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ARTICLE

Kinematics and U-Pb zircon ages of the sole metamorphics of the Marmaris Ophiolite, Lycian Nappes, Southwest Turkey

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ABSTRACT

In the eastern Mediterranean, the Lycian Nappes are found in the structurally uppermost position in the Anatolide-Tauride belt related to the closure of the Neotethys. In Western Turkey, the Marmaris Ophiolite with the metamorphic sole occupies the uppermost tectonic position in the Lycian belt. The metamorphic sole is represented by discontinuous tectonic slices composed of amphibolites, phyllites, micashists and quartzo-feldspathic micaschists. Zircons from the micashists and quartzo-feldspathic micaschists display dark cores and rims. The cores yield ages between 229 and 175 Ma, inner rims yield ages between 153 and 143 Ma and the outer rims show a concordia age of 96.7 ± 0.79 Ma. In terms of their Th/U ratios, the cores and inner rims indicate igneous origin, whereas the outer rims indicate accretion during metamorphism. By dating of these zircons, the deposition time for the protolith of micaschists and quartzo-feldspathic micaschists could be constrained as the Early Cretaceous. Present-day orientation of the kinematic data from the sole metamorphics and the uppermost part of the Karabörtlen formation clearly suggest a top-to-the NE sense of shear. By taking into account the 25°–30° anticlockwise post-emplacement rotation of Southwest Turkey, it follows that the Lycian Nappes were emplaced eastward onto the Menderes Nappes. This tectonic model disagrees with the previous tectonic models suggesting northward or southward movement of the Lycian Nappes onto Menderes Nappes.

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Introduction

The Anatolide-Tauride belt is represented by numerous nappes assembled during the closure of the Neotethys in Southwest Turkey (Figure 1). Tectonic units located in the southern part of the Izmir-Ankara zone are (north to south): (i) Tavşanlı Zone, (ii) Afyon Zone, (iii) Bornova Flysch Zone, (iv) Menderes Nappes, (v) Cycladic Blueschist Unit, (vi) Lycian Nappes, and (vii) Bey Dağları Autochthon (Figure 1). Özgül (1976) reported six sub-belts in the Anatolide-Tauride block of Ketin (1966) based on the lithostratigraphy, metamorphic grades and structural positions.

Although the metamorphic conditions of the northwest blueschist zones (Tavşanlı and Afyon Zones) have been described in detail by several authors (Okay 1980, 1981, 1984, 2002; Okay and Kelley 1994; Candan *et al*. 2005; Pourteau *et al*. 2010, 2013; Plunder *et al*. 2015), their field-based kinematics are still unknown. These blueschist zones are considered as deeply subducted part of the Anatolide-Tauride platform (Okay 1980, 1984). In this zone, radiometric ages of the sole metamorphism range from 101 ± 3.8 Ma (Albian) to 88.5 ± 0.1 Ma (Turonian-Coniacian transition) (Table 1 and references therein). The HP-LT metamorphism in the Tavşanlı Zone occurred between 82.8 and 79.7 Ma (early-Middle Campanian) (Sherlock *et al*. 1999). Plunder *et al*. (2016a,b) reappraise the metamorphic sole formation (10.5 ± 2 kbar, 800 ± 50°C, ~93 Ma) and the blueschist facies overprint (about 12 kbar, 425°C, ~80 Ma) the pre-conditions.

The Menderes Nappes, with a polymetamorphic core and the cover parts (Bozkurt and Oberhänsli 2001 and references therein), are represented by the Bayındır, Bozdağ, Çine and Selimiye nappes in structurally ascending order (Ring *et al*. 1999; Gessner *et al*. 2001a). This nappe stack was dissected into northern, central and southern sub-massifs by bivergent low-angle normal faults in a rolling hinge model (Rimmelé *et al*. 2003a) from Late Oligocene. The Cycladic Blueschist Unit is sandwiched between the Menderes and Lycian Nappes, and is represented by a platform sequence with a low-grade HP metamorphic associations (Oberhänsli *et al*. 1998; Gessner *et al*. 2001b) and

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Supplementary data can be accessed here.

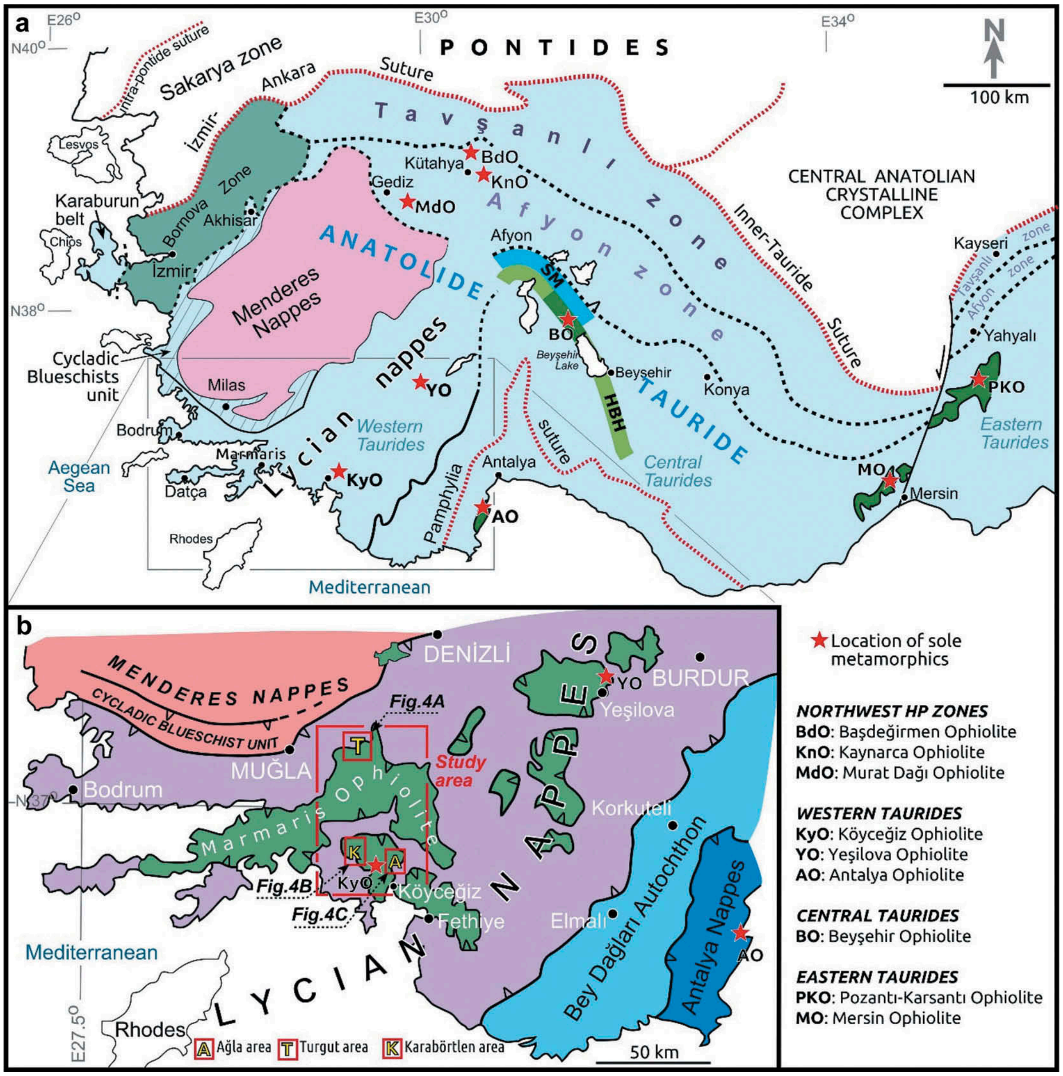

Figure 1. (A) Map showing location of the study area and the main tectonic belts of the West Turkey to the south of the İzmir-Ankara suture. (Compiled following Ketin 1966; Brunn *et al.* 1971; De Graciancky 1972; Özgül 1976; Okay and Tüysüz 1999; Parlak and Delaloye 1999; Okay *et al.* 2001; Robertson *et al.* 2003; Moix *et al.* 2008; Pourteau *et al.* 2010, 2013, 2016). SM: Sultan Mountains Nappes, BO: Beyşehir Ophiolite, HBH: Hoyran-Beyşehir-Hadim Nappes. (B) Map showing the location of the subareas and tectonic setting of the Marmaris Ophiolite in the Lycian belt (simplified after Akdeniz 2011b).

the Selçuk mélange, which is composed of garnet-micaschists with blocks of serpentinites, gabbro and platform limestones (Güngör 1998; Güngör and Erdoğan 2001).

