults, probably thrust faults. The one in the south dips north (105/53N) and the one in the north dips southeast (40/53E).

From this locality there is also a good panoramic view towards the south. The flat top of the hills on the horizon is made up of the Late Jurassic-Early Cretaceous limestones (Bilecik Limestone) of the Sakarya Zone (Fig. 11). Below the limestones there is an Early Jurassic basal clastic unit of sandstones and conglomerates (the Bayırköy Formation), although this is not apparent from this vantage point. These two formations are typical for the Jurassic and Early Cretaceous of the Sakarya Zone. Between the Nilüfer Formation and the Early Jurassic basal clastics there is a strongly deformed greywacke unit, the Orhanlar Greywacke.

Stop 1.5 The Nilüfer Formation and the overlying Orhanlar Greywacke

Locality: on the Bursa-Keles road, the dirt road to the village Dağakca, 19.8 km from the Orhaneli junction, UTM 35T 06 70 593, 44 38 695, Fig. 10.

In northwest Turkey the Nilüfer Formation is overlain by a strongly deformed but generally unmetamorphosed clastic series, which commonly bears exotic blocks of Permian and Carboniferous limestones. The contact is invariably tectonic, although originally it could have been stratigraphic.

Here on the road to the village of Dağakca we will see the contact between the Nilüfer Formation and the overlying greywackes of the Orhanlar Greywacke. We will walk down to the contact after observing the lithological features of the Orhanlar Greywacke.

On the side of the road there are fine-grained brownish weathering (the fresh color is dark grey) sandstones and siltstones. Siltstones show a rough foliation. Bedding in the Orhanlar Greywacke is rarely observed due to strong deformation. Lithologically, the sandstones of the Orhanlar Greywacke are homogeneous greywackes. They consist of angular and poorly sorted fragments of quartz, feldspar, basalt, shale, and mica grains in a clay matrix. Strong shear and incipient recrystallisation of quartz grains is evident under the microscope.

Walking down the road we see the contact between the Nilüfer Formation and the Orhanlar Greywacke. About 40 meters above the contact there are black, dark grey slates and metasiltstones, just above the contact there is a several-meters-thick red, silty cherts. The contact is sheared and is tectonic.

Stop 1.6 Panoramic view towards Uludağ and Orhanlar Greywacke

Locality: the side road to Dağakça village branching from the Bursa-Keles road, 234 km away from the Orhaneli junction, just below Dağakça village, UTM 35T 06 69 123, 44 37 372, Fig. 10.

The road climbs up through the monotonous greywackes towards Dağakca village. Just before the village there is a magnificent view towards the Uludağ to the north. The snow-white layers, which dip steeply towards us, are marbles of the Uludağ sequence; they overlie gneisses (Fig. 10). South of the marble horizon, there is foliated granitoid, which forms a tabular body 17 km wide and only 1.5 km thick. It was emplaced during the Oligocene in the Eskişehir strike-slip fault zone. The entire region between the granitoid and the Nilüfer Valley is made up of the metabasite-marble-phyllite of the Nilüfer Formation. The undeformed Oligocene granite, which cuts the Uludağ series, can be observed as greyish-white crags west of the marble sequence.

Stop 1.7 Early Jurassic sandstones and Late Jurassic limestones of the Sakarya Zone

Locality: the side road to Dağakca village branching from the Bursa-Keles road, 28.2 km away from the Orhaneli junction. Pass through Dağakca and take the side road at 27.9 km, UTM 35T 06 67 412, 44 36 922, Fig. 10.

The road passes through Dağakca and continues southeast. Above the village we can see the flat-lying carbonates of the Bilecik Limestone. Here we are near the top of the hill that we saw from a distance at Stop 1.4. On a side road we can observe the shales and sandstones of the Early Jurassic Bayırköy Formation. They are not deformed and contain plant fragments, lamellibranches and belemnites. The strong contrast in the deformation between the Orhanlar Greywacke and the Bayırköy Formation is obvious. This hiatus of the latest Triassic (Rhaetian) - earliest Jurassic (Hettangian) age marks the Cimmeride orogeny in the Sakarya Zone, associated with the closure of the Paleo-Tethys.

Immediately above the clastics of the Bayırköy Formation one can see the Bilecik Limestone, which forms a flat lying ledge at the top. This was the table mountain topography we observed from Stop 1.4 at the Doğancılar Dam.

We turn back to the Orhaneli-Keles junction on the Doğancılar Dam, and take the road to Orhaneli. Good roadside exposures of the dark green metabasites of the Nilüfer Formation can be seen along the road. After a while we enter the Orhanlar Greywacke; it is the westward continuation of the same large outcrop seen in the previous stops (cf. Fig. 10). Then the road climbs up to the Bilecik Limestone, which forms the core of a broad syncline. In this particular spot the northern contact of the Bilecik Limestone is faulted against the Orhanlar Greywacke, and the Bayırköy Formation is only exposed on the southern limb of the syncline.

Altıner et al. (1991) measured a section in the Bayırköy Formation and Bilecik Limestone one km east of the present road. According to their data the Bayırköy Formation is 136 m thick and consists chiefly of conglomerates, sandstones and siltstones deposited in a fluviatile environment. The overlying Bilecik Limestone has a minimum thickness of 750 meters and is of Callovian to Tithonian age (Middle and Late Jurassic). The basal part of the Bilecik Limestone, a few tens of meters thick, is largely dolomitic, with lenses of ammonitico rosso-type red nodular limestones of Callovian age. The rest of the neritic carbonate sequence consists of bioturbated cherty limestones, packstones and grainstones.

Stop 1.8 The contact between the Orhanlar Greywacke and the Bayırköy Formation

Locality: on the Bursa-Orhaneli road, UTM 35T 06 64 329, 44 36 656, Fig. 10.

In the northern limb of the Dağakça syncline along the Orhaneli road, the Bayırköy Formation consists of siltstones and sandstones with conglomerate lenses, poorly exposed on the old road cut. The clasts in the conglomerates include quartz, metamorphic rock, diabases and Permian limestones. The Orhanlar Greywacke, well exposed along the recently constructed highway consists of strongly deformed and sheared sandstones and shales, resembling a "broken formation", a typical feature of the Upper Karakaya Complex.

Stop 1.9 The Göktepe Fault - the post-Miocene expression of the İzmir-Ankara suture

Locality: on the Bursa-Orhaneli road, 15.9 km away from the Orhaneli-Keles junction. Just past the village of Erenler, opposite the petrol station. The eastern wall of a large harvest field, UTM 35T 06 61 600, 44 32 675, Fig. 10.

Here we are at the southern boundary of the Sakarya Zone at the İzmir-Ankara Neo-Tethyan suture. The suture is represented by a major steeply-dipping fault, the Göktepe Fault, which separates the Sakarya Zone from the ophiolites and blueschists of the Tavşanlı Zone. It corresponds to a profound tectonic break. On one side of the suture there are unmetamorphosed, little-deformed, Late Jurassic limestones, on the other side are rocks metamorphosed at 80 km depth during the Late Cretaceous. Before the days of plate tectonics contacts such as this must have been bewildering. Yet, for all its profoundness, the İzmir-Ankara suture is represented here by a sharp strike-slip fault, which has been active as late as post-Miocene.

The Erenler basin is a small Late Oligocene pull-apart basin nested on the suture (Fig. 10). It consists of poorly-sorted, terrigeneous, monomictic conglomerates, over 300 m in thickness. The generally well-rounded clasts in the conglomerates consist mostly of diabases and minor ultramafic rocks, derived from the Burhanlar peridotites in the south. The conglomerates are overlain by white tuffs, which can be seen in the village of Erenler that is just passed. The tuffs have been dated as Late Oligocene (26.3±21 Ma) by apatite fission track method (Okay et al., 2008b).

On the wall of the harvest/footwall field the Miocene conglomerates are cut by a steeply dipping fault. The steep dip of the fault plane suggests strike-slip rather than dip-slip. The geometry of the Erenler basin implies a dextral strike-slip movement. This Göktepe Fault can be followed for 60 km along strike (Fig. 4) and was probably reactivated as a dextral strike-slip fault during the Late Oligocene associated with the Eskişehir Fault (Fig. 4).

Obviously the activity along the Göktepe Fault dates back to the Paleocene-Eocene, when continental collision between the Sakarya Zone and the Anatolide-Tauride Block took place, or even earlier, to the Late Cretaceous. The east-west elongation of the Topuk granodiorite implies that the Göktepe Fault controlled the intrusion of this pluton during the Middle Eocene (Fig. 10). The Göktepe Fault can be compared to the Insubric Line in the Western Alps, which, although a post-collisional structure, constitutes the Alpine suture in some segments.

Stop 1.10 Burhan ophiolite: ultramafic rocks

Locality: Bursa-Orhaneli road, after Akçabük village, Fig. 10.

After passing through the Göktepe Fault we are in the Tavşanlı Zone of the Anatolide-Tauride Block. Initially we pass through a major peridotite massif, the Burhan ophiolite sheet, which represents the lower parts of an ophiolite (Fig. 10). It consists mainly of dunites and harzburgites with minor gabbros, pyroxenites and chromites, cut by large number of diabase dykes. The eastern part of the Burhan ophiolite, mapped by Lisenbee (1971), consists of north-south trending, subvertical bands, and is a few kilometers in thickness. The peridotites show a distinct tectonic foliation, parallel to the compositional layering, and defined by the preferred orientation of olivine and elongate crystals of enstatite. According to Lisenbee (1972) the contacts between the bands are gradational. The peridotites are younger towards the west and are bounded by a poorly defined fault zone marked by serpentinite slivers, small Neogene basins and Miocene dacite intrusions (Fig. 10). The internal structure of the western part of the Burhan ophiolite is poorly known.

Gravity profiles across the Burhan ophiolite, as well as geological cross-sections, indicate that the maximum vertical thickness of the peridotite is 1.5 km. This contrasts with the actual thickness of over 13 km, measured perpendicular to the compositional layering.

Stop 1.11 Burhan ophiolite: banded, two-pyroxene gabbros

Locality: Bursa-Orhaneli road, 24.0 km away from the Orhaneli-Keles junction, terraced road cut on the side of the new highway, UTM 35T 06 61 112, 44 25 505, Fig. 12.

The gabbros in the Burhan ophiolite form a north-south striking and steeply west-dipping band, less than 100 m thick (Fig. 12). Here on the terraced road cut we see a

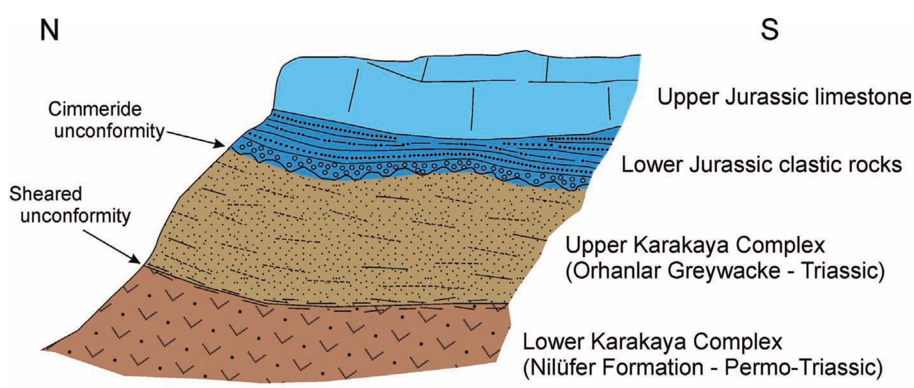


Fig. 11 - Relationships between the Nilüfer Formation, Orhanlar Greywacke, the Bayırköy Formation and the Jurassic limestones as seen from the Doğancılar reservoir.

section from these banded two-pyroxene gabbros. Banding is a primary igneous cumulate feature and is marked by the different proportion of mafic (pyroxene, hornblende, olivine and spinel) and felsic (plagioclase) minerals. The black, irregularly-shaped minerals are spinels, which appear green to dark green under the microscope. The rest is largely colorless clinopyroxene and pleochroic orthopyroxene and minor olivine, hornblende and plagioclase. Plagioclase is altered and consists of very fine-grained aggregates of a high relief mineral (clinozoisite? pumpellyite?) and albite. There is no evidence for blueschist facies metamorphism in the gabbros. The rocks also show no effects of hydration; they must have stayed dry during their long history.

The banded gabbros are cut by ductile fault zones with a reverse sense of shear.

The long chimneys to the west belong to a lignite power plant. The small Neogene basins west and northwest of Orhaneli contain lignite, which is used for generating electricity.

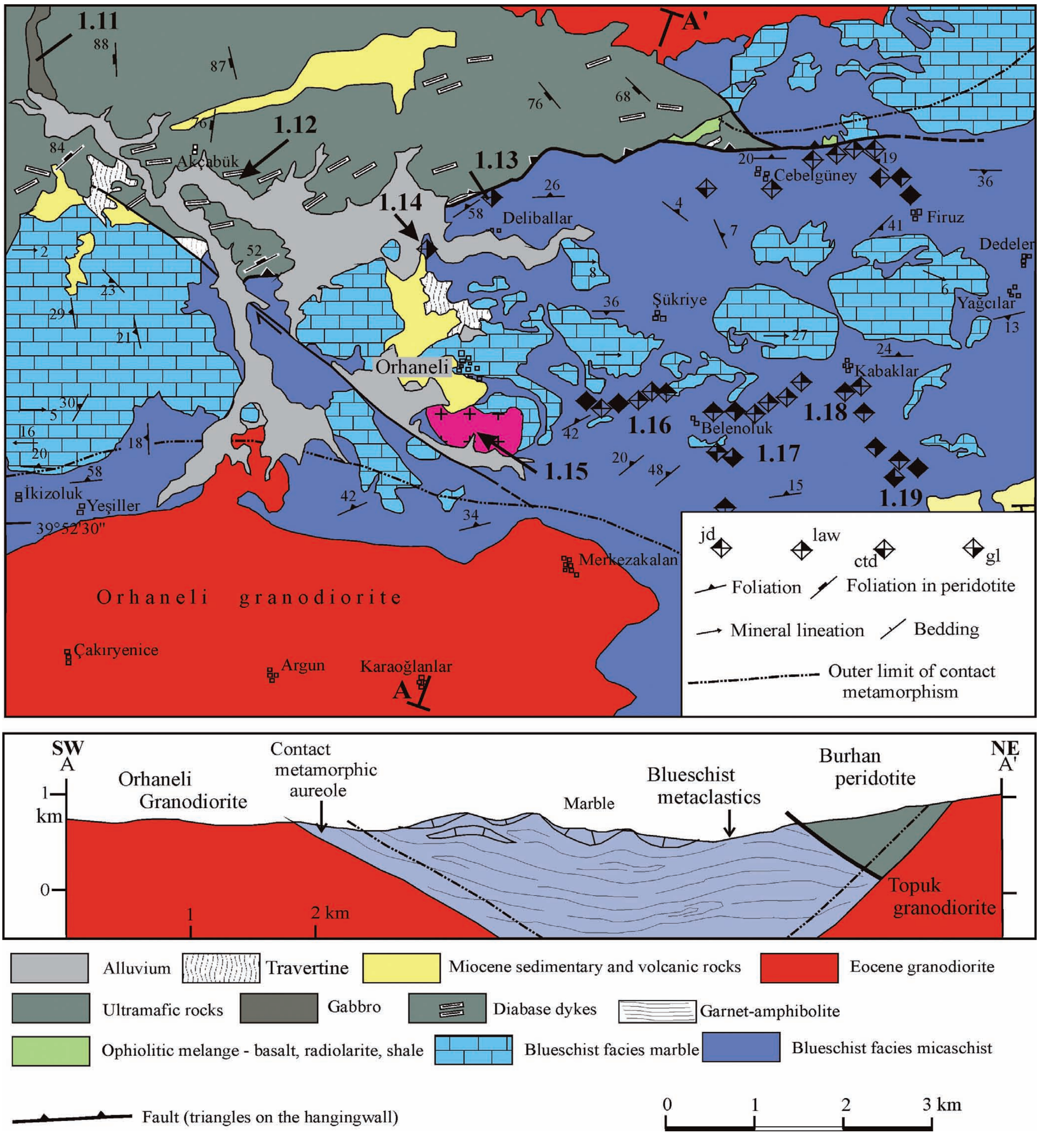


Fig. 12 - Geological map and cross-section of the Orhaneli region showing the field stops. For location see Fig. 4. The geological map is modified from Lisenbee (1972) and Okay (2002). Abbreviations: ctd- chloritoid, gl- glaucophane, jd- jadeite, law- lawsonite.

Stop 1.12 Diabase dykes in the Burhan ophiolite

Locality: Bursa-Orhaneli road, 30.7 km away from the Orhaneli-Keles junction, after the petrol station, just past the junction to the Cr-mine, UTM 35T 06 64 500, 44 22 875, Fig. 12.

The Burhan ophiolite slab, like the other peridotite bodies in the Tavşanlı Zone, is cut by east-west trending, subvertical diabase dykes with chilled margins against the peridotites. The dykes are generally a few meters thick, and vary in abundance from one dyke over several hundred meters to ten dykes over 30 m. They do not extend down to the accretionary complex, and are cut by the basal fault. The chilled margins of the dykes indicate that they were injected into an already cold oceanic lithosphere. One speculation is that their formation is related to the subduction of a spreading centre, which would produce magmatism in the overlying oceanic lithosphere.