The origin and emplacement direction of the Lycian Nappes in the Southwestern Turkey have been reviewed since the late 1960s (Table 2). Several authors suggest that the Lycian Nappes were episodically transported over the Menderes Nappes from north to south and emplaced to the current position (De Graciansky 1968; De Graciancky 1972; Dürr 1975; Dürr *et al.* 1978; Gutnic *et al.* 1979; Şengör and Yılmaz 1981; Şengör *et al.* 1984; Okay 1989; Bozkurt and Park 1999; Collins and Robertson 1997, 1998, 1999, 2003; Dora *et al.* 1995; Rimmelé *et al.* 2003a; Güngör and Erdoğan 2001; Ring *et al.* 1999, 2007; Rimmelé *et al.* 2003a,b; Moix *et al.* 2008). Some other authors (Poisson 1985; Ersoy 1990; Özkaya 1990, 1991; Arslan 2001; Arslan *et al.* 2013) suggest that the Lycian Nappes were originated from the south and the nappes were thrusted northward/northeastward onto the Menderes Nappes, except for the Marmaris Ophiolite emplaced to the structurally uppermost position. The divergence about the origin of the Lycian Nappes arises from lack of detailed kinematic analysis and neglecting the post-emplacement rotation in the Southwest of Turkey.

The Bey Dağları Autochthon comprises mainly carbonate-rich deposits from Triassic to Langhian and is overthrust by the Antalya Nappes in the east and by the

Table 1. Ages of the metamorphic soles in the northwest blueschist zones, western and central Taurides.

Previous studies	Locations		Methods	Ages (Ma)
	Northwest high pressure zones			
Önen and Hall 1993	Kütahya, Başdeğirmen Ophiolite		^{40}Ar-^{39}Ar	94 ± 13
Önen and Hall 2000	Kütahya, Kaynarca Ophiolite		^{40}Ar-^{39}Ar	93 ± 2
Önen 2003	Kütahya, Başdeğirmen and Kaynarca Ophiolite	amph	^{40}Ar-^{39}Ar	93 ± 2
Harris *et al*. 1994	Tavşanlı Zone	phg	^{40}Ar-^{39}Ar	101 ± 3.8
	Interval of Metamorphism in Tavşanlı Zone			108–88
Okay and Kelley 1994	Tavşanlı Zone	phg		88.5 ± 0.1
Yüksel *et al*. 2014	İzmir-Ankara Zone (Murat Dağı)	hbl	^{40}Ar/^{39}Ar	100.7 ± 1.3
	Western and central taurides			
Thuizat *et al*. 1981	Lycian Ophiolites, Köyceğiz	hbl	^{40}Ar/^{39}Ar	98 ± 4–102 ± 4
		plg		83 ± 3–88 ± 4
		mus		93 ± 3–91 ± 3
	Beyşehir Ophiolites	hbl		93 ± 3
		plg		84 ± 3
	Antalya Ophiolites	hbl		94 ± 4
		plg		94 ± 4
	Mean age of sole metamorphism of Tauride Ophiolites			~95
Çelik *et al*. 2006	Lycian Ophiolites, Yeşilova	hbl	^{40}Ar/^{39}Ar	90.7 ± 0.5
		hbl		91.3 ± 0.9
		mus		91.2 ± 2.3
	Lycian Ophiolites, Köyceğiz	hbl		93.1 ± 0.9
		hbl		93.0 ± 0.9
		mus		93.0 ± 1.0
		mus		93.6 ± 0.8
		mus		91.7 ± 0.7
	Beyşehir Ophiolites	hbl		90.9 ± 1.3
		hbl		91.5 ± 1.9
	Antalya (Alakırçay melange)	hbl		90.9 ± 1.3
		hbl		91.5 ± 1.9
Daşçı *et al*. 2015	Konya melange	hbl	^{40}Ar/^{39}Ar	87.04 ± .36–84.66 ± .30
Dilek and Whitney 1997	Kızıltepe Ophiolite (Bolkar Mtn.)	hbl	^{40}Ar/^{39}Ar	~92–90
Parlak and Delaloye 1999	Mersin Ophiolite	hbl	^{40}Ar/^{39}Ar	96.0 ± 0.7–91.6 ± 0.3
Yılmaz and Maxwell 1984	Antalya Ophiolites		K-Ar	73.7 ± 1.1
				78.5 ± 1.7
Dilek *et al*. 1999	Eastern Tauride Ophiolites		^{40}Ar/^{39}Ar	91.0 ± 0.6
				90.8 ± 0.8
This study	Metamorphic sole of the Marmaris Ophiolite, Köyceğiz	Cores and rims of Zircons	U-Pb	96.7 ± 0.79

Amph: Amphibole, phg: phengite, hbl: hornblende, plg: plagioclase, mus: muscovite

Lycian Nappes in the northwest (Özgül 1976; Poisson 1977; Gutnic *et al*. 1979; Ricou *et al*. 1979; Farinacci and Köylüoğlu 1982; Robertson 1993; Poisson *et al*. 2003; Sarı 2006; Sarı and Özer 2009). The lithostratigraphy of the Bey Dağları Autochthon varies along its borders as a result of emplacement of the Lycian and the Antalya nappes. In the Fethiye-Köyceğiz region of the Lycian belt, the Cenomanian-Langhian interval of the Bey Dağları Autochthon is exposed in the Göcek tectonic window (De Graciansky 1968; De Graciancky 1972).

Table 2. Existing tectonic models for the origins and emplacement directions of the Lycian Nappes in SW Turkey.

Origins and emplacement directions of the Lycian Nappes		
Northern oirigin		Southern origin
Translation from north to south over the Menderes Nappes	*Back thrust in course of southward translation*	*Thrust northward/northeastward upon Menderes Nappes*
De Graciansky 1968, De Graciancky 1972 Dürr 1975 Dürr *et al*. 1978 Gutnic *et al*. 1979 Şengör and Yılmaz 1981 (*Load of the Lycian Nappes was the cause of the Main Menderes Metamorphism*) Şengör *et al*. 1984 Okay 1989 Collins and Robertson 1997, Collins and Robertson 1998, Collins and Robertson 1999, Collins and Robertson 2003 (*Episodic emplacements*) Dora *et al*. 1995 Ring *et al*. 1999, Ring *et al*. 2007 Gessner *et al*. 2001a Güngör and Erdoğan 2001 Moix *et al*. 2008	Bozkurt and Park 1999 Rimmelé *et al*. 2003a, Rimmelé *et al*. 2003b	Poisson 1985 (*Kızılca-Çorakgöl basin*, except for the ophiolites occupying the structurally highest position)* Ersoy 1990 *(Western Taurus Trough*)* Özkaya 1990 Özkaya 1991 *(Alakaya basin*)* Arslan 2001 Arslan *et al*. 2013

**Source of the Lycian Nappes located between Menderes Nappes and Bey Dağları Autochthon.*

Cooling ages (^{40}Ar-^{39}Ar) of the metamorphic soles of the Tethyan ophiolites were reported by numerous authors (Thuizat *et al*. 1981; Yılmaz and Maxwell 1984; Önen and Hall 1993; Harris *et al*. 1994; Okay and Kelley 1994; Parlak and Delaloye 1999; Önen and Hall 2000; Önen 2003; Çelik *et al*. 2006; Yüksel *et al*. 2014; Daşçı *et al*. 2015; Plunder *et al*. 2016a,b—details are given in Table 1). Radiometric dating of the sole metamorphics showed that the intra-oceanic subduction within the Neotethys occurred during the late Lower-early Late Jurassic for Dinaro-Hellenic ophiolites, late Lower-early Late Cretaceous for Anatolian, Iranian and Oman ophiolites (Çakır 1996, 2009; references therein). These Neotethyan ophiolites were obducted onto the Adriatic promontory during the late Upper Jurassic-early Lower Cretaceous, and onto the Aegean, Iranian and Oman platforms during late Lower Cretaceous-Palaeocene. This diachrony of the ophiolite obduction in Balkans and Anatolide-Tauride (Menderes-Taurus Block) was considered as a function of distance between Atlantic type continental margin and intra-oceanic subduction zone by Topuz *et al*. 2013a.

In the Southwestern Turkey, the kinematics of the ophiolite obduction still in debate. Therefore, the metamorphic sole along the Marmaris Ophiolite in the Lycian belt provides potential data to unveil the tectonic evolution of the Southwest of Turkey. This paper aims to describe the Late Alpine kinematics for the first time, and presents U/Pb LA-ICP-MS zircon age data in the sole metamorphics of the Marmaris Ophiolite in the Köyceğiz region (Figure 1). Analytical techniques for the kinematic analysis and radiogenic dating are given as supplementary.

Internal stratigraphy of the Lycian Nappes

In Southwestern Turkey, the Lycian Nappes form the structurally uppermost tectonic unit in the Anatolide-Turide belt related to the closing of the Neotethys (Figure 1). The Lycian Nappes are represented by five nappe packages (Şenel 1997; Şenel and Bilgin 1997a,b; Akdeniz 2011a,b). On top of the Menderes Nappes and Cycladic Blueschist Unit, the Ören Tectonic Slice of the Lycian Nappes are exposed in the area between Milas, Bodrum, Marmaris and Köyceğiz (Figure 2). The Marmaris Ophiolite and its metamorphic sole form the structurally highest position on top of the Ören Tectonic Slice.

This paper focuses on the Ören tectonic slice of the Bodrum Nappe package (Akdeniz 2011a,b) and the metamorphic rocks along the sole of the Marmaris Ophiolite in the Köyceğiz region. Stratigraphy of the Ören Tectonic Slice begins at the base with the Permo-Triassic Karaova Formation composed of red and green metapelites, arkosic metapsammites and metarudites (Figure 2). These metaclastics are overlain by the Jurassic-Late Cretaceous platform carbonates represented by the Gereme Formation and Ula Marbles, respectively. These platform carbonates pass gradually upward into the Karabörtlen formation consisting of sandstone-shale alternation in the lower part and strongly sheared and disintegrated sandstone-shale with large blocks of limestone, mafic volcanics and chert in the upper part (Figures 2 and 3). Thin slices of metamorphic rocks and the Marmaris Ophiolite tectonically overlay the Karabörtlen formation.

The metamorphic grade in the Ören tectonic slice decrease upward to the Karabörtlen formation. The lower part of the Ören Tectonic Slice shows a low-grade HP-LT metamorphism manifested by Fe-Mg carpholite, chloritoid and quartz (Oberhänsli *et al*. 2001; Rimmelé *et al*. 2003a,b) in the Permo-Triassic Karaova Formation, and calcite rosetta in the cherty limestones of the Late Cretaceous Ula Marbles (Figure 2). The metapelites in the strongly sheared matrix of the Karabörtlen formation contain illite and chlorite (De Graciancky 1972) indicating a very low-grade metamorphism. No radiogenic age reported for the metamorphic event (Ashworth and Evirgen 1984; Oberhänsli *et al*. 2001; Rimmelé 2003) in the Karaova Formation and rosetta limestones in Ula Marbles (Figure 2). The age of the metamorphism was constrained as Eocene by stratigraphic records and palaeontologic data in the previous studies.

The contact between the Lycian and Menderes Nappes is unconformably covered by post-tectonic sedimentary sequences of the Oligo-Miocene Kale-Tavas basin located between Denizli and Muğla (Hakyemez 1989; Akgün and Sözbilir 2001). The Late Oligocene-Miocene Ören graben units crop out between Milas and Yatağan (Atalay 1980; Gürer and Yılmaz 2002; Kayseri 2010).

Metamorphic sole of the Marmaris Ophiolite

The metamorphic sole of the Marmaris Ophiolite is found as discontinuous, thin tectonic slices between the Karabörtlen formation and the Marmaris Ophiolite in the Köyceğiz and Fethiye regions (Figure 4). Although they were described by De Graciancky (1972), their kinematics, origins and ages have not been clearly defined yet. The various metamorphic rocks along the sole of the Marmaris Ophiolite were described by De Graciancky (1972) and Bernoulli *et al*. (1974) as 'les terrains métamorphiques/écailles de terrains crystallines' which involved into the 'complex intermédiaire' between tectonic slices of platform sequences and an ophiolite slab. Tectonic slices of these metamorphic rocks were named as the İğdir

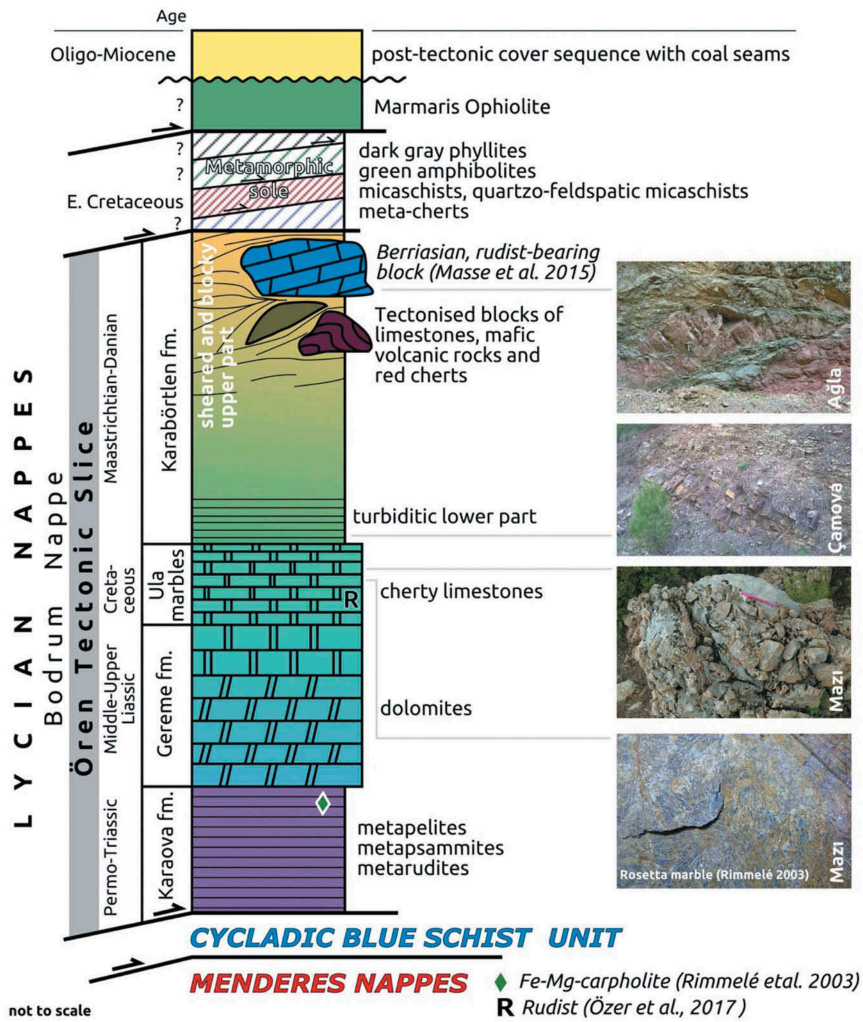

Figure 2. Lithostratigraphy, tectonic setting and revised ages of the rock units of the Ören Tectonic Slice. (Compiled following Brinkmann 1967; Brunn *et al*. 1971; Oberhänsli *et al*. 2001; Rimmelé *et al*. 2003a,b; Akdeniz 2011a,b; Özer *et al*. 2017).

metamorphics consisting of amphibolites, amphibole-gneisses, garnet-schists, quartz-schists, metacherts, marbles and metaplagiogranites in the Burdur region (Akdeniz 2011a,b).

Rock types of the metamorphic sole

The metamorphic sole in the Köyceğiz region is represented by thin tectonic slices composed of dark grey phyllites, green amphibolites, white micaschists and quartzo-feldspathic micaschists, red and beige meta-cherts (Figure 5). This sole metamorphics displays an inverted metamorphic gradient Rimmelé 2003 between the Karabörtlen formation showing very low-grade metamorphism and the Marmaris Ophiolite.

The strongly sheared uppermost part of the Karabörtlen formation displays an anastomosing foliation close to the upper contact with the metamorphic sole rocks (Figure 3A). Along the contact zone, the metapsammites show rough foliation identified by elongated quartz and feldspar grains with mica beards and cleavage domains of tiny sericites and chlorites. Some resistant grains have pressure fringes composed of quartz fibres and tiny sericite crystals. A very low-grade metamorphism was diagnosed by illite and chlorite in this strongly sheared uppermost part of the Karabörtlen formation (De Graciancky 1972).

Dark grey phyllites crop out mainly around Ağla (Figure 4B) and show a prominent linear fabrics (Figure 5A, B). Tiny chlorite and quartz grains are the main minerals of the phyllites, they also contain abundant opaque crystals. Several thin sections of dark grey phyllites present fine-grained lepidoblastic texture where 90% consists of fine-grained crystals (biotite, muscovite, chlorite, quartz, plagioclase/albite, apatite and opaques).

Around Ağla, green amphibolites with a continuous foliation and a prominent stretching lineation are found (Figure 4). They rarely contain garnet porphyroblasts (Figure 5E, F), and consist of hornblende, tremolite/

Figure 3. Internal structures of the Karabörtlen formation. (A) Strongly sheared and disintegrated uppermost parts due to the emplacement of the Marmaris Ophiolite with sole metamorphics around Ağla village. (B) Undisturbed turbiditic, lowermost parts with well-preserved primary stratification around Çamova and Mazı villages.

actinolite, clinopyroxene, plagioclase, epidote, clinozoisite, sphene, ilmenite and opaques. Chlorite and sericite are products of retrograde metamorphic alteration of amphibole and plagioclase, respectively. The occurrences and localities of the glaucophane-bearing meta-volcanic or meta-sedimentary rocks in the Köyceğiz region were described by Van Der Kaaden and Metz (1954) and Van Der Kaaden (1966). Rimmelé *et al*. (2003a,b) redefined these relic glaucophanes in the uppermost part of the Karabörtlen formation and in the amphibolites as Mg-riebeckite and crossite that indicate a transition between epidote-blueschist-facies and greenschist-facies (Figure 6C).

Metacherts are found as a very thin (10–20 m) tectonic slice sandwiched between dark grey phyllites and quartz-micaschists around Ağla, and are represented by alternation of red and beige chert bands. These chert bands show tight, rootless folds. Thin sections of the metacherts show abundant, tiny garnet porhyroblasts with deformed internal foliation (Figure 5G, H). They have minor amounts of microcrystals of muscovite, garnet and apatite. Acicular reddish-brown piemontite microcrystals are also found in these metacherts.