The mineral assemblage in the dykes is altered plagioclase and igneous hornblende and augite. Plagioclase is represented by albite and turbid aggregates of very small pumpellyite grains. This observation is critical since it indicates that the dykes, and by inference the Burhan ophiolite slab, have not undergone the regional blueschist metamorphism that is observed in the immediately underlying rocks.

Here on the road cut we see a number of diabase dykes in the sheared and fractured, partially serpentinized, black peridotites. They are boudinaged and form one-to-three-metre long lenses.

Stop 1.13 The Burhan ophiolite and the underlying blueschist sequence (Fig. 12)

Locality: On the Bursa-Orhaneli road, just before entering Orhaneli, along the village road to Deliballar, UTM 35T 06 69 675, 44 22 150, Figs. 12 and 13.

Just before entering the town of Orhaneli, we take the small dirt road on the left, which leads to the village of Deliballar. We disembark the minibus next to a dirt road close to large barracks, and go on foot for about one hour. The aim of this small excursion is to study the blueschist marbles and metabasites, subophiolite metamorphic rocks, and the overlying ultramafic rocks.

The barracks, now in disuse, was a collecting ground for manganese ore, used in making the tips of matchsticks. As people no longer use matches, the mine, which lies several kilometers away, has been abandoned. Exposed on the road cuts around the barracks are blueschist facies marbles. Some primary brecciation structures are still recognizable in some marble horizons, which can speculatively be ascribed to the collapse of the Mesozoic carbonate platform of the Anatolide-Tauride Block.

Farther on along the road there are some calcschist horizons (calcite + phengite ± sodic amphibole) and rare metabasites. Along the small path leading to the hilltop, the calcschists and marbles are intercalated with the blue metabasites. This shows that the marbles were also metamorphosed in the blueschist facies. Initially they must have been composed of aragonite, but now they are all calcite-marbles. As we will see later, marbles make up an important part of the Tavşanlı Zone blueschist facies rocks.

As we start climbing up the hill one can encounter loose blocks of blue metabasite. The few-millimetre-large laths of grayish-white lawsonite can easily be observed with the naked eye. Lawsonite crystals are commonly shaped as rectangles or as wedges (in two dimensions), and are invariably idioblastic. They are set in a blue matrix of sodic amphibole, commonly of crossite in composition. These are the characteristic blueschist metabasites of the Tavşanlı Zone. The mineral assemblage is sodic amphibole + lawsonite + chlorite + sodic pyroxene + phengite + leucoxene ± garnet ± opaque. Sodic amphibole and lawsonite together make up over 80% of the rock. In metabasites, sodic amphibole is almost always crossite, reflecting the composition of the parent rock. Phengite, chlorite, sodic pyroxene (chloromelanite in composition) and leucoxene are commonly present in small amounts. Garnet is rare in the metabasites of the Tavşanlı Zone; metamorphic temperatures in these rocks were generally not high enough to generate garnet. However, in this locality there is at least one metabasite with red garnets, a few millimeters wide, coexisting with lawsonite and crossite.

The top of the hill is made up of silicified serpentinites. The mesh-texture of the serpentinites can be seen as a ghost texture in some of these silica-rocks. Serpentinization and silicification are commonly observed along the basal tectonic contact of the Burhan ophiolite body. The silicification is a late, post-tectonic feature, due to fluid circulation along the fault contact.

In this locality the contact between the silicified peridotites and the underlying blueschists can be located to within a few meters. This tectonic contact juxtaposes blueschists, metamorphosed at 80 km depth, under the ultramafic rocks, which have not been buried deeper than 20 km. Considering this major omission of strata, what is striking about this contact is the lack of any major brittle structures in the underlying blueschist marbles and calcschists. The structures in the blueschists, such as foliation, mineral lineation, and isoclinal folding is largely syn-metamorphic. Thick sequences of mylonites, retrogression of blueschist facies mineral assemblages, and brittle structures overprinting ductile extensional structures - features present in extensional core complexes -

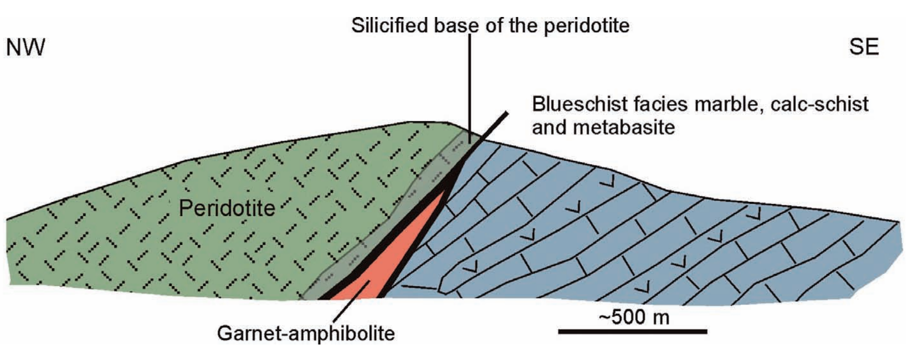


Fig. 13 - Cross-section of the southern margin of the Burhan ophiolite showing the relationships between the blueschists, the subophiolite metamorphic rocks and the peridotite. For location of this section see Fig. 12.

are not observed here. Instead we see a late, upper-crustal, brittle fault.

We descend the hill on the opposite side from which we climbed up. Notice the black mineral trails of chromium-spinel, which stand out in the yellowish-brown silicified serpentinites. When we reach the bottom of the valley, turn left and follow the small path. Farther along the path are poor exposures of garnet-amphibolites. This is a small slice between the Burhan ophiolite and the blueschists (Figs. 12 and 13).

There is another larger, and better-exposed, slice of garnet-amphibolite farther west. The mineral assemblage in the garnet-amphibolite is hornblende + plagioclase + garnet + epidote + rutile ± opaque (Okay et al., 1998). The garnet-amphibolites show locally an incipient high-pressure metamorphic overprint, characterised by tiny laths of lawsonite in the albitized plagioclase, and thin rims of blue sodic amphibole around hornblende. However, it has certainly not undergone the same blueschist metamorphism observed in the marbles, calcschists and metabasites of the Orhaneli Group. Rather, its metamorphism can be compared to that of the Ovacık Complex.

Geothermobarometry of the garnet-amphibolite assemblage indicates P-T conditions of about 8 kbar and 700°C (Okay et al., 1998). The metamorphic conditions of the incipient blueschist facies metamorphism is around 6 kbar and 200°C. This gives an unusual isobaric cooling path for the garnet-amphibolites (Fig. 14). One way to explain this P-T path is through the gradual cooling of the garnet-amphibolites at a subduction zone; the garnet-amphibolites having been formed initially through intra-oceanic slicing at the inception of subduction (see Fig. 9 of Okay et al., 1998).

Stop 1.14 Blueschist metacherts near Orhaneli

Locality: Bursa-Orhaneli road. Just before entering Orhaneli turn left 300 m after passing a petrol station (Petrol Ofisi). Follow the small dirt road for about one km (passable by car). Stop near the house and walk up the bush-covered hill. On foot it takes about 15 minutes from the petrol station. UTM 35T 06 69 137, 44 22 179, Fig. 12.

The banded, quartz-rich rocks sticking out in the bush-covered small hill are blueschist facies metacherts. The metacherts are distinctly banded, isoclinally folded and have the quartz + hematite + phengite + sodic amphibole + garnet + lawsonite ± epidote mineral assemblage. Quartz makes up over 80% of the mode. Phengite is visible as tiny shiny flakes. The small black laths are hematite, which alters to reddish goethite (?). Thus, the red mineral is not piemontite! Other minerals are not recognisable by naked eye. It is interesting to note that the sodic amphibole, which is a magnesium-riebeckite, is completely colorless in thin section. Because of the high oxygen fugacity during the metamorphism of this rock, no Fe^{2+} was available for the sodic amphibole. In fact, there is hardly any Fe^{2+} in these rocks; almost all the iron is represented by Fe^{3+}. Garnet in these metacherts forms submillimetric idioblastic grains and is rich in spessartine end-member. In such highly oxidised rocks lawsonite, epidote and hematite coexist peacefully!

Sodic amphiboles contain independently variable $Fe^{2+}/(Fe^{2+}+Mg)$ and $Fe^{3+}/(Fe^{3+}+Al)$ ratios; therefore, their composition is highly dependent on the prevailing oxygen fugacities (effective oxygen partial pressure) during the metamorphism. It is possible to deduce the oxygen fugacity during the metamorphism from the composition of sodic amphiboles (Okay, 1980c).

Stop 1.15 Ordovician jadeite metagranitoid

Locality: the road between Orhaneli and the village of Belenoluk. Less than one kilometre after leaving Orhaneli, in the direction of Harmancık, turn left and follow the road signs to the villages of Belenoluk and Ağachisar. The outcrops of the metagranitoid are around the ugly rubbish dump of Orhaneli, UTM 35T 06 71 161, 44 18 63, Figs. 12 and 15.

Blueschists in Orhaneli-Keles region form a predominantly metaclastic sequence; metabasites and other magmatic rocks are generally absent. An exception is this unusual outcrop of metagranitoid, interpreted as a tectonic slice from the basement.

The Kapanca metagranitoid crops out in the core of a synform south of Orhaneli, has a thickness of about 400 meters and takes up an area of 14 km^2 (Fig. 16, Okay et al., 2008a). Despite complete recrystallization, the granitic texture is generally well preserved (Fig. 15) and the chemical composition of the rock is similar to a granite except for the low K_2O content. The granitoid is underlain by the Triassic micaschists and marbles of the Kocasu Formation. The Kapanca metagranitoid is made up essentially of quartz and jadeite with minor chloritoid, lawsonite, glaucophane and phengite. Single zircon U-Pb evaporation analysis on zircons from two metagranitoid samples have yielded Middle Ordovician (467.0±4.5 Ma) ages (Fig. 16; Okay et al. 2008a). These ages are interpreted as the crystallization age of the granitic magma.

Similar HP/LT paragenesis observed in the surrounding micaschists and the subparallel attitude of the foliation indicate that both units share a common metamorphic and deformational history. The micaschists surrounding the metagran-

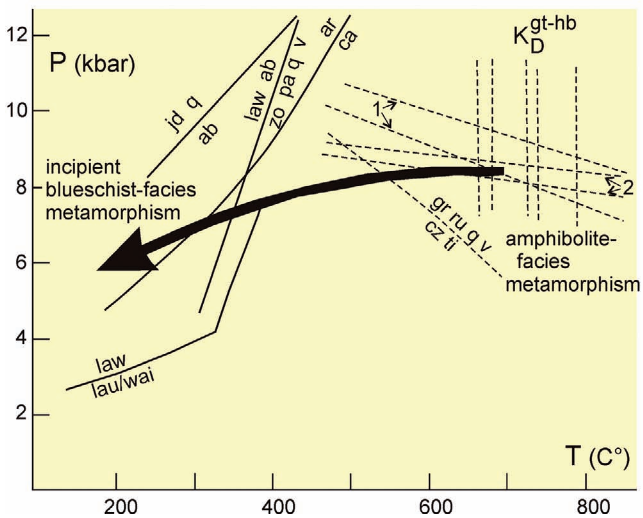


Fig. 14 - Pressure-temperature (P-T) path of garnet-amphibolites from the base of the peridotite. P-T conditions of the amphibolite facies metamorphism at 8.5±3 kbar and 700C are constrained by the Graham and Powell's (1984) garnet-hornblende geothermometer (K^{gt-hb}, vertical dashed lines) and by reactions (1) pargasite + hornblende + ferrohornblende = edenite + grossular + almandine + quartz + H_2O and (2) pargasite + ferrohornblende + pyrope = edenite + grossular + almandine + quartz + H_2O, for minerals in the two analyzed samples. Conditions of incipient blueschist-facies metamorphism at 6±2 kbar and 200±100°C are constrained by the lawsonite + albite stability. Other reactions are calculated using Holland and Powell's (1990) THERMOCALC program. Abbreviations: ab- albite; ar- aragonite; cc- calcite, cz- clinozoisite; gr- grossular; jd- jadeite; lau- laumantite; law- lawsonite; pa- paragonite; sph- titanite; q- quartz; ru- rutile, v- H_2O; wai- wairakite; zo- zoisite (modified from Okay et al., 1998).

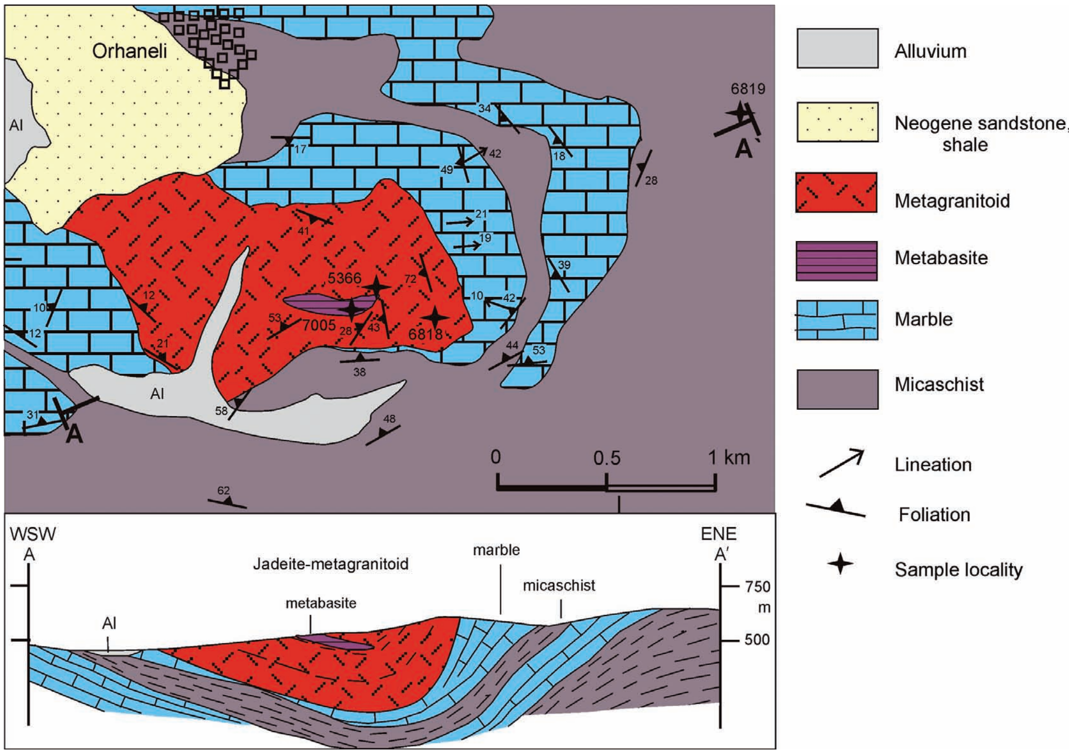


Fig. 15 - Geological map and cross-section of the Kapanca metagranitoid south of Orhaneli. For orientation see Fig. 12 (modified from Okay et al., 2008a).

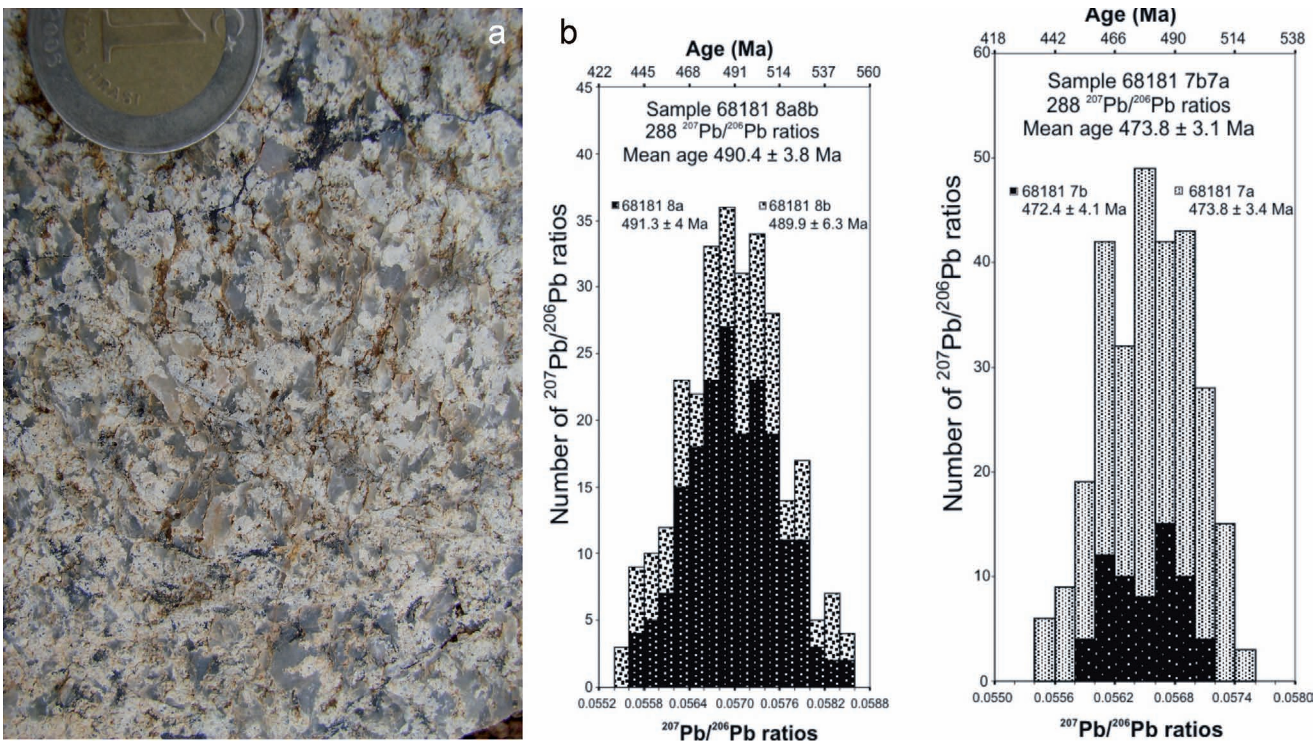


Fig. 16 - (a) Kapanca metagranitoid. The dark regions are quartz and the white regions are jadeite. (b) Single-zircon evaporation Pb-Pb ages from the Kapanca granitoid (modified from Okay et al., 2008a).

itoid have yielded clastic zircons as young as Permian-Carboniferous showing that the granitoid cannot have intruded into the micaschists. It must have been tectonically emplaced in the Kocasu Formation before the HP/LT metamorphism.