The largest outcrops of white micaschists and quartzo-feldspathic micaschists are found around Karabörtlen, Turgut and Ağla (Figure 4). Around Ağla, there is a thin tectonic slice of quartzo-feldspathic micaschists with high strain zones on top of the phyllites and metacherts (Figure 5C, D). Quartzo-feldspathic micaschists are composed of quartz, biotite, muscovite, chlorite, sericite, plagioclase/albite, garnet, apatite, zircon and opaques. The plagioclase crystals are considerably altered to sericite and chlorite crystals displaying a retrograde metamorphic alteration of biotite crystals. Muscovite-garnet schists are generally made up of homogenously distributed muscovite crystals within a quartz-rich granoblastic groundmass. Euhedral and inclusion free garnet microcrystals are also scattered in quartz groundmass (Figure 6A). Apatite, piemontite, zircon and opaque minerals are the accessory minerals in the micaschists. The granoblastic quartz crystals

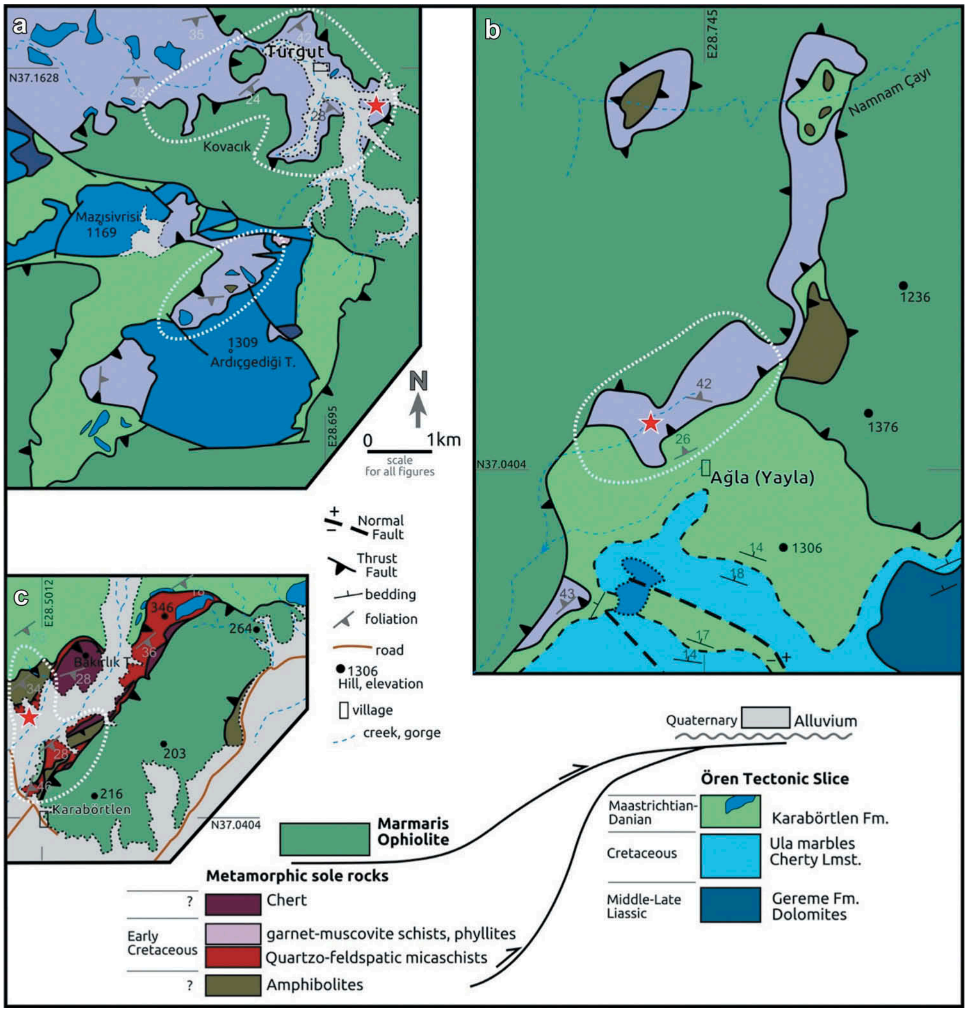

Figure 4. Geological maps of the metamorphic sole of the Marmaris Ophiolite in the Köyceğiz region (after de De Graciancky 1972). (A) Turgut area (along the Muğla-Denizli main road), (B) Ağla area (8 km north of Köyceğiz) and (C) Karabörtlen area (15 km west of Köyceğiz). Structural data were mainly measured in areas indicated by dashed white lines. Red stars show locations of samples for zircons dated.

show undulatory extinction and contain micro-cracks. Around Karabörtlen (Figure 4C), muscovite-garnet schists and massive quartzo-feldspathic micaschists are found as thin tectonic slices sandwiched between strongly sheared metapelites of the Karabörtlen formation and the Marmaris Ophiolite. They show continuous foliation around Karabörtlen, however they are found as small massive bodies around Bakırlık Tepe (Figure 4C) with equigranular granoblastic texture (Figure 6B) as a result of high temperature sole metamorphism. Geochemical characteristics of these leucocratic massif bodies and white quartzo-feldspathic micaschists with continuous foliation are high silica contents (between 76.43% and 90.83%) indicating a quartzo-feldspathic sandstone origin. These tectonic slices of quartz-rich metasediments with platform sequence affinity contain zircon grains displaying eroded cores and rims (Figure 7A).

U-Pb La-ICP MS dating of zircons

Cathodoluminesence (CL) images of the zircons extracted from the white micaschists and quartzo-feldspathic micaschists show dark, eroded, relic cores with irregular shapes and rims (Figure 7A). The zircons are euhedral and subhedral, short prismatic crystals with inclusion-free transparent rims (Figure 7A). Grain sizes of zircons range from 125 to 175 µm, with length/width ratios of 1/2. The zircon crystals display well-developed {110} prism and two pyramids, {101} and {211}, corresponding to low temperatures (600–650°C) belonging to subtypes L1 and S1 morphologies according to the classification scheme of Pupin (1980).

Their CL images clearly exhibit relic cores diagnosed by dark and patchy zones. The inner rims are marked by zonally internal CL images, whereas the outer rims are

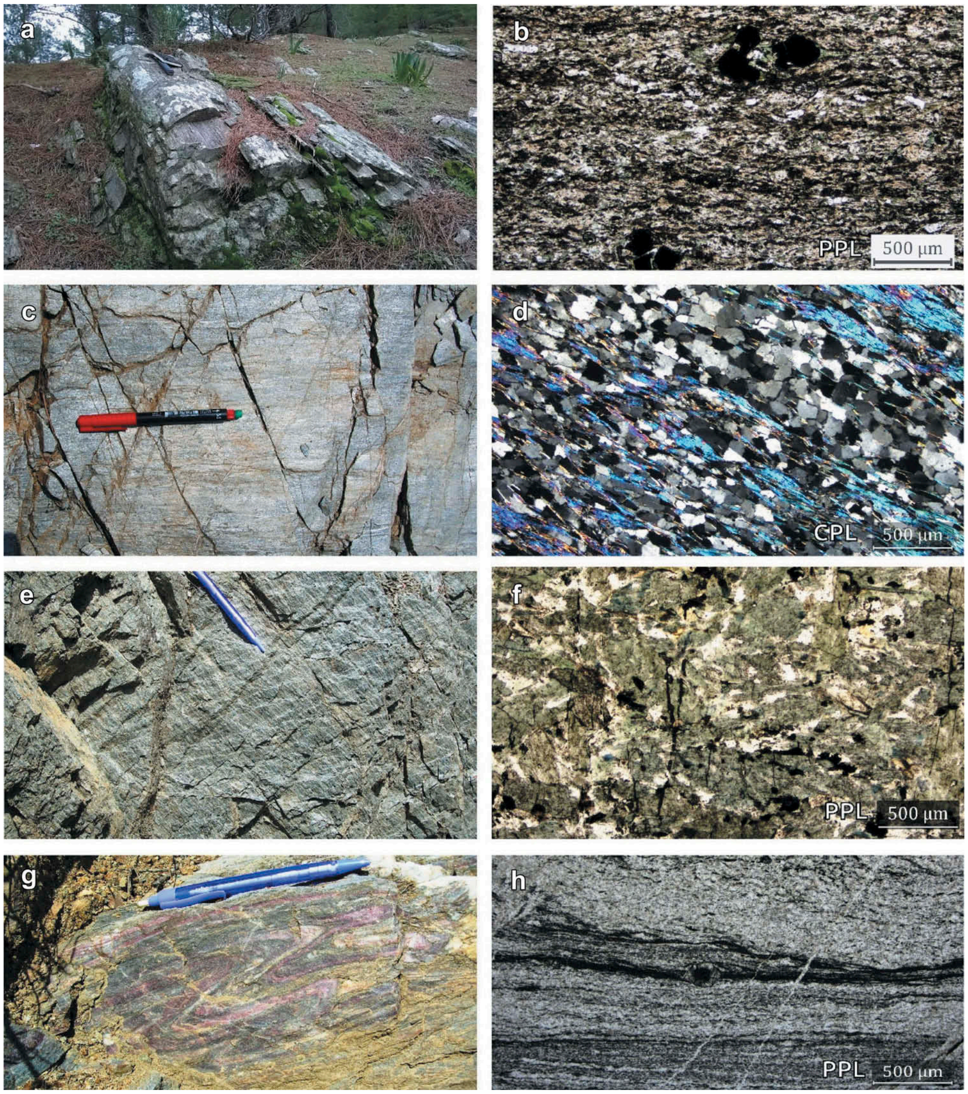

Figure 5. Field views (left) and photomicrographs of various metamorphic rocks in the metamorphic sole of the Marmaris Ophiolite. (A and B) Phyllites, (C and D) Garnet-micaschists and quartzo-feldspathic micaschists, (E and F) amphibolites and (G and H) metacherts. (PPL: Plane Polarized Light; CPL: Crossed Polarized Light)

semi-transparent, bright and featureless (Figure 7A). This heterogeneous internal structure of the zircons suggests that multiple age populations may exist. Seventeen points on the short stubby zircon crystals have been analysed including both relic cores and rims.