The crystalline basement of the Anatolide-Tauride Block is made up generally of Pan-African (570-520 Ma) granitoids (Satır and Friedrichsen, 1986; Kröner and Şengör, 1990; Hetzel and Reischmann, 1996; Loos and Reischmann, 1999; Gürsü and Göncüoğlu, 2006). These granitoids of Late Proterozoic-Early Cambrian ages crop out over large areas in the Menderes Massif. Granitoids of similar age cover large areas in the northern parts of Africa and Arabia. On the other hand, Ordovician magmatic rocks are described from Western Europe in small continental plates, which have rift off from the northern margin of Gondwana during the Early Paleozoic (e.g., von Raumer et al., 2002). The Ordovician granitoid in the Tavşanlı Zone represents the eastward extension of this Ordovician magmatism. The Ordovician acidic magmatism is probably related to the rifting of continental terranes, such as the İstanbul Zone, from the northern margin of Gondwana (Okay et al., 2008a).

The Kapanca metagranitoid forms massive, very hard, pale grey rocks with several-millimeters-large jadeite grains and quartz with minor glaucophane, chloritoid, white mica and lawsonite. In these rocks the jadeite is snow-white, similar to feldspar; the greyish blue grains are sodic amphibole. The texture of the rock is reminiscent of that of a microgranite. In the center of the Kapanca metagranitoid there is a small outcrop of metabasite with glaucophane, lawsonite and garnet.

Stop 1.16 Blueschist facies sodic metasediments east of Orhaneli

Locality: the road between Orhaneli and the village of Belenoluk. Continue from Stop 10.5, pass the ugly rubbish dump of Orhaneli, take a right turn at the junction at 4.1 km. The section starts at 4.7 km, next to a small spring; we will walk till 5.9 km, UTM 35T 06 72 846, 44 18 648, Fig. 12.

This road section exposes a sequence of blueschist-facies metasedimentary rocks, remarkable for the preservation of the unstable blueschist facies assemblage jadeite, lawsonite, and glaucophane, as well as for the presence of a unique mineral paragenesis involving jadeite + chloritoid + lawsonite + glaucophane.

The metamorphic rocks in this section are fully recrystallized and exhibit a penetrative foliation locally modified by a later crenulation cleavage. They show a complex folding and a weak east-west-trending lineation. They can be broadly divided into two lithologies. The first is a grey to black, strongly schistose phyllite/micaschist, originally a pelite, and the second is a light grey to black, massive and hard rock, informally called "greyfels". The greyfels occur as bands, 2-200 cm thick, in the grey micaschists, and probably represent calcareous sandstone beds in shales. The whole sequence was initially a sandstone-shale sequence, probably with a Triassic depositional age.

The micaschists consist essentially of phengite and quartz, locally with minor lawsonite, chloritoid, chlorite and graphite. The greyfels show two different mineral assemblages; the common variety consists mainly of lawsonite and quartz, with minor jadeite, carbonate, phengite and chlorite. The rare, but more significant, mineral assemblage in the greyfels is jadeite + chloritoid + glaucophane + lawsonite + phengite + quartz. The jadeite + chloritoid subassemblage in this location is apparently unique in the world and tightly constrains the P-T conditions of the blueschist-facies metamorphism.

Unfortunately, it is not easy to identify the minerals in these rocks by hand lens. A few clues: the black (rarely pinkish) spots in the greyfels, which might be mistaken for chloritoid, are in fact lawsonite. The common rusty red spots in the greyfels are either the reddish brown alteration products of a carbonate (ankerite?) or reddish brown oxychlorite. Chloritoid may occasionally be recognised in the micaschists as splaying aggregates of long prismatic crystals. The greyfels layers, with jadeite + chloritoid + glaucophane + lawsonite subassemblages, will be pointed out in the road section.

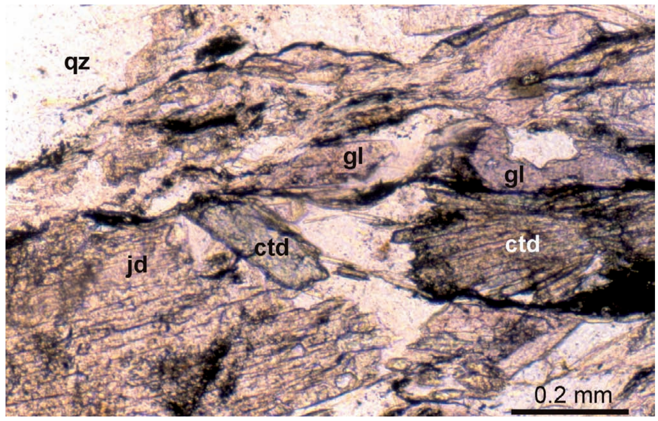


Fig. 17 - Photomicrograph from the blueschist facies grayfels with jadeite (jd), chloritoid (ctd), glaucophane (gl), phengite and quartz (qz).

Mineral compositions, phase relationships and P-T conditions in the Kocasu sequence

The petrology of the blueschist metasediments east of Orhaneli is described in Okay (2002). Okay and Kelley (1994) have described the western part of the blueschist micaschist belt around the Kocasu Valley in the west, which shows slight lithological and petrologic differences from that of the Orhaneli area.

All the analysed jadeites contain over 85-mol% jadeite component, the rest is largely aegirine (1-7%). Sodic amphiboles from greyschists are glaucophane-ferroglaucophane solid solutions, with very minor ferric iron and calcium, as shown by the Ca/(Ca + Na) ratios less than 0.01. There is very little zoning in the sodic amphiboles. Lawsonite compositions are close to the ideal structural formula, with only minor substitution of Al by Fe^{3+}. Chloritoids are Fe^{2+}-rich, with $Fe^{2+}/(Fe^{2+}+Mg)$ ratios of over 0.84. They show no zoning and contain minor Mn and Fe^{3+}. The maximum Si content of the analysed phengites is 30.56 per formula unit (on the basis of 11 oxygens). Chlorite shows a range of Fe/(Fe+Mg) ratios (0.45 to 0.75), and is richer in Fe and Al compared to the chlorite from the metabasites of the same metamorphic grade.

The jadeite + paragonite + quartz assemblage in the Orhaneli region constrains the pressure between 12 and 25 kbars by the reactions (Fig. 18)

Albite = jadeite + quartz
Paragonite = jadeite + kyanite + H_2O
Quartz = coesite

Phengites with up to 30.56 Si per formula unit in the greyschists indicate minimum pressures of 14 kbar, according to Massone and Schreyer's (1987) phengite geobarometer. The jadeite + chloritoid + glaucophane + quartz mineral assemblage places tight constraints on the metamorphic pressure, pointing to a pressure of about 24 kbar (Fig. 18). A similar pressure estimate is obtained from the chloritoid + glaucophane + paragonite + chlorite + quartz mineral assemblage, through the pressure sensitive equilibrium reaction (cf. Theye and Seidel, 1991):

Chloritoid + glaucophane + H_2O =
paragonite + chlorite + quartz.

The stability of lawsonite and jadeite, a paragenesis observed in some greyschist in the Orhaneli area, gives a maximum temperature of 560°C at 20 kbar (Fig. 18). Minimum temperatures of 420°C at 22 kbar are given by the stable coexistence of chloritoid and glaucophane (Fig. 18):

Chloritoid + glaucophane + H_2O =
jadeite + quartz + chlorite.

The transition from lawsonite-blueschist facies to epidote-blueschist and eclogite facies occurs between 450 and 500°C. The P-T conditions for eclogite- and epidote-blueschist facies rocks from the Cyclades with garnet, omphacite and epidote paragenesis in metabasites, were 470±30°C and 15±3 kbar (e.g., Schliestedt, 1986; Okrusch and Bröcker, 1990). The temperatures in the Orhaneli region, where the metabasic mineral paragenesis is sodic amphibole + lawsonite generally without epidote, must therefore have been less than 450°C. Epidote is a rare and probably secondary mineral in the Orhaneli region, and it is generally found in altered greyschists associated with albite and chlorite.

Taking these factors into account, the peak P-T conditions of blueschist metamorphism in the Orhaneli area were 430±30°C and 24± 3kbar (Fig. 18).

Stop 1.17 Panoramic view: Blueschist metasediments and the overlying blueschist marbles

Locality: on the road between Orhaneli and Keles, near the village of Kabaklar. 111 km after Orhaneli, UTM 35T 06 77 675, 44 19 071, Fig. 12.

After seeing the road section we board the minibus at 5.9 km and drive eastward. The road section exposes further blueschist micaschists; eastward there are also marble bands and boudins surrounded by schists, starting at 6.5 km. These marble bands were probably original limestone intercalations in the upper parts of the Kocasu sequence. However, because of the deformation and the competence contrast between the schists and marbles, most marble horizons are boudinaged and show sheared contacts with the micaschists. Most of this shearing is post-metamorphic. At the junction at km 7, we take the road on the left and pass through Belenoluk at 7.6 km. After the village there is another junction at 8.2 km; we again take the road on the left, which climbs up a hill. Then we drive down a small valley with springs and, invariably, with sheep herds and sheep dogs. This small spring leads to the major Kocasu River.

At 111 km there is a good view of the deeply-incised Kocasu Valley. The northern part of the Kocasu Valley is made up of massive blueschist marbles, several hundred meters thick; the blueschist metasedimentary sequence, which we have been crossing, dips under the marbles. The marbles occupies the core of a major east-west trending syncline (Fig. 12). Below us there is the village of Kabaklar. We will stop briefly to look at this view.

Stop 1.18 Jadeitite

Locality: on the road between Orhaneli and the village of Belenoluk, east of Orhaneli; immediately south of the village of Kabaklar. Between 122 and 123 km after Orhaneli, UTM 35T 06 78 188, 44 18 833, Fig. 12.

Immediately after the village of Kabaklar we will stop and study the road cut on the right. The dark grey phyllites are made up essentially of phengite (80% of the mode) with minor chloritoid and graphite. 100 m farther on we come to an interesting outcrop. In this outcrop there are two types of rock. The first one is composed mainly of jadeite (over 80%

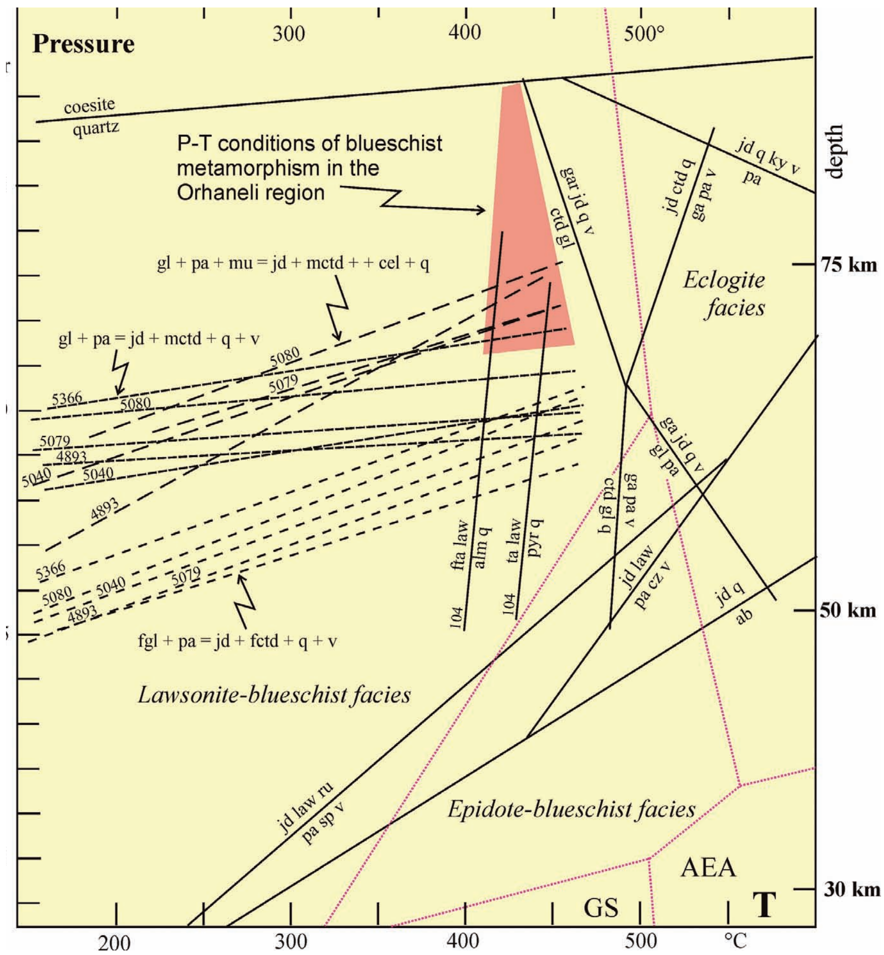


Fig. 18 - Pressure-temperature (P-T) diagram showing equilibria relevant to the estimation of the P-T conditions of the Orhaneli greyschists. Facies boundaries are after Evans (1990). All reactions were calculated using Powell and Holland's (1988) and Holland and Powell's (1998) THERMOCALC. The garnet-forming equilibria represent an average of the ferrous and magnesian end member reactions for almandine and pyrope activities of 0.26 and 0.00061, respectively, and the data from sample 5080. As paragonite does not occur with the jadeite-chloritoid-sodic amphibole subassemblage, the dashed reaction lines in the Figure involving these minerals provide minimum pressure estimates. Abbreviations: ab = albite; alm- almandine; cel = celadonite; clin = clinochlore; coe = coesite; ctd = chloritoid; cz = clinozoisite; di = diopside; fctd = Fe-chloritoid; fgl = ferroglaucophane; fta = ferrotalc; ga = garnet; gl = glaucophane; jd = jadeite; ky = kyanite; law = lawsonite; mctd = Mg-chloritoid; pa = paragonite; q = quartz; pyr = pyrope; ru = rutile; sa = sodic amphibole; sp = sphene; ta = talc; v = H2O; AEA = albite-epidote amphibolite; GS = greenschist facies (modified from Okay, 2002).

of the mode) with minor quartz, phengite and oxychlorite. Jadeite forms splaying crystals, 2-3 mm large, and can be recognized by a hand lens. The second type has a granular texture and is composed of jadeite + lawsonite + quartz. The ~2-mm-long greenish grey crystals in the rock are altered jadeite. The origin of these rocks is enigmatic.

Stop 1.19 Jadeite - chloritoid - glaucophane schists

Locality: on the road between Orhaneli and the village of Belenviran, east of Orhaneli. 17.0 km after Orhaneli, UTM 35T 06 79 187, 44 16 787, Fig. 12.

After the jadeitite stop the road continues southward, descending into the Kocasu Valley and passing through poorly exposed metasediments and marbles. After crossing the Kocasu Valley at 15.5 km, the road starts climbing up towards Keles. Along this section of the road there are micaschists and jadeite-chloritoid-glaucophane fels. We will stop briefly near the top of the hill to look at the metasediments. One very fresh jadeite-chloritoid-glaucophane fels occurs as a 15-cm-thick, hard band amidst schistose black micaschists. The elongated black crystals of glaucophane, defining a strong lineation, are visible to the naked eye. The mineral assemblage in this rock is jadeite + chloritoid + glaucophane + lawsonite + phengite + quartz. 30 m farther on there are dark to light schists of jadeite, lawsonite and quartz, with minor phengite and graphite. Lawsonite forms the dark equant grains visible through a hand lens.

We drive towards Keles for about two km more. When we reach the top of the plateau we can observe the gently undulating Neogene topography extending eastward towards Keles. This bears a testimony to the strong post-Miocene uplift, that affected the region of Orhaneli.

From here we drive for about an hour to Tavşanlı, where we will eat and spend the night.