Most of the dark cores in the zircons (Figure 7A) yield ages between 175 and 229 Ma (Ladinian to Early Aalenian) (Supplementary Table 1), and their Th/U ratios range between 0.67 and 1.09 indicating an igneous origin (Rubatto and Gebauer 2000). Inner rims yield ages between 143 and 153 Ma (Figure 7B, upper row), and show Th/U ratios between 0.36 and 0.91 that indicate an igneous origin (Rubatto and Gebauer 2000). One zircon yields age of (Figure 7A, left lower corner) 150.2 ± 3.0 Ma and 145.6 ± 3.9 Ma for its inner and outer parts, respectively.

Kinematics of the sole metamorphics

In majority of the existing tectonic models (Table 2), movement directions of the Lycian Nappes are based on their internal stratigraphy, current positions of their contacts and structural positions. Here we present new field-based kinematic data from the uppermost part of the Ören Tectonic Slice and more particularly from the metamorphic sole of the Marmaris Ophiolite.

In the Köyceğiz region, meso- and micro-structures in the uppermost part of the Karabörtlen formation and the metamorphic sole reveal the tectonic transport direction of the Ören Tectonic Slice and the Marmaris Ophiolite (Figures 10 and 11). Along the turbiditic lower part of the Karabörtlen formation the primary structures such as bedding planes (Figure 3B), sole marks and

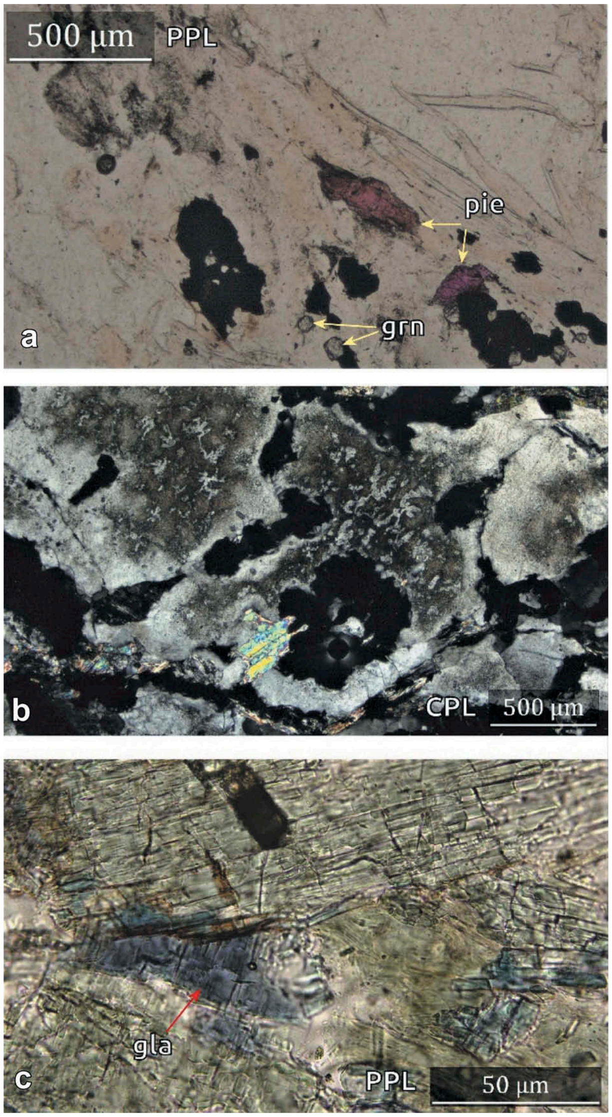

Figure 6. Photomicrographs of (A) piemontite-garnet quartzo-feldspathic micaschists (pie: piemontite, grn: garnet indicated by yellow arrows), (B) fine-grained quartzo-feldspathic micaschists with granoblastic texture and (C) relic glaucophane crystal (Mg-riebeckite; gla: glaucophane, indicated by yellow arrows) in amphibolites in metamorphic sole of the Marmaris ophiolite. (PPL: Plane Polarized Light; CPL: Crossed Polarized Light)

trace fossils are clearly observed, whereas the upper part, mapped as 'Wild Flysch' by De Graciancky (1972), shows a penetrative foliation (Figure 8) and lineation close to the upper contact with the tectonic slices of the metamorphic sole and Marmaris Ophiolite. In the uppermost part of the Karabörtlen formation lineation is marked by stretched pebbles (Figure 8A) and fibrous quartz infillings of mode I veins. The tectonic slices of dark grey phyllites, green amphibolites, red and beige metacherts, white muscovite-garnet schists and quartzo-feldspathic micaschists show a continuous foliation with linear fabric (Figure 8C, D). The foliation is mainly defined by mica flakes and stretched quartz and feldspars in metasedimentary tectonic slices, and preferred orientation of amphiboles in green amphibolites. The preferred orientation of amphibole crystals shows a prominent foliation with lineation in the green amphibolites (Figure 8B). Linear fabric in the metamorphic sole is diagnosed by stretching lineation described by preferred orientation of mica and quartz grains along foliation planes and axes of mesoscopic folds, boudin lines (Figure 8D), quartz rods and crenulation axis in the metasedimentary tectonic slices. Linear fabrics measured in the metamorphic sole and the strongly sheared uppermost part of the Karabörtlen formation clearly shows a northeast trend (Figure 9).

Sigmoidal foliation, σ-clasts, kink bands are mesoscopic asymmetric structures associated with this linear fabric consistently indicate a top-to-the NE sense of shear (Figure 10). Besides, σ-clasts, quarter folds, S/C fabric, micro-kinks and rotated garnet porphyroblasts in oriented thin sections (Figure 11) suggesting a top-to-the NE sense of shear in the metamorphic sole.

Discussion

Radiogenic dating of the relic cores and rims of the zircons impart the ages of their source rocks in the provenance area and constrain the ages of maximum deposition and metamorphism of the garnet micaschists and quartzo-feldspathic micaschists embedded into the metamorphic sole of the Marmaris Ophiolite. Ages from the cores of zircons indicate magmatic activity in the provenance area between 229 and 175 Ma (Ladinian to Early Aalenian). The inner rim ages indicate a recycling of zircons into an igneous activity between 153 and 143 Ma (Late Kimmeridgian to Early Berriasian). Afterwards, both recycled and newly formed zircons during this magmatic phase were incorporated into the quartzo-feldspathic sandstones deposited in a basin with an affinity to the volcanic arc. Finally, their outer rims report a metamorphic event occurred between 100.4 and 93.5 Ma (Cenomanian, concordia age 96.7 ± 0.79 Ma) along the sole of the Marmaris Ophiolite. On this basis, the deposition time of the quartzo-feldspathic sandstones that were protoliths of the white micaschists and quartzo-feldspathic micaschists could be constrained as Early Cretaceous.