DAY 2
Road description between Tavşanlı and the village of Gümüşyeniköy

In the morning we leave Tavşanlı and drive towards Kütahya, passing road cuts in the well-exposed Neogene sediments. At 17.4 km we leave the main asphalt road and turn left (north), taking a village road, signed Çobanköy-Gümüşgölcük-Şenlik. The road passes through the Neogene

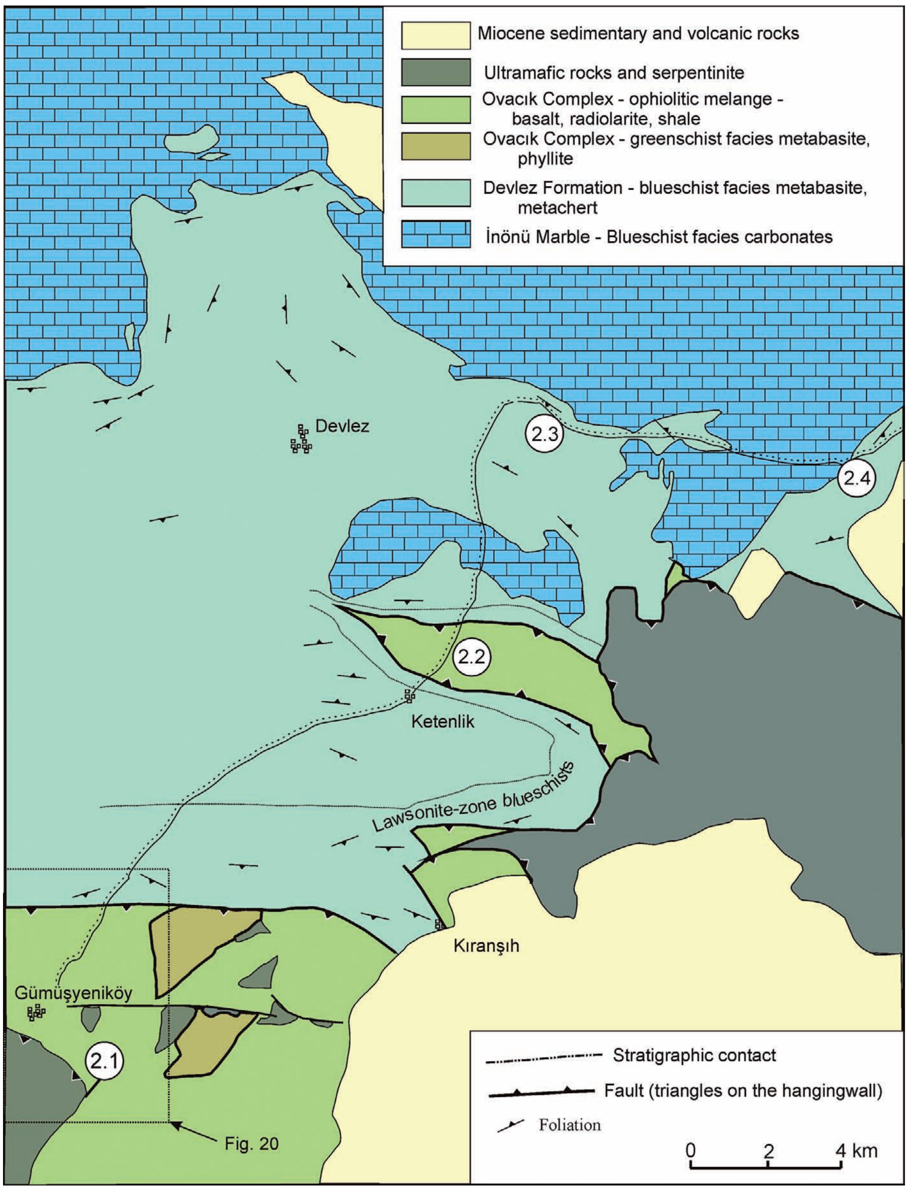


Fig. 19 - Geological map of the region northeast of Tavşanlı showing the location of Stops 2.1 to 2.4. For location see Fig. 4 (modifed from Okay, 1981).

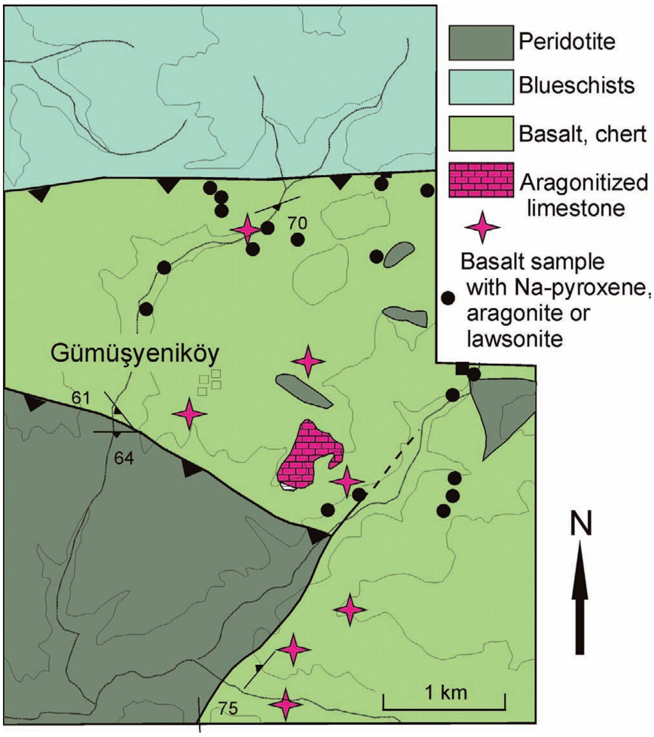


Fig. 20 - Geological map of the region around Gümüşyeniköy showing the location of the aragonitized limestone at stop 2.1. For location see Fig. 19. (modified from Topuz et al., 2006).

deposits with small lignite mines along the road. At 26.0 km we enter the village of Şenlik and take the road to Eğriöz, which is the road on the left at the village fountain. After about one km past Şenlik there are isolated outcrops of accretionary complex and peridotite, surrounded by Neogene sediments; however, the road passes mainly through Neogene conglomerates and sandstones. At 34.5 km there is a road junction; we take the road to the left, which leads to the village of Gümüşyeniköy. Peridotites emerge under the Neogene cover at 37.2 km as the road descends to the Kocasu Valley, the same river we saw on Stop 1.7. At 41.2 km we enter the village of Gümüşyeniköy.

Stop 2.1 Aragonitized limestones in the accretionary complex

Locality: one kilometre south of the village of Gümüşyeniköy, Tavşanlı; 41.2 km after Tavşanlı, UTM 07 35 369, 43 94 627, Figs. 19 and 20.

We park the car near the village mosque of Gümüşyeniköy, and walk about a kilometre south.

The village of Gümüşyeniköy sits in a large region of accretionary complex of basalts, red radiolarian cherts, shales, bedded manganese deposits, serpentinites, talc and rare limestones, which show an incipient blueschist-facies metamorphism (Figs. 19 and 20; Okay, 1982). Medium to thickly bedded, red limestones outcrop in small village quarries. In one of these quarries basaltic pillow lavas are seen to stratigraphically overlie the red limestones. These limestone beds are traceable for a few hundred meters along strike. A remarkable feature of these rocks is the prograde aragonitization observed in the limestone beds (Topuz et al., 2006). Aragonite has nucleated in the centre of the limestone beds and has been growing towards its lower and upper surfaces, replacing the original micrite (Fig. 21). In thin section the individual aragonite crystals are several centimeters across; commonly a single aragonite crystal occupies the whole of the thin section. Aragonitization appears to postdate the stylolites, which are subparallel to the bedding in the limestones. To the best of our knowledge this is the only locality of prograde aragonitization in the world; in all other occurrences aragonite has partially transformed back into calcite. The prograde aragonitization indicates very low metamorphic temperatures, possibly below 200°C, at pressures of above 7 kbar.

Stop 2.2 Lawsonite Zone blueschists and the accretionary complex

Locality: between the villages of Ketenlik and Göynücek, Tavşanlı; 500 m after the village of Ketenlik. 51.8 km after Tavşanlı, UTM 07 41 000, 44 00 780, Fig. 19.

From Gümüşyeniköy we drive north, initially in the accretionary complex, recognisable from the red color of the soil. At 44 km we enter proper blueschists, which structurally underlie the accretionary complex (Fig. 19). The blueschists in this northeastern Tavşanlı region consist of a sequence of intercalated metabasites, metacherts, metashales and metagabbro bodies, of over two kilometers in thickness, named the Devlez Formation. Blue metabasites, consisting mainly of sodic amphibole and lawsonite, are the dominant lithology. This sequence rests on white, massive marbles (İnönü Marble), several kilometers in thickness. The large-scale structure in this region is a large, southward plunging synform, whose core is made up by the Devlez Formation (Fig. 19). The blueschist-facies metaclastic rocks (the Kocasu Formation), which underlie the marble sequence in the Orhaneli area, are not exposed northeast of Tavşanlı.

The road from Gümüşyeniköy continues for several kilometers among poorly exposed blueschists. At 49.6 km we come to a junction and take the road on the right. Farther on, at 52.2 km, there is another junction; this time we follow the road to the left, towards the village of Ketenlik. A few hundred meters after the village of Ketenlik, we stop and walk for about 1.4 km along the road, studying the road section. In this section we will see the northern contact of a klippe of the accretionary complex, which lies over the blueschists of the Devlez Formation.

Immediately outside the village of Ketenlik the contact between the Devlez Formation and the accretionary complex is exposed. The village lies in the glaucophane-lawsonite blueschists of the Devlez Formation. These rocks give much better outcrops in the subsequent stop. Here they are tectonically overlain by the accretionary complex consisting of basalts, red radiolarian cherts and red shales, which show a foliation and a beginning of blueschist metamorphism. At the contact there is a small lens of serpentinites. The basalts consist mainly of lawsonite, sodic pyroxene, chlorite and leucoxene (Fig. 22). Sodic pyroxene is pseudomorphous after igneous augite. The sodic amphibole, found here as blue stringers, is just starting to form. Such metabasites are termed "lawsonite zone metabasites" and they constitute a stage in the prograde blueschist metamorphism in the Tavşanlı Zone (Fig. 23).

We can walk to the northern contact of the klippe of the accretionary complex at 54.5 km, and see the strikingly blue metabasites of the Devlez Formation under the klippe.

Stop 2.3 The Blueschists of the Devlez Formation

Locality: between the village of Göynücek and Dodurga, Tavşanlı, Fig. 19.

After driving for about 600 meters among the blueschists, we enter white massive marbles at the base of the blueschists; the road passes through the marbles for about one kilometre. There is a road junction at 56.1 km; we take the road to the left, and after driving through poorly exposed blueschists, enter the village of Göynücek at 58.7 km. There are good outcrops of the blueschists of the Devlez Formation after the village of Göynücek. At 60.8 km we can see from a distance the blueschist facies marbles, which cover a very large area and extend for 15 km northwards, right up to the İzmir-Ankara suture (Fig. 4). There are good road sections of Devlez blueschists between 61.5-62.1 km, 62.7-63.0 km and at around 64.3 and 64.6 km. We will walk along at least one of these sections to see the petrological and structural aspects of the Devlez Formation. The mineralogy and petrology of the blueschists in this region is described in detail in Okay (1980a).

Stop 2.4 The contact between the Devlez blueschists and the İnönü Marble

Locality: between the villages of Göynücek and Dodurga; 62.5 km after Tavşanlı, UTM 35S 07 44 913, 44 05 172, Fig. 19.

The road from Göynücek to Dodurga continues eastward in Devlez blueschists, crossing the core of a complex syncline (Fig. 19). At 64.9 km we enter the underlying İnönü marbles and drive for about 23 km amidst the white marble. We reenter the overlying Devlez blueschists at 67.4 km. If there is time we can study the contact between the Devlez Formation and the İnönü Marble. At the contact there is a metaquartzite horizon, about 50 m thick. There is a common lineation and foliation in the Devlez Formation and the underlying İnönü Marble. It is clear that the limestones were metamorphosed and deformed together with the overlying sequence of basic tuff, radiolarian cherts and pelagic shales. It is also probable that the primary contact between these two formations is stratigraphic. One evidence for this is the presence of the quartzite horizon on top of the marbles, which can be traced for several kilometers along the contact.

From this contact eastward the overlying Devlez blueschists are well exposed until the km 68, when the road enters the overlying Neogene sediments.

Stop 2.5 Tectonostratigraphy of the Tavşanlı Zone

Locality: Dodurga Dam, between Dodurga and Bozüyük; 119.6 km after the Orhaneli-Balıkesir-Tavşanlı triple junction.

At 71.5 km the village road from Göynücek joins the main Dodurga road; there is a fountain decorated with tiles at this junction. We turn left (north) and reach Dodurga at 76.4 km. There are Neogene sediments exposed along this road.

The Dodurga region is of historical interest, in that this area was the cradle of the Ottomans. In the 13th century they dwelled here as a nomadic tribe grazing their sheep in the pastures of Dodurga and Domaniç (20 km farther west) before forming an Empire. At that time this was a frontier region between the Byzantines in the west and the Anatolian Seljuks in the east. The region has since changed little in terms of landscape or people's habitat.

The blueschist marbles extend behind Dodurga. After a few miles from Dodurga, at 79.6 km, there is a side road towards a small irrigation dam. The outcrops around the dam reveal in miniature the tectonostratigraphy of the Tavşanlı Zone. Along the road towards the dam, there is a good section of blueschist metabasites, metatuffs and phyllites. These rocks are tectonically overlain by the accretionary complex of basalts, radiolarian cherts and pelagic shales exposed on the eastern wall of the dam. A peridotite body with a basal horizon of yellowish-brown silicified serpentinites overlies the accretionary complex.

The road between Dodurga and Eskişehir

From the Dodurga Dam there is a drive of about 15 km northwards towards Bozüyük. The first part of the road is in poorly exposed blueschist marbles, schists and peridotites, and the second part in the Neogene. This region was studied by Servais (1982). One of the battles of the 1920-23 Turkish-Greek war took place near this road and there is a war cemetery for the fallen Turkish soldiers along the road (İntikam Tepe Şehitliği). Eleven kilometers after the Dodurga Dam we pass through the large village of Saraycik; one kilometre before Bozüyük there is a good panoramic view to the north. Here we are on the northern margin of the Tavşanlı Zone, and the town of Bozüyük lies at the contact between the Sakarya and Tavşanlı Zones (Fig. 4). The İzmir-Ankara suture in this region is marked by a post-Miocene fault, the Eskişehir Fault, which forms the eastward extension of the suture fault we saw in the Stop 1. 9.

The hills behind Bozüyük are made up of a Carboniferous granitoid, which is thrust over the metabasite-marble-phyllite sequence of the Nilüfer Formation. The Early Jurassic Bayırköy Formation and the Late Jurassic Bilecik Limestone lie unconformably over the granite. Bilecik Limestone makes a ledge and is easily recognizable from this point. The Permian-Triassic metabasite-marble-phyllite sequence (Nilüfer Formation) crops out over large areas north of Bozüyük and north of Eskişehir.

Triassic blueschists and eclogites north of Eskişehir

At Bozüyük we join the main Bursa-Eskişehir highway. From here to Eskişehir is 44 km. From Eskişehir we will drive north towards Sarıcakaya, which lies in the Sakarya Valley north of the Sündiken Mountains to find the Sarıcakaya junction pass the campus of the Anadolu University, and then turn left (north) at a junction marked by a large mosque with two minarets next to the Sakarya Hospital (UTM 36 S 02 88 843 44 08 087). Drive north pass through the village of Muttalip; after this unattractive village the roads bifurcates, take the road to the right towards Sarıcakaya.

The Eskişehir plain at an altitude of 750 meters is bounded in the north by the east-west trending Sündiken mountain chain, which rises to 2000 meters before dropping precipitously to the valley of the Sakarya River flowing at about 500 m. The Sündiken Mountains are made up of Paleo- and Neo-Tethyan accretionary complexes (Fig. 4). The Paleo-Tethyan accretionary complex is represented by the Nilüfer Formation (Lower Karakaya Complex), which we saw in the first stop south of Bursa. In the Sündiken Mountains, the Nilüfer Formation consists of several large Eocene thrust sheets made up predominantly of metabasites showing Triassic greenschist and blueschist/eclogite facies metamorphism. Triassic eclogite and blueschist facies rocks occur as a thrust sheet, 25 km long and over 2 km thick (Okay et al., 2002). This Muttalip thrust sheet consists mainly of metabasites with minor marbles, phyllites and metacherts, and rare lenses of serpentinite. The common blueschist facies mineral assemblage in the metabasites is sodic amphibole + epidote + albite + chlorite + phengite ± garnet. Sodic amphibole commonly shows replacement by barroisite, and there is continuous petrographic transition from blueschist-metabasites to barroisite-bearing epidote-amphibolites. Eclogite

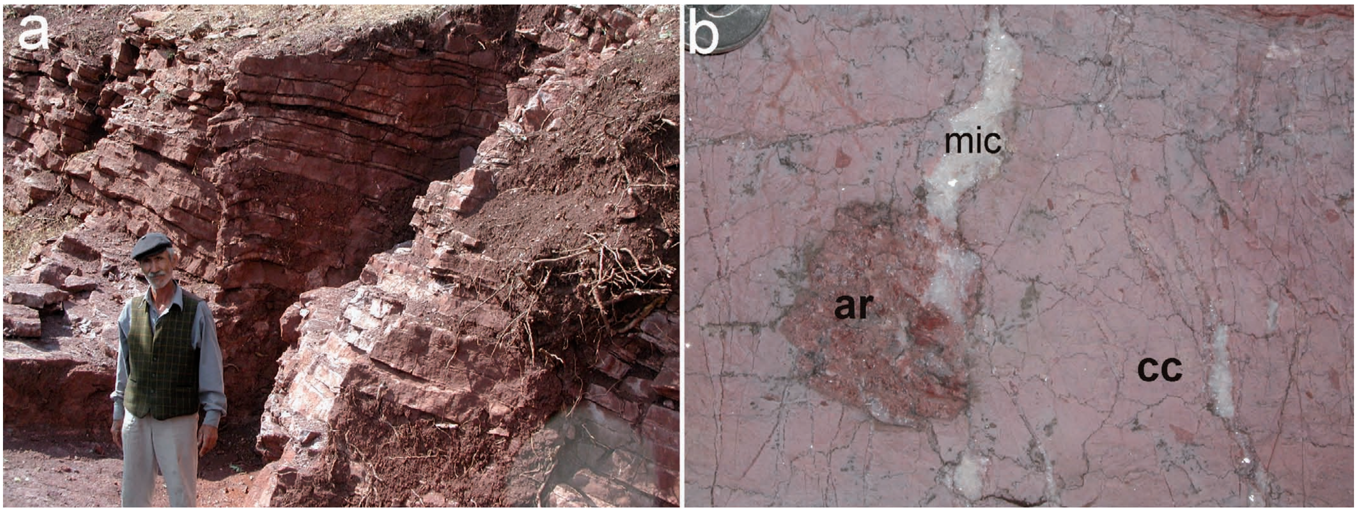


Fig. 21 - (a) Aragonized red limestones in a village quarry. (b) A large aragonite crystal growing in pink micritic calcite. A late calcite vein cuts both the micritic calcite and the aragonite.