In Southwest Turkey, some tectonic belts such as Bornova Flysch Zone, Menderes Nappes and Karaburun belt contain Early Triassic acid igneous rocks that possibly supplied zircons to quartzo-feldspathic sandstones, which are found as white micaschists and quartzo-feldspathic micaschists in the metamorphic sole. In the Akhisar region (Figure 1), on

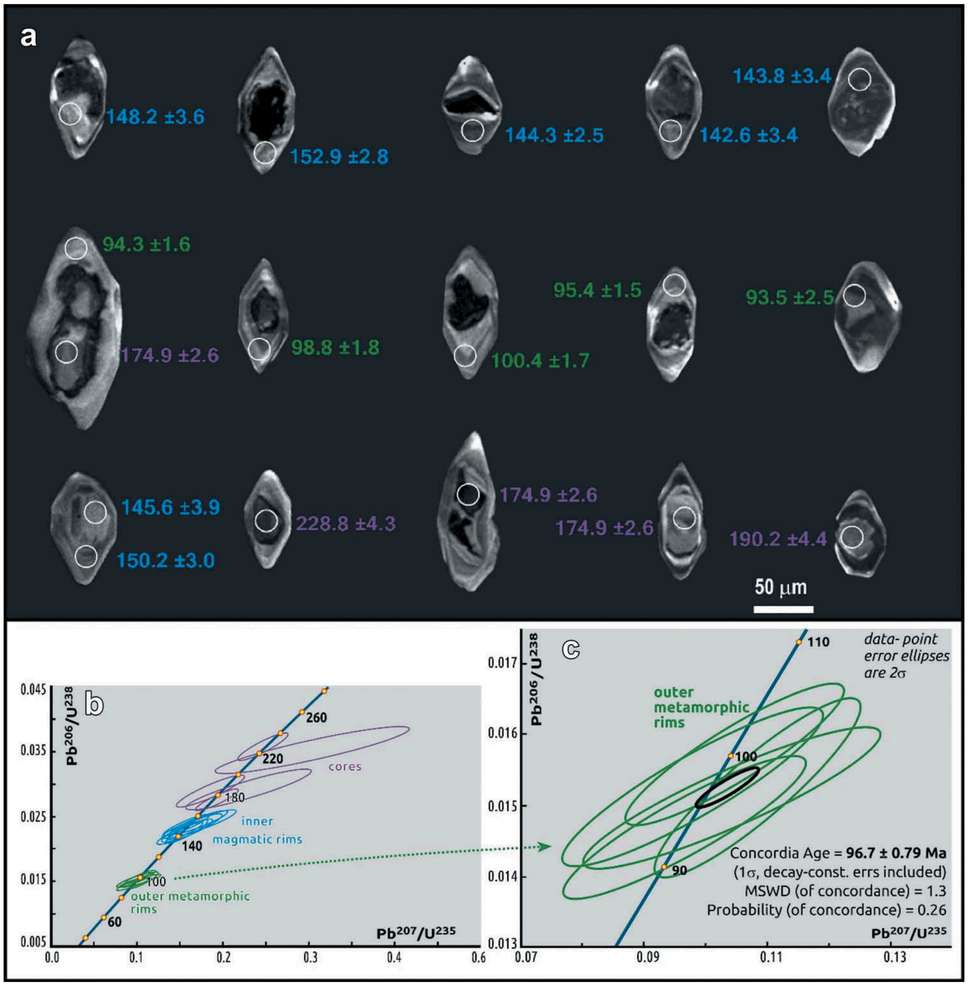

Figure 7. (A) Representative Cathodoluminesence images of zircons extracted from muscovit-garnet schists and quartzo-feldspathic micaschists showing relic cores, magmatic and unzoned, metamorphic rims. White circles mark locations of LA ICP MS analytical sites, (B) U/Pb concordia plots and age distributions for all zircons: relic cores [220–175 Ma, purple lines], inner magmatic rims [143–153 Ma, blue lines] and outer rims [93.5–100.4 Ma, green lines]. (C) Enlarged U/Pb concordia plots for featureless outer rims accreted during Cenomanian sole metamorphism (96.7 ± 0.79 Ma) (Cohen et al. 2013).

top of the Menderes Nappes, the Permo-Triassic Karaova Formation representing the lowermost stratigraphic position of the Ören Tectonic Slice contains rhyolite intercalations with zircons yielding a concordia age of 237.4 ± 1.1 Ma (the Earliest Ladinian) (İşintek *et al*. 2018). The Karaova Formation itself witnessed the Middle Triassic acid igneous activity and it might be the source of the core parts of the zircons in the sole metamorphics of the Marmaris Ophiolite. In addition, the acid magmatic events during Early Triassic in the Attic-Cycladic Zone of the Aegean (Chatzaras *et al*. 2013), the Afyon Zone (Akal *et al*. 2012) of the Northwest of Turkey, the Karaburun belt (Erkül *et al*. 2008; Akal *et al*. 2010) of Western Turkey, the Dededağ Granite in the Menderes Nappes (Koralay *et al*. 2001) and the Kavacık granite (224.5 ± 2.0 Ma–230.0 ± 2.8 Ma) in the Bornova Flysch Zone (Güngör *et al*. 2016) in the İzmir-Ankara Zone could be considered as the source of the core part of the zircons described in this paper. In addition to these possible source areas in the Anatolide-Tauride, the Pontides also contains Permo-Triassic magmatism in the Sakarya Zone (Ustaömer *et al*. 2016; Akdoğan *et al*. 2018; Topuz *et al*. 2018).

Magmatic activity during the Late Jurassic-Earliest Cretaceous (153–143 Ma) has not been reported in the Anatolide-Tauride. Jurassic magmatic activity (172–162 Ma) occurs in the Central Pontides to the north of the İzmir-Ankara suture and along the Zagros suture (Okay and Topuz 2017). In the Sakarya Zone of the Central Pontides, Çimen *et al*. (2018) reports Middle Jurassic (176 ± 6 Ma–163 ± 9 Ma) Devrekani Metadiorite and Granitoid. Eastern Pontides also contain Jurassic volcanic suite ranging from highly depleted basalts to dacites representing a continental arc setting (Şen 2007 and references therein). In the east Tethys, Early Jurassic oceanic spreading (184 ± 4

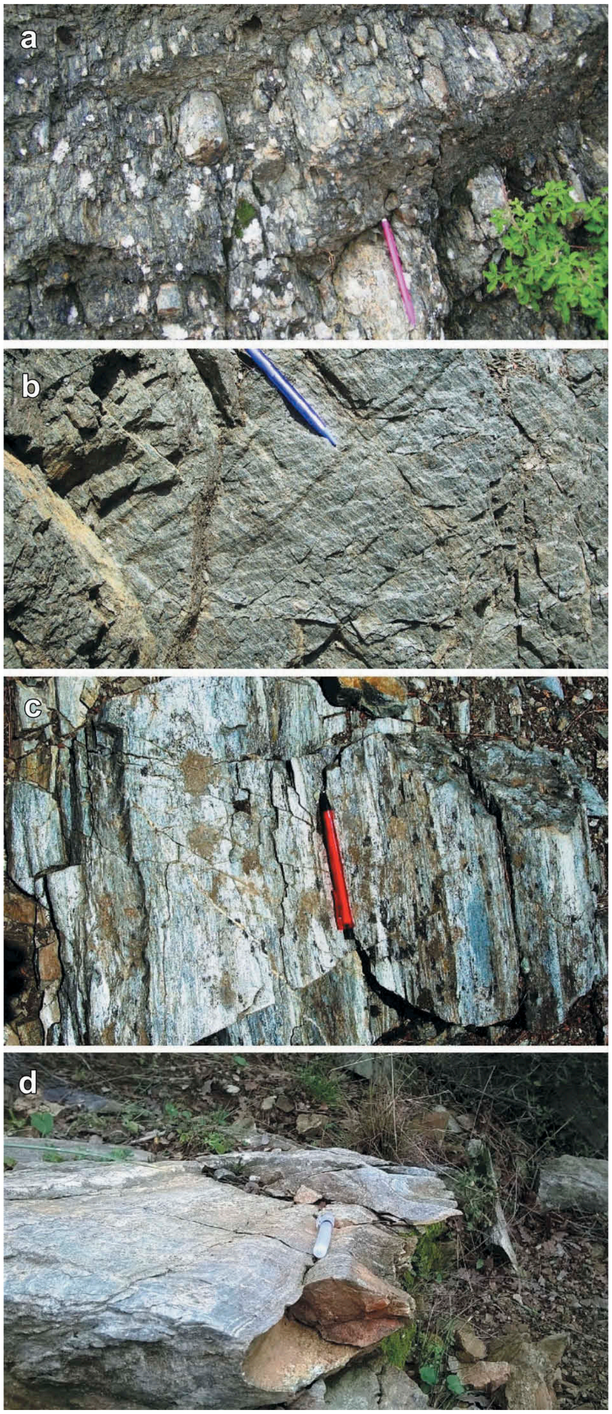

Figure 8. Field views of the linear fabric both in the Karabörtlen formation and the metamorphic sole in the Köyceğiz region. (A) Strongly elongated pebbles in the debris flow of the Karabörtlen formation around Mazı village, (B) stretching lineation on continuously foliated amphibolite around Ağla village, (C) stretching lineation on foliation surface of white-pink quartzo-feldspathic micaschists and garnet-micaschists around Karabörtlen village and (D) Boudin line in quartz micaschists around Karabörtlen village. Width of all views are about 50 cm.