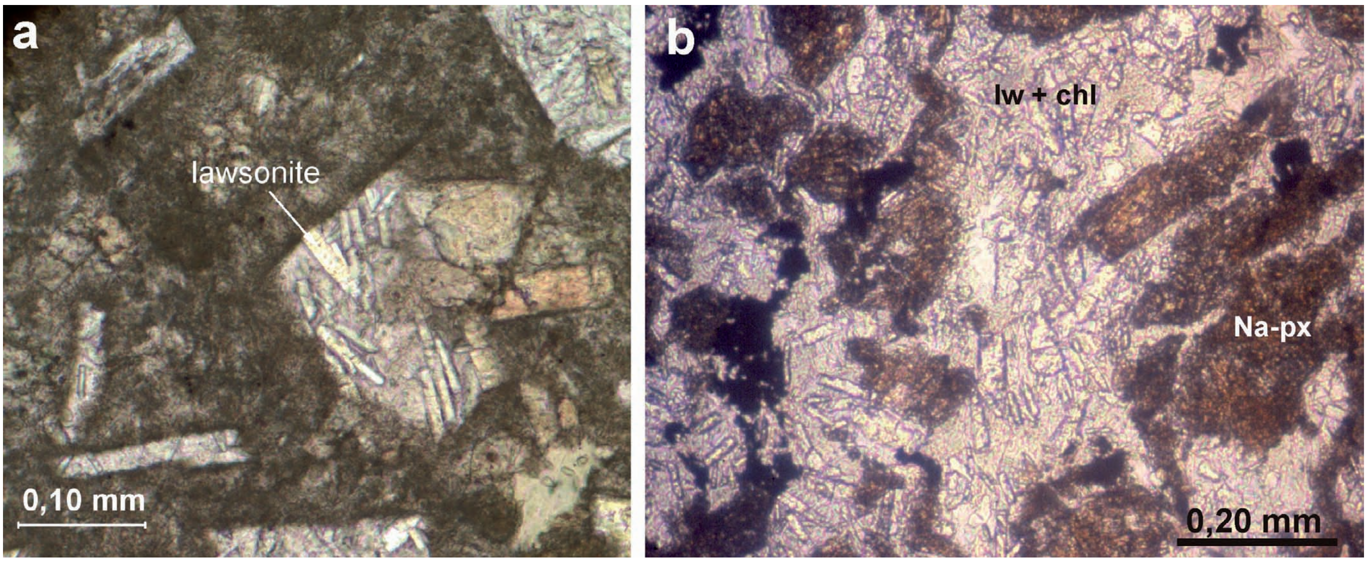


Fig. 22 - Figure 2.4. Photomicrographs from the basalts of the accretionary complex illustrating incipient blueschist metamorphism and lawsonite zone blueschists. (a) Lawsonite laths in albite along with magmatic augite and altered volcanic glass. (b) Sodic pyroxene (Na-px) pseudomorphs after augite set on lawsonite plus chlorite (lw + chl).

with the mineral assemblage of garnet + sodic pyroxene + sodic-calcic amphibole + epidote is found only in one locality. P-T conditions of the epidote-blueschist facies metamorphism are estimated as 450±50°C and 11±2 kbar. The blueschist formation was followed by a decrease in pressure and increase in temperature, leading to the development of barroisite-bearing epidote-amphibolites. Phengite, sodic amphibole and barroisite Ar/Ar ages from three metabasic rocks range between 215 and 205 Ma, and indicate Late Triassic high-pressure metamorphism. The Triassic blueschists in northwest Turkey constitute part of a much larger allochthonous tectonic unit of Triassic mafic volcanic rocks. They probably represent the upper layers of a Triassic oceanic plateau, which was accreted to the Laurasian margin during the latest Triassic.

The Muttalip thrust sheet is overlain tectonically by a Cretaceous ophiolitic mélange (the Ovacık Complex) consisting of basalts, radiolarian cherts, pelagic shales, serpentinites and pelagic limestones. Like their equivalents in the Orhaneli and Tavşanlı regions, the basalts from the Ovacık

Fig. 23 - A 2-m-thick massive metabasite boudin of sodic pyroxene, lawsonite, and chlorite surrounded by a foliated rim of late sodic amphibole and lawsonite.

Complex from north of Eskişehir show an incipient blueschist facies metamorphism with lawsonite, sodic pyroxene, sodic amphibole and aragonite (Okay et al., 2002).

In the Sündiken Mountains and also in the Ankara region, the Cretaceous and Triassic accretionary complexes are tectonically imbricated, with no evidence for an intervening Cimmeride continent. This close spatial association of the Triassic and Cretaceous blueschists along the İzmir-Ankara suture suggests that the suture represents a long-lived plate boundary of Late Paleozoic to Early Tertiary age and that the Cimmeride orogeny in Anatolia was not collisional but accretional.

Stop 2.6 Triassic Blueschists and barroisite-metabasites
Locality: Eskişehir-Sarıcakaya road, ~11 km northeast of Eskişehir. UTM 36 S 95 046 - 44 15 131, Fig. 24.

The lower flanks of the hills overlooking the Eskişehir plain expose blueschist metabasites. The metabasites show a well-developed foliation, tight folding and compositional banding on a millimeter-scale. They are interfolded with thin marble and calc-schist horizons. The blueschist metabasites consist of crossite/glaucophane, albite, epidote, phengite, chlorite and locally garnet. They are intercalated with barroisite-metabasites with barroisite, epidote, albite, chlorite, phengite, carbonate and sphene. The barroisite is a late mineral and in thin section can be seen to be replacing sodic amphibole.

A sample from this locality (T39) gave a single grain phengite age of 214.1±25 Ma, and a single grain barroisite age of 207.8±4.4 Ma (Late Triassic, Okay et al., 2002).

Stop 2.7 Triassic eclogite and barroisite-metabasites of the Lower Karakaya Complex in the Muttalip thrust sheet
Locality: ~15 km northeast of Eskişehir, a few hundred meters before the village of Karadere. UTM 36 S 95 246 - 44 18 063, Fig. 24.

From Stop 2.6 we leave the main road to Sarıcakaya and take the village road towards Karadere, climbing up the Sündiken Hills. The metabasites, well exposed along the road and in the gullies, are predominantly barroisite-bearing with sodic amphibole preserved only in the cores of some

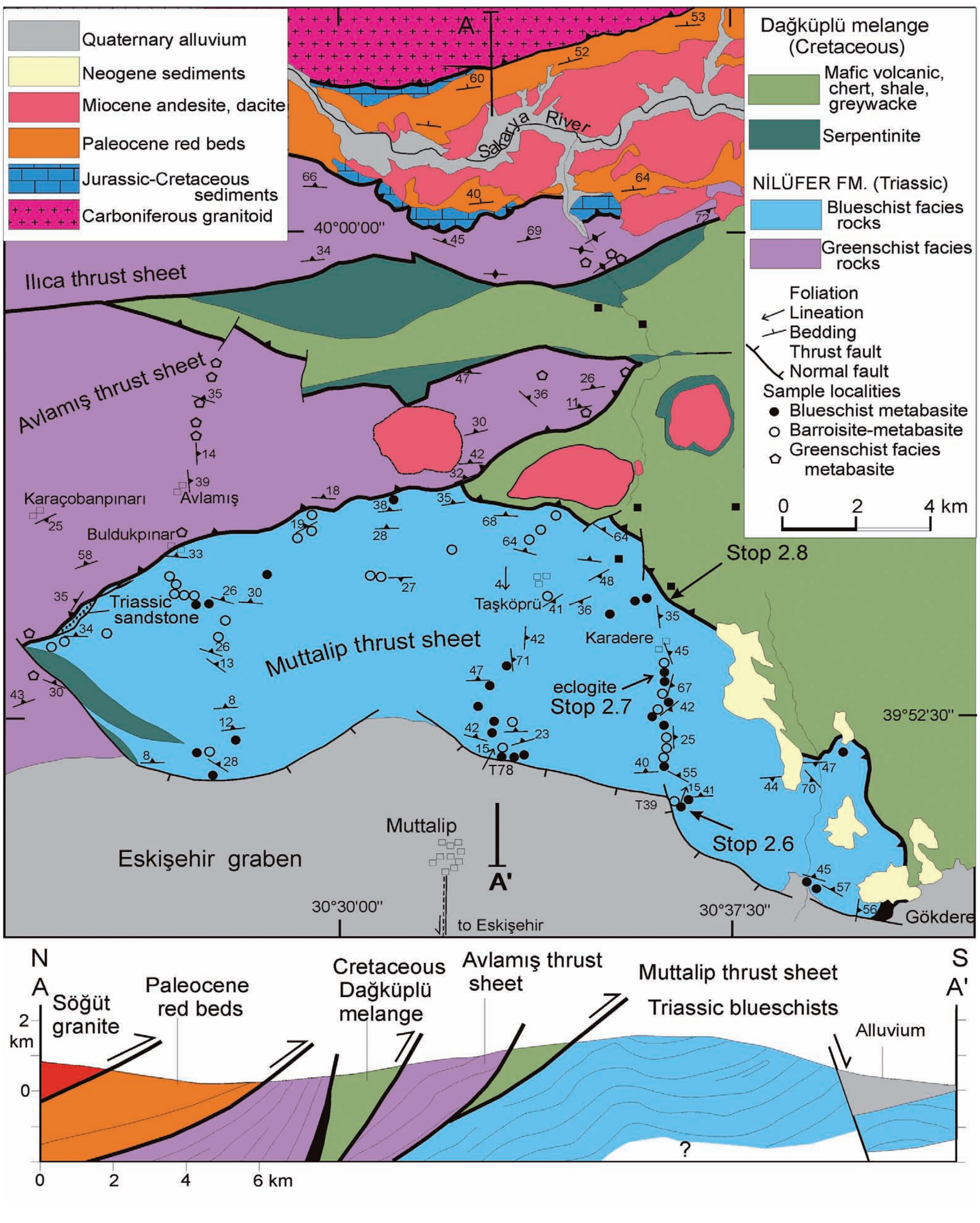


Fig. 24 - Geological map and cross-section of the region north of Eskişehir showing the field stop localities. For location see Fig. 4 (modified from Okay et al., 2002).

Ca-Na amphiboles. A few hundred meters before the village of Karadere, there is a small eclogite lens, about 3 m thick, within coarse-grained garnet-barroisite metabasites. The garnet-barroisite metabasites are in contact in the south with a calc-silicate rocks and metacherts with crossite, barroisite, quartz, phengite and garnet.

The eclogite is medium grained and has a strange texture of long finger-like aggregates of omphacite enclosing garnet. Under the microscope it consists of strongly poikilitic garnet, pale green omphacite, pale blue glaucophane largely replaced by dark bluish green katophorite, phengite, minor epidote, rutile and late albite (Fig. 25).

It is the only eclogite body thus found in the Sündiken Mountains and together with the eclogite east of Bandırma on the southern shores of the Marmara Sea, constitutes the only known Triassic eclogites in the Alpine-Himalayan chain.

Stop 2.8 Contact between the Triassic barroisite-metabasites of the Lower Karakaya Complex and the overlying Cretaceous ophiolitic melange (the Ovacık Complex).

Locality: ~18 km northeast of Eskişehir, a few hundred meters east of the village of Bozdağ. UTM 36 S 95 009 - 44 20 389, Fig. 24.

After Karadere village the road runs parallel to the thrust contact between the Triassic barroisite-metabasites and the overlying Cretaceous ophiolitic mélange. We can see the contact east of the village of Bozdağ along the Yarıkkaya stream, where barroisite-metabasites dip at gentle angles beneath unmetamorphosed radiolarian cherts. The latest phase of thrusting is Eocene in age.

DAY 3

Sivrihisar Massif

Eskişehir-Halilbağı-Okçu-Sarıkavak-Sivrihisar-Ankara

In the morning, we will drive ~65 km from Eskişehir to the Sivrihisar Massif, leaving the main highway at Kaymaz. We will spend most of the time examining the HP rocks, including lawsonite eclogite, in the vicinity of the village of Halilbağı. As time permits, will also survey some other interesting metamorphic and tectonic aspects of the massif.

Fig. 25 - Triassic eclogite from north of Eskişehir consisting of garnet, sodic pyroxene and sodic amphibole.

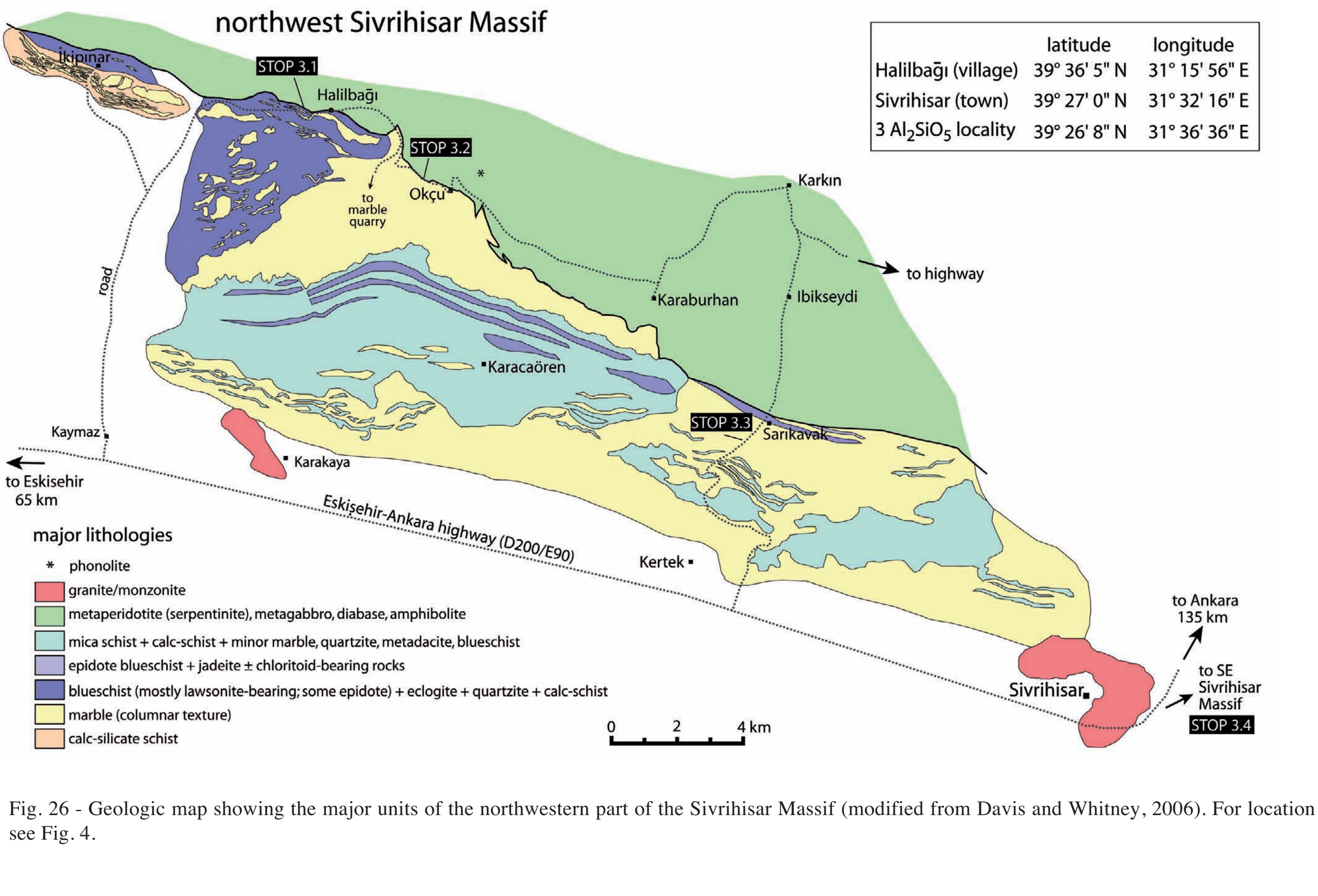


Fig. 26 - Geologic map showing the major units of the northwestern part of the Sivrihisar Massif (modified from Davis and Whitney, 2006). For location see Fig. 4.