Ma–178 ± 4) Ma is represented by the Refahiye Ophiolite which was incorporated into the Late

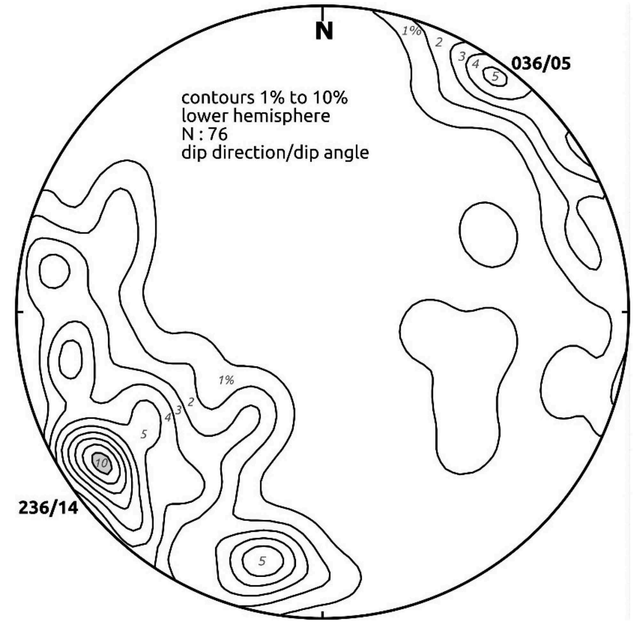

Figure 9. Equal area contour plot showing concentration of position of linear fabric measured in strongly deformed uppermost part of the Karabörtlen formation and thin tectonic slices of metamorphic rocks along sole of the Marmaris Ophiolite in the Köyceğiz region. Plot clearly shows a NE-trending linear fabric in the uppermost part of the Ören Tectonic Slice and metamorphic sole. Minor N-trending lineations could be related to oblique refolding of the earlier lineations.

Cretaceous accretionary complexes without Cimmerian continental ribbon (Topuz *et al.* 2013b).

In the Köyceğiz region, the lower Th/U ratios (<0.18) in the outer rims of the zircons (Supplementary Table 1) indicate a metamorphic event (Rubatto and Gebauer 2000) with a concordant age of 96.7 ± 0.79 Ma (Figure 7C) along the sole of the Marmaris Ophiolite. Formation of the outer metamorphic rims shortly predates the cooling age (93 ± 1.0 Ma, Table 1) obtained by ^{40}Ar-^{39}Ar dating of hornblendes, plagioclases and muscovites in the metamorphic sole (Çelik *et al.* 2006). This short time interval between new zircon crystallisation and cooling ages (^{40}Ar-^{39}Ar) of the green amphibolites indicates a fast cooling (Kohn *et al.* 2015) of the ophiolite. In the same area, around Ağla, the Marmaris Ophiolite contains 90-Ma-old metasomatic zircon crystal (Akbulut *et al.* 2016). Thus, not only the sole metamorphics, but also the Marmaris Ophiolite itself contains zircon crystals which define the age of the sole metamorphism.

The ages of the sole metamorphism in the northwest blueschist zones (Tavşanlı Zone) vary between 108 and 88 Ma (Table 1 and references therein). This sole metamorphism was overprinted by incipient blueschist metamorphism at 80–90 Ma (Late Turonian to early-Middle Campanian) (Okay *et al.* 1998; Plunder *et al.*

Figure 10. Mesoscopic shear sense indicators in the uppermost part of the Karabörtlen formation and the metamorphic sole around Karabörtlen and Ağla villages. (A) Sigmoidal foliation in the metapelitic uppermost part of the Karabörtlen formation, (B) σ-clast of gabbroic part preserved amphibolites, (C) kink band in amphibolites and (D) sigmoidal foliation in quartzo-feldspathic micaschists. All these asymmetric features consistently indicate a top-NE shear sense. Width of views is about 50 cm in (A), 25 cm in (B) and (C), 75 cm in (D).

2016a). However, the sole metamorphics sandwiched between the Karabörtlen formation and the Marmaris Ophiolite does not show a metamorphic overprint.

From the very structurally lowest part of the Ören Tectonic Slice to the Marmaris Ophiolite a top-to-the NE sense of shear is consistent (present-day position). In the Milas region, western Lycian Nappes, along the lower contact zone of the Ören Tectonic Slice and the Menderes Nappes the oldest linear fabrics and associated asymmetric structures indicate a top-to-the NE sense of shear (D1 phase) related to juxtaposition of two nappe piles (Arslan 2001; Arslan *et al*. 2013). Bozkurt and Park (1999) also defined a top-to-the N and top-to-the NE sense of shear in the structurally upper part of the Menderes Nappes composed of metabauxite-bearing platform carbonates with metapelite intercalations, ranging in age from Triassic to Cretaceous. Along the southern part of the Menderes Nappes, these platform carbonates (Milas and Kızılağaç formations) show regional scale, tight, overturned and isoclinal folds with E-striking and moderately to steeply south dipping axial planes (Konak *et al*. 1987), and the asymmetry of these regional scale folds also suggest that the nappes were stacked during northward movement. Not only along the lower contact of the Ören Tectonic Slice with the Menderes Nappes, but also along its uppermost part and in the metamorphic sole, the asymmetry of structures consistently shows a top-to-the NE sense of shear during the emplacement of the Lycian Nappes. In the Köyceğiz region, present-day position of this kinematics is inconclusive and it needs a correction by considering palaeomagnetic data disclosing post-emplacement rotation in Southwest Turkey (Figure 12). The palaeomagnetic studies (Kissel *et al*. 1993; Van Hinsbergen 2010; Van Hinsbergen *et al*. 2010;) carried on the Lycian Nappes and Bey Dağları Autochthon, the west subsection of the Isparta Angle, showed that Southwestern Turkey was subjected a 25°–30° anticlockwise rotation in conjunction with doming and exhumation of the Menderes Nappes from Middle Langhian to Early Zanclean (15–5 Ma ago). Following an emendation of this post-emplacement rotation of the Lycian Nappes to pre-Middle Miocene, the trend of their linear fabrics is approximately E-W with a top-to-the E sense of shear (Figure 12). The new kinematic model of the Lycian Nappes described here disagrees with the existing tectonic models that suggest either northward or southward movement of the Lycian Nappes (Table 2).

Along the Western and Central Taurides, the metamorphic soles of the peridotites related to the closure of the Neotethys are found in the Burdur, Beyşehir, Mersin and Pozantı-Karsantı areas. Kinematic data

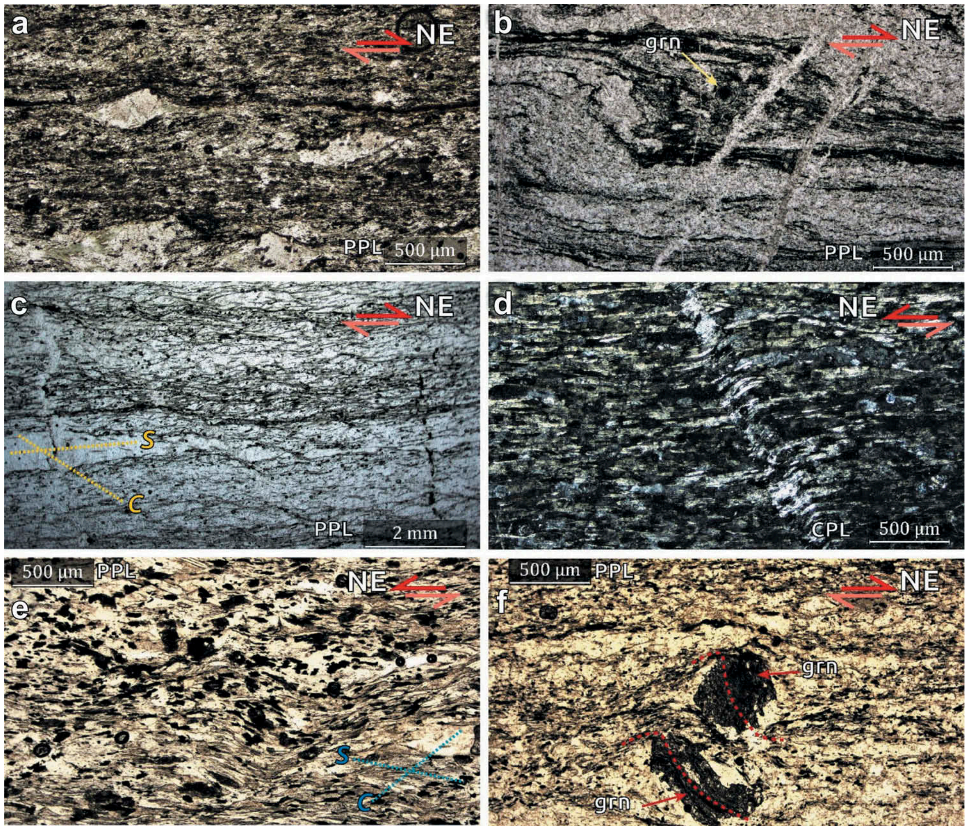

Figure 11. Photomicrographs of shear sense indicators in metamorphic sole of the Marmaris Ophiolite. All views from thin sections prepared parallel to the stretching lineation and perpendicular to the associated foliation. (A) σ-clasts in phyllites, (B) quarter fold in garnet quartz micaschists, (C) S/C relationship in quartz micaschists, (D) kink band in amphibolites, (E) S/C relationship in quartzo-feldspathic micaschists and (F) rotated garnets in garnet quartz micaschists. All asymmetric structures consistently indicate a top-NE shear sense. (PPL: Plane Polarized Light; CPL: Crossed Polarized Light).

about the metamorphic sole of ophiolites along the eastern part of the Central Taurides are little known, as yet kinematic data from the metamorphic sole of the Pozantı-Karsantı Ophiolite in the eastern part of the Anatolide-Tauride were described by Polat and Casey (1995). The dynamothermal metamorphic sole with inverted metamorphic gradient indicates a top-to-the NE sense of shear during emplacement of the Pozantı-Karsantı Ophiolite onto the Menderes-Taurus block in the Aladağ region. The current position of this sense of movement in the platform carbonates, metamorphic sole and ophiolites necessitate an emendation by considering the post-emplacement rotation. Piper *et al.* (2002) described a 40° post-Lutetian clockwise rotation along the Anamas-Akseki platform in the Central Taurides. In the light of this clockwise rotation, top-to-the SE sense of shear along the metamorphic sole of the Pozantı-Karsantı Ophiolite described by Polat and Casey (1985) can also be corrected to a top-to-the E movement. In addition, the eastern continuation of the Lycian Nappes which are known as the Beyşehir-Hoyran Nappes (Özgül 1976) in the Central Taurides also show a corrected top-to-the E sense of shear during the Lutetian related to closure of the Neotethys (Güngör 2013; Ungun 2015).