Overview of Sivrihisar metamorphism

The Sivrihisar Massif (Figs. 4 and 26) is dominated by marbles and lesser amounts of other metasedimentary rocks (calc-silicate schists, quartz-phengite schists, quartzites) and metabasites. There are also rare lenses of metadacite and metaperidotite. The Sivrihisar Massif resembles the coherent blueschist sequence of the rest of the Tavşanlı Zone, but Sivrihisar differs from the rest of the zone because the massif contains eclogites, which primarily occur as pods within layers of blueschist (Kulaksız, 1978).

Metamorphic conditions recorded by Sivrihisar high-pressure (HP) rocks range from lawsonite eclogite and blueschist facies near the village of Halilbağı (Whitney and Davis, 2006) to epidote blueschist throughout much of the rest of the massif (Fig. 26) (Davis and Whitney, 2006; 2008; Çetinkaplan et al., 2008). All lithologies record HP conditions in their mineral assemblages and/or textures, including metasedimentary rocks such as glaucophane-phengite ± lawsonite ± garnet in quartzite (Fig. 27a), and calcite pseudomorphs after aragonite in marble (Fig. 27b).

In the southeast submassif, east of Sivrihisar town and the Eskişehir-Ankara highway (Figs. 4 and 9), HP assemblages are preserved only in a thin belt along the northern edge of the massif (Whitney, 2002; Seaton et al., 2009). The rest of the southern submassif is comprised of regionally metamorphosed (Barrovian) rocks and granitic intrusions (Whitney, 2001; Kibici et al., 2008). Metamorphic grade (temperature) increases with increasing distance from the contact with the HP rocks, and all evidence for HP metamorphism has been erased in rocks that experienced metamorphic conditions of staurolite zone or higher during the Eocene (Whitney et al., 2010).

Stop 3.1 Lawsonite blueschist, lawsonite eclogite, phengite-quartzite, columnar marble, calc-schist, contact with meta-ultramafic/mafic unit

Locality: northwestern Sivrihisar Massif, west of Halilbağı village; UTM 03 49 898, 43 84 921; European 1950 grid, Fig. 26.

Good outcrops of the HP rocks can be accessed by easy walking after parking at the side of the paved road between Kaymaz and Halilbağı, just west of Halilbağı village (Fig. 26). Cars can pull off the road west of the village of Halilbağı at a bend in the road and park by trees near a spring; larger vehicles can park at the side of the road further west where the road is straighter and wider.

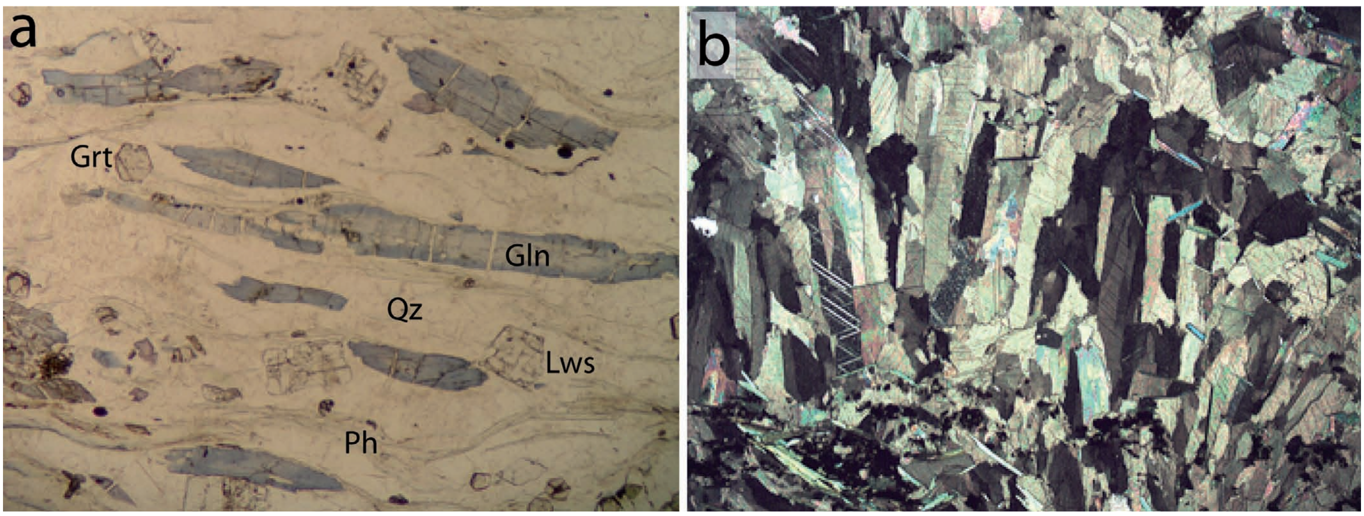


Fig. 27 - (a) Quartzite containing zoned glaucophane + garnet + lawsonite + phengite. Plane polarized light. Field of view = 4 mm. (b) Marble with columnar texture (rod-shaped calcite = aragonite pseudomorphs?). Crossed polarized light. Field of view = 4 mm.

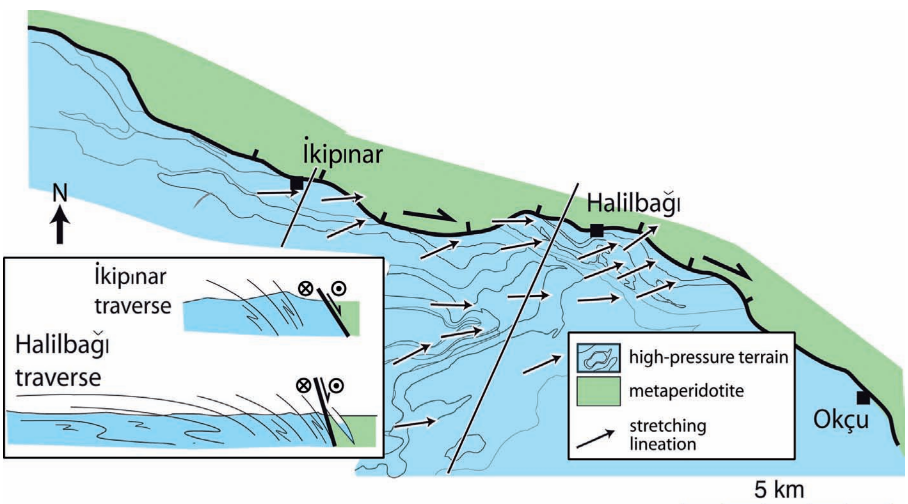


Fig. 28 - Simplified map of the region between İkipınar and Okçu, showing representative mineral lineations and structural cross sections along two traverses. Thin lines in the blueschist/eclogite facies unit (high-pressure terrain) are foliation trajectories (from Teyssier et al., 2010).

The outcrops north and south of the road expose a series of interlayered blueschists, quartzites, calc-schists, and marbles. The best outcrops that are easily accessible are on the edges of the stream valleys. If you walk north of the road through a sequence of blueschists, eclogites, quartzites, and marbles, you will eventually come to the poorly outcropping contact with the metamorphosed ultramafic/mafic unit, which in this region consists of serpentinites and diabase dikes. Locally, slivers of lawsonite blueschists occur within serpentinites along the fault contact (Fig. 28). South of the road is a similar sequence, although here there is also a metadacite pod (not to be confused with the nearby Tertiary dacites) and very large eclogite pods.

Overview of Halilbağı region

Near the village of Halilbağı (Stop 3.1), the region that exposes the highest-pressure rocks in the massif, hundreds of lawsonite eclogite pods occur within lawsonite blueschists and quartz-phengite schists. Eclogite pods are typically elliptical, range in size from a few cm to several meters, and may have lawsonite or epidote blueschist facies assemblages at their margins. Some pods represent boudinaged folds with fold axes parallel to lineation in the host blueschists (Davis and Whitney, 2008).

P-T conditions for blueschists and eclogites have been estimated using pseudosections constructed via Perple_X software for the Fe^{3+}-free system Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O (NCFMASH) (Davis and Whitney 2006). Results indicate pressures up to ~25 kbar at 500°C for lawsonite eclogite; 18 kbar at 600°C for epidote eclogite; 12-15 kbar at ~400°C for lawsonite blueschist; and similar pressures but higher temperatures for epidote-bearing blueschist (~500°C) (Fig. 29).

P-T paths for some eclogites and blueschists are counterclockwise (Fig. 29), as indicated by the presence of epidote inclusions in garnet in rocks that contain lawsonite in the matrix. In other blueschists and eclogites, garnet contains lawsonite inclusions in rocks with matrix lawsonite. Along some lawsonite eclogite pod margins, lawsonite eclogites are partially transformed to lawsonite blueschists.

Lithologic layering and foliation generally dip gently to moderately, and steepen toward the main fault between the HP rocks and the meta-ultramafic/mafic complex to the north. The strong foliation carries a prominent oblique stretching lineation that is oriented east-northeast (Fig. 28). Marble units display columnar calcite pseudomorphs after aragonite; calcite rods are systematically inclined relative to foliation, consistent with top-to-east-northeast shear (Seaton et al., 2009). Microstructures in blueschists, eclogites, marbles, and quartzites throughout the massif reveal a consistent top-to-east or northeast sense of shear that developed at HP conditions; the planar and linear fabrics formed in uniform normal/dextral oblique shear across the HP terrain.

Kinematic vorticity analysis of lawsonite in blueschist layers documents a major component of pure shear; eclogite pods and blueschist slivers in the fault zone that juxtaposes the HP sequence with metaperidotites experienced a larger component of simple shear. Kinematic vorticity data are consistent with oblique extrusion at depth in the subduction zone, and local simple shear at the fault contact with serpentinites. A combination of oblique unroofing from beneath a weak serpentinized hanging wall and pure shear extrusion in the subduction channel accounts for rapid exhumation along a low geothermal gradient and the rare preservation of lawsonite eclogites during exhumation to the Earth's surface.

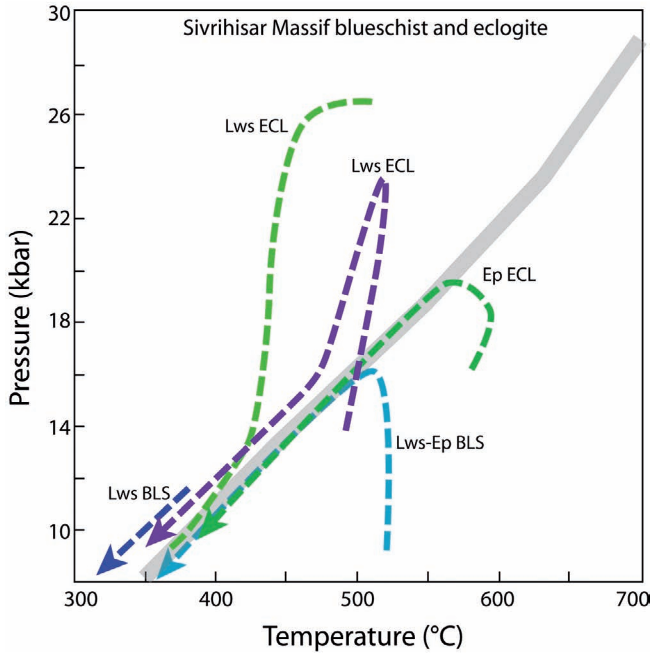


Fig. 29 - Pressure-temperature (P-T) paths for Sivrihisar blueschist and eclogite. Maximum P-T conditions were determined using pseudosections calculated for whole rock compositions in the CNFMASH system with Perple_x. Paths were drawn using information from phase stability fields predicted by pseudosections as well as using constraints from mineral modes, compositions, and zoning. Paths are consistent with textural observations, where available; e.g., lawsonite eclogite with garnet containing epidote inclusions.

At Stop 3.1, blueschists, quartzites, and calc-schists contain pods of eclogite, which are seen in some cases as elliptical lenses that are more resistant to erosion than the host rock; eclogite pods with intact contacts with host rocks can also be observed.

Most eclogite pods in this region are lawsonite-bearing, but some contain epidote, either as a retrograde phase at the pod margin or as a primary phase throughout the matrix of the pod. Lawsonite commonly occurs as a primary matrix phase, but is also present in lawsonite veins and segregations. These veins contain coarse lawsonite, and some also contain phengite ± garnet. A typical lawsonite eclogite assemblage is omphacite + garnet + lawsonite + phengite + rutile ± glaucophane (Fig. 30a). Tourmaline occurs in some eclogites in this region. Retrogressed eclogite pods contain chlorite after garnet.

Blueschists in this region are typically fine-grained (Fig. 30b). A common assemblage is glaucophane + lawsonite + phengite ± garnet ± omphacite + rutile (may be rimmed by sphene) ± tourmaline. Some blueschists contain magnetite. Quartz and plagioclase are rare, but garnet-bearing blueschists may contain quartz inclusions in garnet. Chlorite occurs at garnet rims and in fractured garnet in rocks that have experienced retrogression. Some blueschists contain calcite in the matrix or in veins. In this region, most contain lawsonite as the primary Ca-Al silicate, but some layers also contain epidote in apparent equilibrium with lawsonite (Davis and Whitney, 2006).

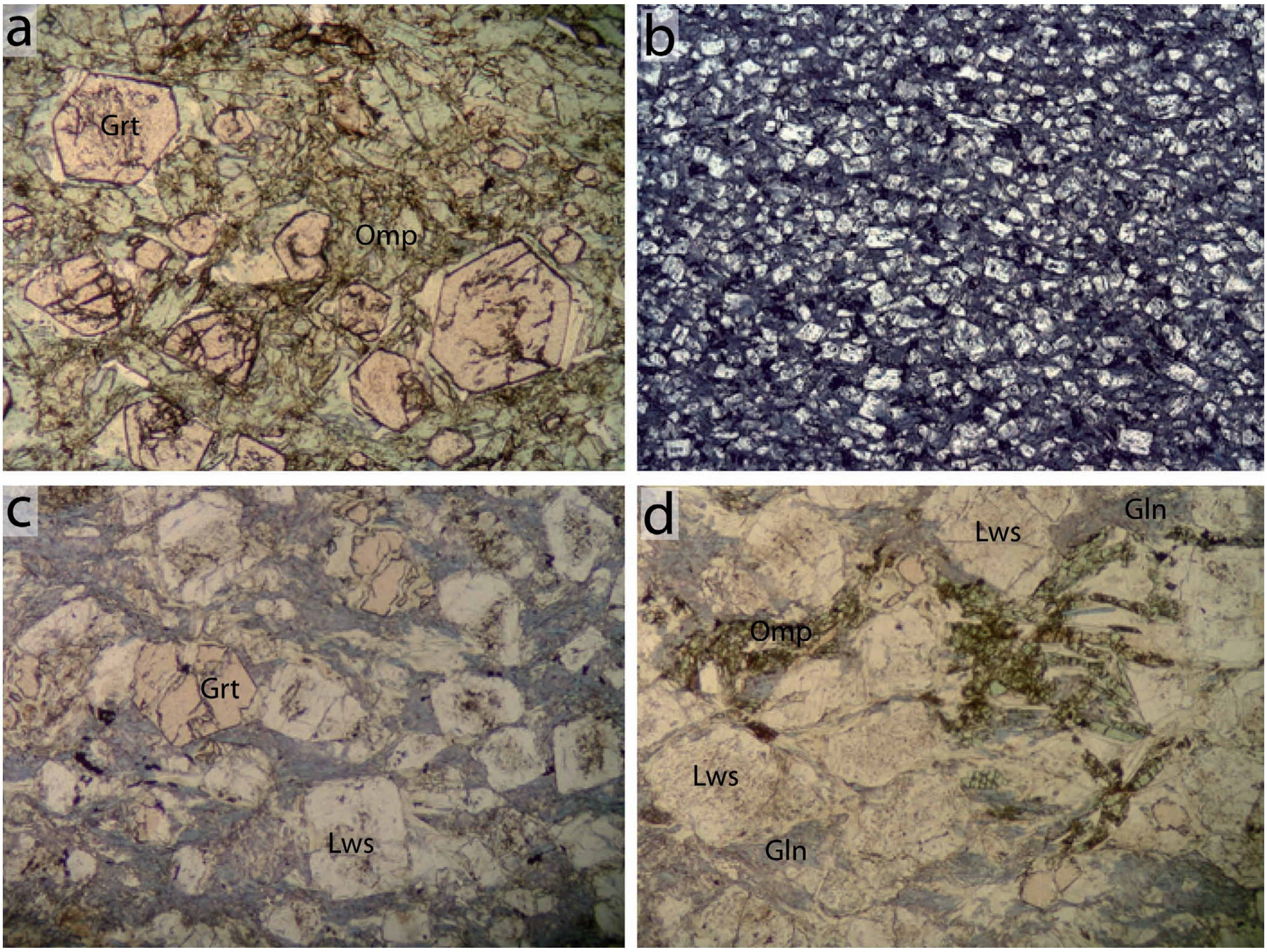


Fig. 30 - Photomicrographs (all photos: plane polarized light, field of view = 4 mm). (a) Eclogite (garnet + omphacite + minor phengite, glaucophane, and lawsonite + secondary chlorite). (b) Lawsonite blueschist. (c) Lawsonite + garnet + glaucophane blueschist. (d) Lawsonite + garnet + glaucophane + omphacite blueschist/eclogite.