Conclusions

We presented movement direction of the Lycian Nappes and U/Pb LA-ICP-MS ages of zircons from the metamorphic sole embedded into the Marmaris Ophiolite in Southwestern Turkey. The most important findings of our study are as follows:

(1) Kinematic data along the contact zone between the Ören Tectonic Slice and the metamorphic sole of the Marmaris Ophiolite show a marked asymmetry indicating a top-to-the NE sense of shear. By considering 25°–30° regional anticlockwise post-emplacement rotation, the movement direction of the Lycian Nappes was from W to E (Figure 12).
(2) The kinematics of the Lycian Nappes described here disagrees with the existing tectonic models

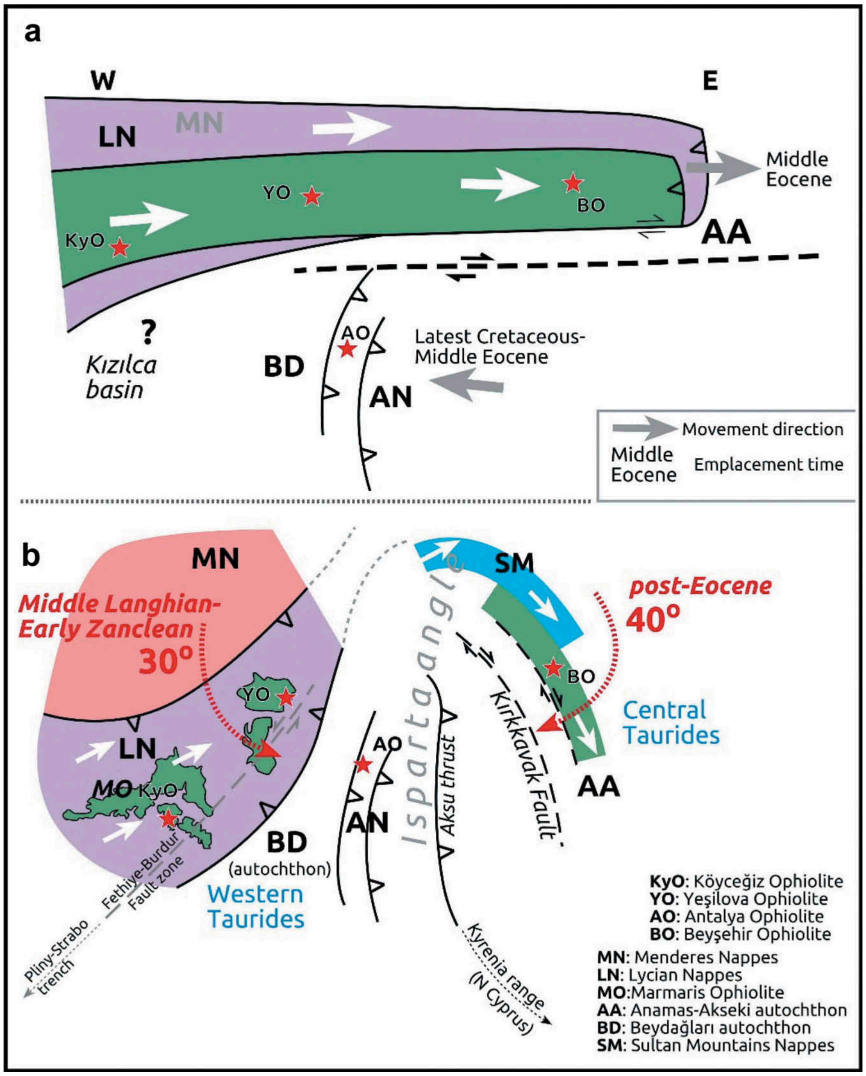

Figure 12. Simplified evolution of the Western and Central Taurides (modified after Güngör 2013). (A) Latest Cretaceous-Middle Eocene nappe movement (movement direction of Antalya Nappes is form Poisson *et al*. 2003; Robertson *et al*. 2003). (B) Post-Eocene rotation of Central Taurides and early Middle Miocene-Early Pliocene rotation of the Western Taurides (Van Hinsbergen *et al*. 2010).

suggesting N-S translations either northward or southward.

(3) CL images of zircons separated from the micaschists and quartzo-feldspathic micaschists in the sole metamorphics display dark cores and episodic rim generations.

(4) Ages from the cores of zircons scatter between 229 and 175 Ma and indicate igneous activity in the provenance area of the metamorphic sole. The inner rims with igneous affinity indicate that dark relic cores of zircons were involved into magmatic event between 153 and 143 Ma, then these recycled and newly formed zircons in this event were together involved into the quartzo-feldspathic sandstones, finally their outer rims describe a metamorphic event between 100.4 and 93.5 Ma (Cenomanian, concordant age 96.7 ± 0.79 Ma) along the sole of the Marmaris Ophiolite.

(5) The deposition time of quartzo-feldspathic sandstones that were protoliths of the white micaschists and quartzo-feldspathic micaschists can be constrained as Early Cretaceous.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendices

Field study

The methodology of field-based kinematic data collect includes systematic descriptions and measurements of the mesoscopic shear criteria in outcrops oriented perpendicular to the foliation and parallel to the associated stretching lineation, and examinations of microscopic structures in oriented thin sections.

Analytical Techniques

Zircons were separated in the mineral separation laboratory at the Geological Engineering Department of Dokuz Eylül University from around 15 kg garnet-muscovite schists and quartzo-feldspathic micaschists samples using standard mineral separation techniques. These rocks were crushed to coarse sand size with a tungsten carbide jaw crusher. Subsequently, zircons were concentrated by flotation on shaking table, sieving, magnetic separation and heavy liquids. A representative batch of 60 zircon crystals with grain sizes of 150–300 µm was manually picked and mounted in Araldite 2020 resin. After polishing, cathodoluminescence (CL) images were taken using a CL detector connected to a Jeol JX A-8900RL electron microprobe at Institute for Geosciences, University of Mainz. U, Th and Pb isotopes were measured by LA-ICP-MS (Institute for Geosciences, University of Mainz) using an Agilent 7500ce quadrupole ICP-MS system coupled to an ESINWR193 ArF excimer laser system with a193 nm output wavelength. The laser system is equipped with the ESITwoVol2 sample chamber (10 cm × 10 cm). After pre-ablation, analyses were conducted using a spot size of 20 µm, 20 s of background measurement, 30s ablation time and 20s washout time. The repetition rate was 10 Hz at energy density of 3.3 J cm^{-2}. The instrument was tuned for maximum sensitivity at low oxide formation rates of < 0.5. The dwell times for individual masses are 10 ms for masses 232 and 238, and 30 ms for 202, 204 and 208. Dwell times of 40 and 60 ms were used for masses 206 and 207, respectively. For a first step data reduction, the time-resolved signal was processed using the program GLITTER 4.4.1 (www.glitter-gemoc.com, Macquarie University, Sydney, Australia). Time dependent laser and mass spectrometer induced inter-element fractionation (Pb/U), mass fractionation, as well as common lead, were corrected afterwards using an Excel spreadsheet of ComPbcorr#318 (Andersen, 2002). The inter-element fractionation during ablation was corrected linearly. For this purpose, ablation conditions such as spot sizes and ablation times were kept constant during each session. The interference of ^{204}Hg on ^{204}Pb was corrected by measuring ^{202}Hg and calculating ^{204}Hg using the natural ^{204}Hg/^{202}Hg ratio of 0.2299. Ages, uncertainties and concordia diagrams were produced using Isoplot3 for Excel (Ludwig 2003). Concordia ages are plotted with 2σ uncertainty ellipses and discordia intercept ages are given at 95% confidence (Table S2). Analyses were calibrated using a GJ-1 (GEMOC) zircon (Slama *et al*. 2008). Reproducibility and accuracy were controlled by repeated analyses of Plesovice and 91,500 reference zircons, from Jackson *et al*. (2004) and Wiedenbeck *et al*. (1995) respectively, treated as unknown samples; measured values (1RSD = X % ?) deviate less than 2% from the published values

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