Blueschists also occur at the margins of some eclogite pods. These pod margins are typically characterized by fine-scale (mm to sub-mm) alternating layers of lawsonite blueschist and eclogite. Locally, glaucophane rims omphacite at pod margins and garnets have complex textures and zoning (Davis and Whitney, 2008).

Quartzites (likely metachert) are banded and crenulated. Assemblages vary depending on bulk composition of the quartzite, but common assemblages are quartz + phengite + garnet + Na-amphibole ± lawsonite ± piemontite (Fig. 27a) and quartz + phengite + omphacite. In Na-amphibole-bearing quartzites, the amphibole may be a colorless, pure-Mg glaucophane (some with blue Fe-richer rims), a blue Fe-Mg glaucophane, or riebeckite.

Marbles exhibit a columnar texture comprised of thin rod-shaped calcite crystals interpreted to be pseudomorphs after aragonite (Fig. 27b). The rods are oriented at an angle (typically 50-90°) relative to foliation defined by compositional layering (alternating pure calcite and calcite + quartz ± phengite layers). In some layers, the rods are at a very shallow angle relative to foliation. This angle is interpreted to indicate varying amounts of shearing along the foliation planes.

Calc-silicates also occur in this region and is typically comprised of calcite + quartz + phengite + oxides ± chlorite, but locally contains glaucophane and/or omphacite.

Stop 3.2 Steep fault contact between the high-pressure rocks and serpentinite

Locality: between the villages of Halilbağı and Okçu, on western edge of Okçu village, UTM 03 53 357, 43 83 790, Fig. 26).

Serpentinite breccias and view of the fault contact with the HP unit (Fig. 26). This fault contact was originally mapped as a thrust fault (Gautier, 1984), although there are no kinematic data to support this interpretation. The fault contact is now very steep, as can be seen by looking east at the hillside just beyond the village of Okçu. Serpentinites outcrop to the north, interlayered marbles and blueschists to the south. Locally near the fault contact, mylonitic marbles and quartzites are observed in the HP unit (note: the small peaks to the east-northeast of Okçu are Oligocene-Miocene phonolite volcanoes).

Stop 3.3 Epidote-blueschist, marble and calc-schist

Locality: between the villages of Karkın and Sarıkavak, UTM 03 64 308, 43 75 742, Fig. 26.

After driving east through the poorly outcropping meta-ultramafic/mafic unit to the north of the Sivrihisar Massif, we will turn south at the village of Karkın towards Sarıkavak and then across a small paved road that provides an excellent north-south transect through the massif.

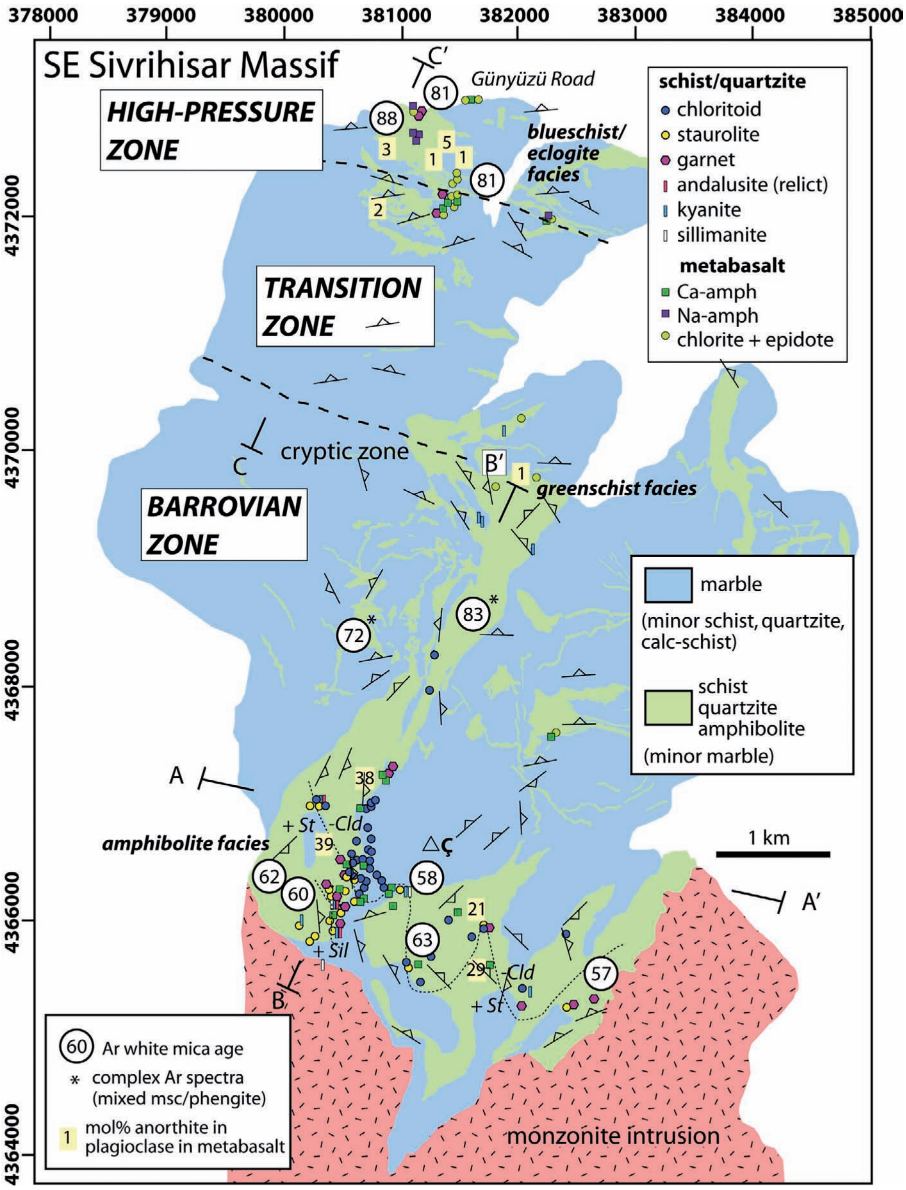


Fig. 31 - Geologic map of the blueschist-to-Barrovian transition area in the SE Sivrihisar Massif. The distinction of the domains (high-pressure, transition, 'cryptic', Barrovian) is based in part on calcite microstructures (Seaton et al., 2009). Index minerals and isograds are from Whitney et al. (2011). Ç = Çurukçal (Çaldağ on some maps), the most prominent marble peak in the region.

Epidote blueschists crop out in a thin east-west trending unit near the village of Sarıkavak (Fig. 26). The hills in this region primarily expose alternating sequences of columnar marbles, calc-schists, and rare blueschists; locally, metadacites occur (some with Na-amphibole).

At the high point on the road, before it descends to the southern plain and the Eskişehir-Ankara highway, there is a prominent quartzite exposed along the road and on the ridgeline.

We will make a brief stop along the road, depending on time and interest in this traverse.

Southeastern Sivrihisar Massif

This part of the massif records a complete and continuous transition from blueschist/eclogite facies to Barrovian metamorphism at medium pressures and a range of temperatures, up to sillimanite zone conditions. Although it is possible that the blueschist-to-Barrovian sequence represents two entirely different domains juxtaposed along a fault, observations of mineral compositions and textures in this region are more consistent with the hypothesis that the Barrovian rocks previously experienced HP conditions but have been variably overprinted during post-subduction collision and exhumation.

The HP region of the southeast Sivrihisar Massif (Figs. 4, 9 and 31) can be accessed from the Günyüzü Road, which has an exit off the Eskişehir-Ankara highway, east of the town of Sivrihisar (Fig. 26). This region is characterized by north- to northeast-dipping marble units interleaved with quartzite, schist and metabasite layers (blueschist with retrogressed eclogite pods). Blueschists in this region contain epidote, but some of them have pseudomorphs of white mica and epidote after lawsonite.

Foliation and lineation are consistent over the northernmost kilometer of the map area (Figs. 31 and 32). The HP marble units display a strong foliation and a pronounced north-trending lineation defined by rod shape calcite crystals. Toward the south, the transition zone between HP and Barrovian metamorphic rocks consists of more massive marbles with scattered outcrops of schists, quartzites, and thin metabasite layers and pods; the metabasites are comprised of blueschist and eclogite partially retrogressed to greenschist assemblages.

South of the transition zone between HP and Barrovian

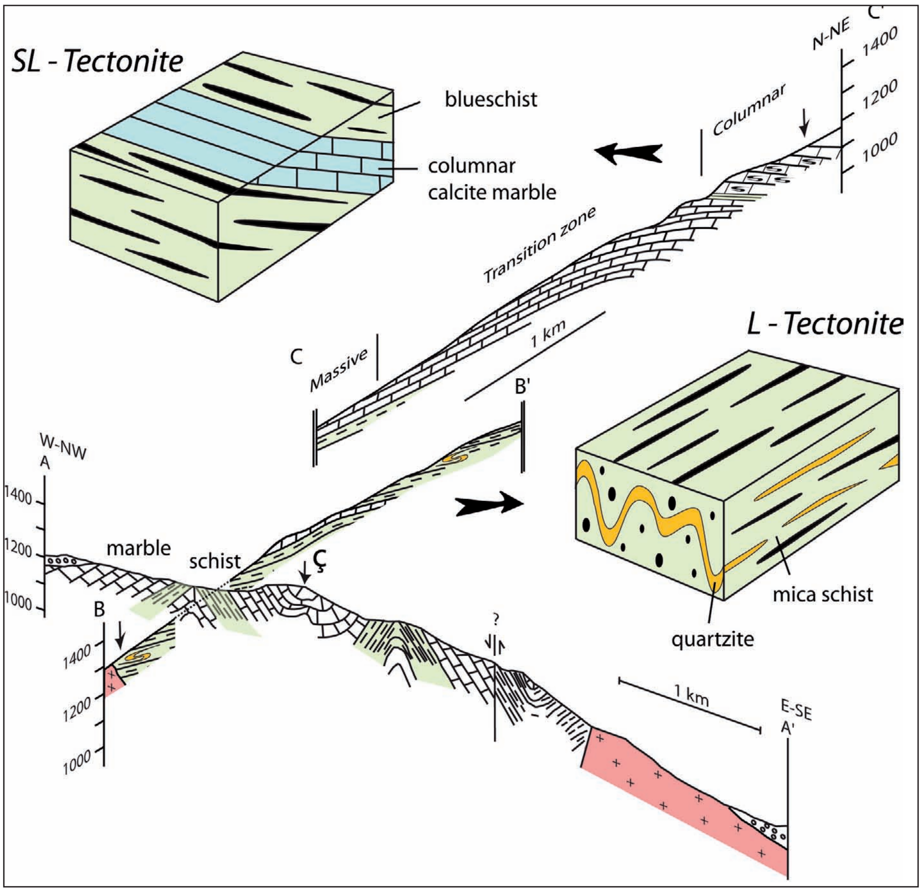


Fig. 32 - Schematic cross sections (see Fig. 31 for locations), highlighting the difference in structural features of the Barrovian (L-tectonite) and high-pressure (SL-tectonite) domains. From Whitney et al. (2011).

domains (Fig. 31), quartzite, schist, and marble layers are oriented north-northeast, nearly orthogonal to foliation in the northern region, and are sandwiched, over a north-south distance of ~5 km, between massive marble units to the east and west. In the Barrovian zone, deformation has produced intense lineation (L-tectonites) and complex folds with hinges that are consistently parallel to lineation. Throughout the Barrovian sequence, lineation is defined by the rod shape of quartz aggregates and the alignment of minerals, including mica, chloritoid, and Al_2SiO_5 polymorphs. Folds vary from upright to recumbent and can be highly disharmonic. Near the contact with the monzonite in the south, metasedimentary units wrap around km-scale upright folds, as the north-plunging regional structure closes.

In the HP zone, the overall structure is similar to that encountered in the Sivrihisar HP domain to the northwest, and consists of blueschists and HP marbles with a dominant east-west foliation and an oblique lineation plunging to the northeast. The structure of the Barrovian sequence deviates from this regional pattern and likely developed during constrictional strain that produced lineation-parallel folds on all scales.

$^{40}Ar/^{39}Ar$ cooling ages for phengite in blueschists from the northernmost part of the field area range from 81-88 Ma; cooling ages for muscovite in the Barrovian domain range from 58-62 Ma (Seaton et al., 2009; unpublished data). Two samples from the low-grade end of the Barrovian sequence have complex spectra and intermediate ages; these represent analyses of a mixed population of phengite and muscovite (Fig. 31).

Temperatures of the Barrovian metamorphism increases towards the contact of the intrusion (Fig. 31), but there are several lines of evidence that suggest this temperature increase was not primarily driven by the intrusion: (1) The temperature increase from ~300-700°C is associated with an apparent increase in pressure from <3 kbar to 6-7 kbar; (2) The presence of a strong regional lineation and foliation, including a constrictional fabric in quartzite and syn-kinematic growth of index minerals such as kyanite, are not typically associated with post-tectonic contact metamorphism; (3) The Ar/Ar hornblende age of the intrusion (Sherlock et al., 1999) is at least several milion years younger than the Ar/Ar muscovite age of rocks in the Barrovian sequence (Seaton et al., 2009; Whitney et al., 2011); and (4) The thermal and microstructural effects of contact metamorphism can be detected in marbles, schists, and quartzites within a few meters of the intrusion contact, but beyond that, effects seem to be limited to infiltration of late fluids possibly associated with crystallization of the granitoid.

Stop 3.4 Barrovian overprint over the high-pressure rocks

Locality: southern (Barrovian) end of the blueschist-to-Barrovian sequence, near the quarries on the south face of Çurukçal peak, north of the road between the highway and Tekören village, UTM 03 80 376, 43 66 226, Figs. 31 and 33.

This region can be easily accessed from the Tekören road (exit from Eskişehir-Ankara highway; same exit as for the large TŞOF restaurant - petrol station - motel complex - an excellent and inexpensive place to stay when visiting the Sivrihisar Massif), but head east-southeast of the highway rather than west-northwest to the TŞOF complex. Follow the Tekören road but turn off before the village. There are multiple dirt roads, but most lead to the same place: a series of marble quarries at the base of the most prominent marble

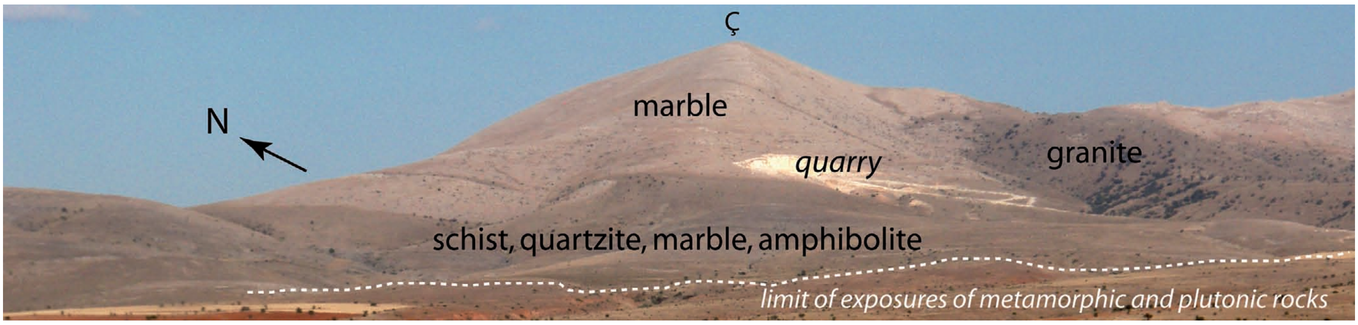
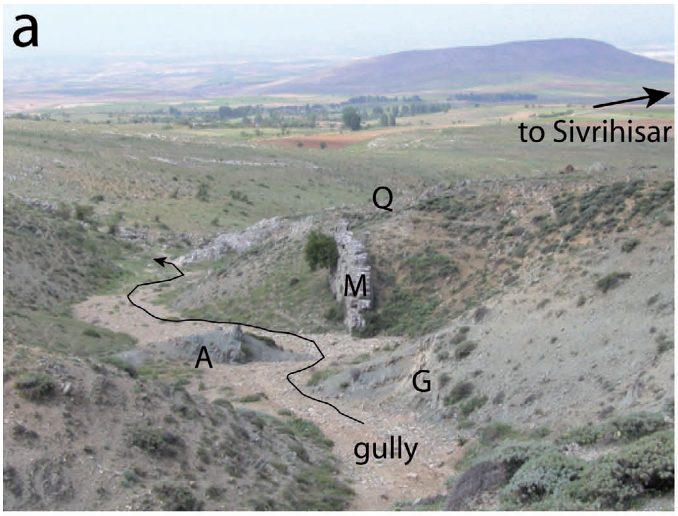


Fig. 33 - Photograph from the south-southwest of the marble peak in the southeast Sivrihisar Massif showing the quarry (near parking area) and the region of the Barrovian sequence structurally below the large marble unit. The contact with the granite/monzonite can also be seen.



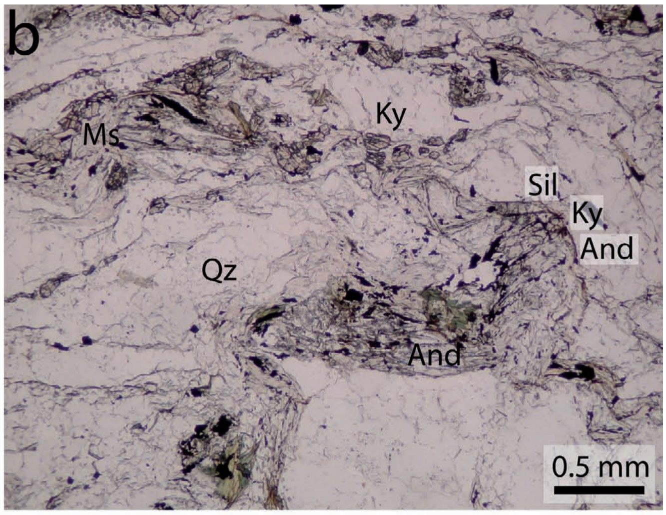


Fig. 34 - (a) Field photograph of part of the gully that exposes outcrops of the Barrovian sequence: A- amphibolite, G- garnet schist (with chloritoid inclusions in garnet); M- marble; Q- quartzite, locally Al_2SiO_5-bearing. View approximately south. (b) Photomicrograph of the 3 Al_2SiO_5 quartzite. Plane polarized light. (c) Field photograph of the "triple point" quartzite (location Q in (a), but here viewed from south to north).

peak (Fig. 33). The quarries may be active, so watch out for large trucks on the road. You can park just west of the quarries on flat grassy areas.

The best place to access outcrops of the Barrovian sequence is in the most prominent gully oriented approximately north-south, south of the Çurukçal marble peak (Fig. 34a). If you follow the gully south, you will see the granitoid (monzonite) pluton that is also visible in the surrounding hills as the dark rock that weathers into prominent ridges - e.g., the sharp (*sivri*) fortress or citadel (*hisar*) near the town of Sivrihisar, with excellent examples of spheroidal weathering. The intrusion has been dated at 53±3 Ma by

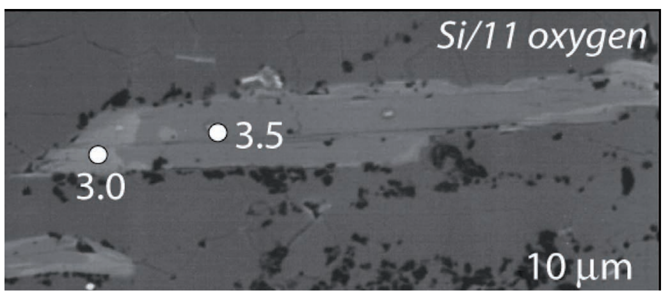


Fig. 35 - Backscattered electron image of zoned white mica with phengitic core and muscovite rim.

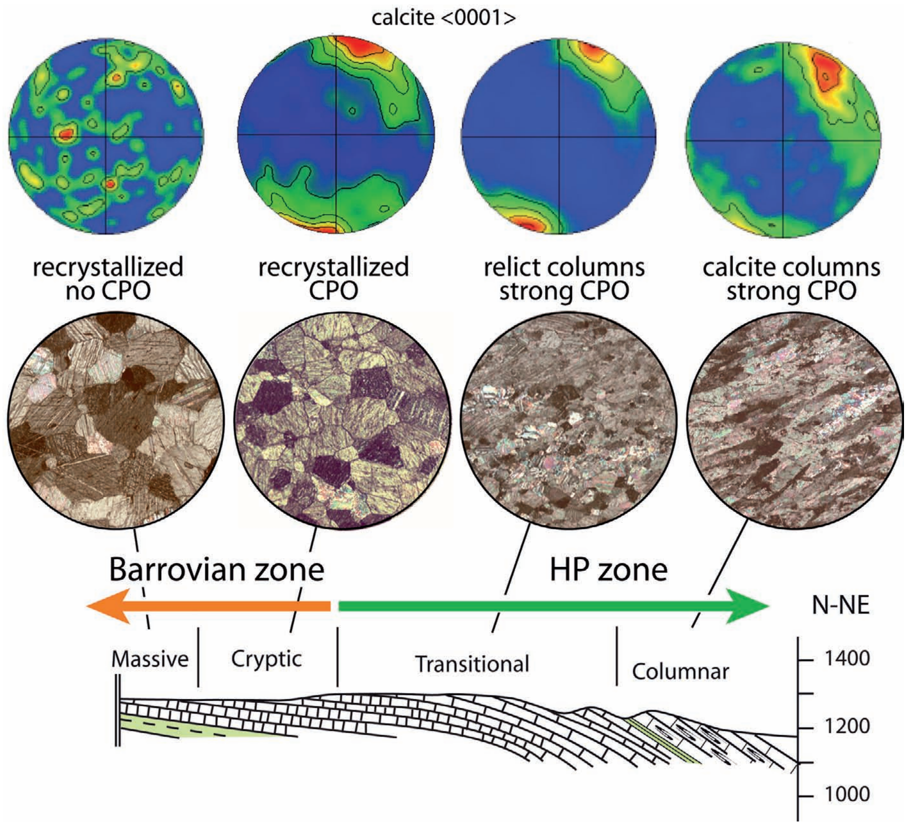


Fig. 36 - Calcite textures from the northern (high-pressure[HP]) zone to the southern (Barrovian zone) in the southeast Sivrihisar Massif (from Seaton et al., 2009). CPO- crystallographic preferred orientation.

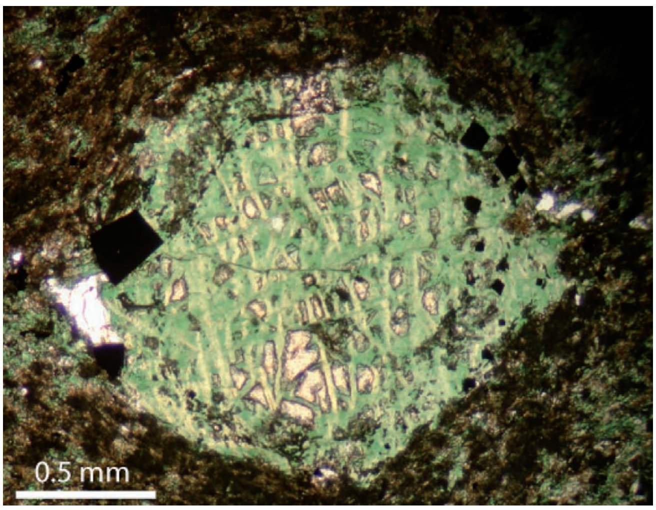


Fig. 37 - Chlorite pseudomorph after garnet, with relict garnet (high relief, colorless) that has the same composition as garnet in eclogite from the northwest Sivrihisar Massif.

hornblende $^{40}Ar/^{39}Ar$ methods (Sherlock et al., 1999).

Near the contact, the pluton has intruded the metasedimentary sequences in small sills and veins. Within a few meters of the contact, the schists contain sprays of fibrolite. The marbles are characterized by a granoblastic texture of calcite containing exsolved blebs of dolomite. Walking up the gully (north) towards the big marble peak, you will see abundant white and gray (graphitic) marbles, including localized brecciated zones that are very graphitic. Interlayered schists contain staurolite (some of which is partially to completely replaced by fine-grained white mica) and quartz-mica schists contain staurolite ± sillimanite, some with relict kyanite.

A particularly interesting site in the gully is at 39°26'8"N, 31°36'36"E (Fig. 34). In this vicinity you will see a nearly vertical slab of marble, a blue-green very fine-grained outcrop of lineated (L-tectonite) amphibolite (hornblende-plagioclase-biotite), a garnet-mica schist, and a variety of quartzites, including a reddish weathering one that locally contains coexisting andalusite, kyanite, and sillimanite (Fig. 34 b-c). A nearby white quartzite (quartz-muscovite) has not been observed to contain Al_2SiO_5. The reddish weathering quartzite continues to the north-northwest but Al_2SiO_5 polymorphs are not consistently present in all parts of the layer.

The 3-Al_2SiO_5 quartzite layer also contains garnet, staurolite, phengite, and complex intergrowths of Ti-magnetite and rutile (Whitney, 2002). Although the peak of metamorphism may have been close to the Al_2SiO_5 "triple point", the polymorphs do not represent an equilibrium assemblage. The inferred crystallization sequence of the polymorphs is andalusite → kyanite → sillimanite, based on textural observations.

The Al_2SiO_5 polymorphs are fine-grained and difficult to detect in outcrop, but the sillimanite in this quartzite is prismatic (not fibrous) and defines a strong lineation, and is therefore likely unrelated to the intrusion. All 3 polymorphs are deformed, particularly andalusite. Al_2SiO_5 occurs in the muscovite quartzite, but is not observed in nearby garnet muscovite schist. Garnets in schist contain inclusions of chloritoid, and some schists in this part of the sequence contain staurolite in the matrix.

Further north (up the gully), you will cross from the staurolite zone to the chloritoid zone. There is a narrow (meters thick) region in which chloritoid and staurolite coexist in schists (+ garnet), but up-section from this region, only chloritoid is observed. Chloritoid is very abundant in schists

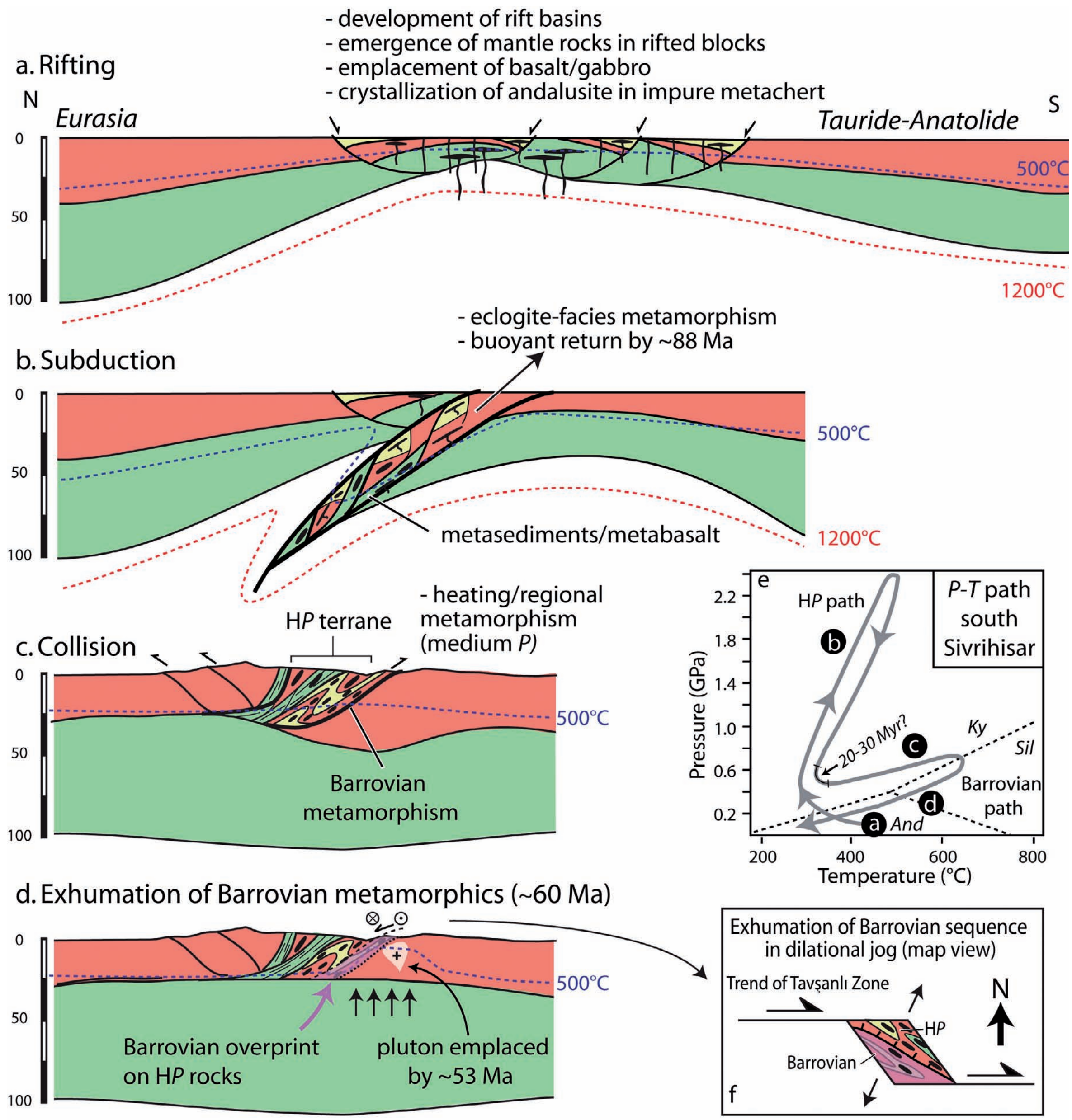


Fig. 38 - Tectonic model to explain the transition from blueschist/eclogite facies to Barrovian metamorphism in the southeast Sivrihisar Massif (from Whitney et al., 2011). Andalusite may be related to low-P-high-T metamorphism during rifting and basaltic intrusion. During later subduction, basaltic sills are metamorphosed to blueschist and eclogite facies conditions; kyanite ± chloritoid forms in metachert. During collision and suturing of Neotethys, Barrovian metamorphism partially overprints the HP-LT metamorphism. These rocks are exhumed in a transtensional bend in the plate boundary, accounting for the strong constrictional fabric and closely spaced isograds. A schematic pressure-temperature (P-T) path for the Barrovian rocks includes an early HP-LT path prior to heating at lower pressures.

and quartzites in the outcrops in the hillside just below the thick white marble layer.

The marble in this region is coarse grained, locally contains graphite, and has no crystallographic preferred orientation (CPO) of calcite (Seaton et al., 2009). The main peak is comprised entirely of this massive white marble, which displays compositional layering of calcite-rich layers alternating with layers that contains some quartz ± muscovite. A large fold can be seen in the hillside, defined by the layering.

If time permits, you can walk around the west side of the marble hill, staying in the schist-quartzite unit that continues to the north. In the region west of the marble peak and continuing to the north, quartzites and schists are texturally complex and mineralogically diverse. For example, in some rocks in this region, white mica contains phengite-rich cores (up to 30 Si per formula unit) and muscovite rims (Fig. 35). Kyanite ± andalusite ± chloritoid ± staurolite occur, including some quartzites that contain all four.

Further north, the middle of 3 ridges contains quartzites (including some with kyanite or chloritoid), marbles, and greenschist facies metabasites (chlorite + epidote ± actinolite + albite). Some of the marbles in this region are fine-grained, gray, and dolomitic. The ridges to the east and west are dominated by marbles.

The western ridge has continuous exposures to the Günyüzü Road to the north, and is an excellent place to see the complete transition to HP rocks. Seaton et al. (2009) used electron backscattered diffraction to detect textural changes in marbles along this zone. They identified four distinct zones (not including the contact metamorphic zone near the monzonite): the HP zone (distinct columnar texture, strong CPO); a transition zone in which the columnar texture is partially preserved and grains record a CPO; a 'cryptic zone' (coarse, equant grains that have the same CPO as the HP marble to the north); and a Barrovian zone characterized by coarse, equant, randomly oriented calcite grains (Fig. 36).

At the north end, marble is columnar, exactly as observed in the northwestern part of the massif where pristine HP rocks are exposed. Metabasic rocks are interlayered with columnar marbles and phengite-quartzites (locally containing small Fe-Mn-rich garnet) and resemble more altered equivalents of the metabasites in the northwest part of the massif. Blueschists contain glaucophane + epidote (some with small tabular pseudomorphs after lawsonite); retrogressed eclogite pods contain partial to complete pseudomorphs after garnet. The euhedral shape of garnets is preserved, and some contain relict garnet (Fig. 37). The matrix is composed of chlorite + epidote ± actinolite. The degree of retrogression increases from north to south.

Locally, in a fault zone along the Günyüzü Rd, pods of serpentinite crop out. The outcrops north of the road are part of a fault block or landslide of Barrovian rocks.

To sum up this entire transect, comprised of sillimanite-bearing rocks in the south and blueschist/eclogite in the north, experienced subduction and HP metamorphism, but the terrain was partially overprinted during exhumation and/or later metamorphism associated with collision and final closure of NeoTethys (Fig. 38). Evidence for the early HP metamorphism is partially preserved through the chloritoid zone but is completely erased beyond the staurolite isograd (≥550°C). Some kyanite and chloritoid at the low-grade end of the Barrovian sequence may have been inherited from earlier HP metamorphism. Andalusite may have formed during a pre-subduction phase of rifting of the Tauride-Anatolide platform or shallow marine setting in the Neotethys, when basalts (protoliths of the blueschists and eclogites) intruded the sedimentary sequence (Fig. 38).

ACKNOWLEDGMENTS

The senior author was supported in his studies in northwest Turkey over many years by TÜBİTAK and TÜBA grants. Whitney's work in the Sivrihisar area was supported by US National Science Foundation grant EAR-0711263. The authors thank Luca Pandolfi and Marco Scambelluri for helpful reviews.

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Received, September 13, 2010
Accepted, December 15, 2010