Structure and tectonics of subophiolitic mélanges in the western Hellenides (Greece): implications for ophiolite emplacement tectonics

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The Jurassic Vourinos ophiolite is part of the Western Hellenide ophiolite belt in Greece and rests tectonically on the Pelagonian microcontinent. The Vourinos and coeval Pindos ophiolite to the west display suprasubduction-zone geochemical affinities, and represent remnants of oceanic lithosphere formed in a rifted incipient arc–forearc setting within the Pindos Basin. In structurally descending order, and from west to east, the subophiolitic mélange beneath the Vourinos ophiolite contains the Agios Nikolaos Formation (ANF) and a rift assemblage, both of which display ENE-vergent thrust faults, shear zones, and folds. The ANF comprises schistose mudstone with pebbles, cobbles, and boulders of arenite and wacke derived from the crystalline basement of Pelagonia. Imbricated along ENE-directed thrust faults and metamorphosed up to lower amphibolite facies, the ANF represents continental rise deposits of the rifted Pelagonian margin. The rift assemblage includes blocks of basaltic lavas, ribbon chert, micritic cherty limestone, metagabbro, dolerite dikes, and serpentinite breccia that are commonly in thrust contact with each other and are tectonically imbricated with the Pelagonian carbonates; however, primary intrusive and depositional contacts are locally well preserved. Gabbro and dolerite dikes are locally intrusive into the recrystallized carbonates and metapelitic rocks of the Pelagonian microcontinent. Lavas display mid-ocean ridge basalt within plate basalt affinities and represent Upper Triassic rift units that erupted during the separation of Pelagonia from Apulia. Gabbro, dolerite, and serpentinite breccia are the products of a magmatic rifting episode prior to the onset of seafloor spreading in the Pindos Basin. The Vourinos subophiolitic mélange thus consists of passive margin and rift assemblages that were tectonically overridden by the Vourinos ophiolite in the Middle Jurassic. The Avdella mélange beneath the Pindos ophiolite to the west includes a chaotic matrix including ophiolitic clasts and blocks, reeval to pelagic limestones, and olistostromal turbidites that range in age from Triassic to Jurassic–Cretaceous. The Avdella mélange rests tectonically on a Cretaceous–Eocene flysch unit and the Cretaceous–Eocene shelf and slope deposits of the Apulian margin along west-directed thrust faults. The evolutionary history of the Vourinos and Avdella subophiolitic mélanges indicates diachronous tectonic emplacement of the Mesohellenic oceanic slab, first in the east as a result of a trench-continent (Pelagonia) collision in the Middle Jurassic, then in the west due to the Eocene collision of Apulia with Eurasia.

Keywords: subophiolitic mélange; Western Hellenides of Greece; Pindos Basin; Pelagonian microcontinent; passive margin sequence; rift lavas; suprasubduction-zone ophiolite

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Introduction

Jurassic to Cretaceous ophiolites in the Alpine orogenic belt (Figure 1) represent fragments of oceanic lithosphere generated during the Wilson cycle evolution of Tethyan basins (Dilek and Flower 2003). These ocean basins developed in response to successive episodes of the break-up of Gondwana and evolved as latitudinal, east–west-oriented basins separated by discrete continental fragments. Most eastern Mediterranean ophiolites are spatially associated with both Triassic–Jurassic volcanic rocks and subophiolitic mélanges that rest tectonically on passive margin sequences of ribbon continents (i.e. Pelagonia in the Balkans and Tauride platform in southern Turkey; Figure 1). These extrusive rocks display within-plate-type alkaline basalt (WPB) to transitional and mid-ocean ridge basalt (MORB) chemistry and are intercalated with hemipelagic to pelagic sedimentary rocks. They appear to represent rift-related magmatic pulses along

Figure 1. Simplified geological map of the Balkan Peninsula and the Aegean region, showing the distribution of Tethyan ophiolites (in green) and active plate boundaries (modified from Dilek and Flower 2003). AC, Antalya Complex; IA, Isparta Angle; IAESZ, Izmir–Ankara–Erzincan Suture Zone; IPO, Intra-Pontide ophiolites; KF, Kefalonia Fault; NAFZ, North Anatolian Fault Zone; MO, Mirdita ophiolite; PO, Pindos ophiolite; VO, Vourinos ophiolite. Black arrow shows the convergence direction of the African lithosphere at the Hellenic Trench.
the northern periphery of Gondwana (Juteau 1980; Pe-Piper 1982, 1998; Pamic 1984; Shallo et al. 1990; Jones and Robertson 1991; Dilek and Rowland 1993; Malpas et al. 1993; Saccani et al. 2003), prior to the onset of seafloor spreading and oceanic crust formation in the Tethyan basins (Dilek and Flower 2003).

Subophiolitic mélanges units form thin (several hundred metres) slivers of thrust sheets sandwiched between the metamorphic soles or upper mantle peridotites in the upper plate and the continental margin units in the lower plate along Tethyan suture zones (Shallo 1990; Wakabayashi and Dilek 2003; Dilek et al. 2005, and references therein). Oceanic rocks within the mélanges include ophiolitic material, fragments of seamounts, rift lavas, and high-grade metamorphic rocks (mainly metamorphic sole rocks), whereas detrital material and blocks in the mélanges are generally derived from continental margin units (shelf, slope, and rise sedimentary rocks) as well as continental rocks (Hsu 1968; 1974, 1988; Liou et al. 1977; Cloos and Shreve 1988a, 1988b). The mélanges matrix may consist of mudstone, sandstone, or serpentinite depending on the mélanges-forming processes (Phipps 1984; Raymond 1984; Yilmaz and Maxwell 1984; Dilek 1989; Shallo 1990; Polat et al. 1996; Dilek et al. 1999; Scherreiks 2000). In most cases, subophiolitic mélanges units, continental margin rocks, and ophiolitic peridotites are tectonically imbricated in the direction of ophiolite emplacement. Subophiolitic mélanges provide crucial information about the tectonic, metamorphic, and sedimentary processes and their P–T conditions during advancement of ophiolitic thrust sheets onto continental margins; they can also constrain the maximum age of the timing of ophiolite emplacement. Because they contain material from the rift–drift tectonics of the basins prior to their terminal closure, these subophiolitic mélanges can also give us significant clues about the tectonic, sedimentary, and magmatic processes and events involved in the early stages of the geodynamic evolution of the basins and their continental margins.

In this paper, we document the internal stratigraphy and structure of a subophiolitic mélangé associated with the Jurassic Vourinos ophiolite in the Western Hellenides in northern Greece. We then analyse our data and interpretations in a regional tectonic framework to derive some conclusions about the tectonic processes involved in the formation of the Vourinos ophiolite and its subophiolitic mélangé and in the emplacement of the ophiolite–mélangé units onto the Pelagonian continental margin. The Vourinos subophiolitic mélangé is typical of most mélanges associated with the Tethyan ophiolites in the eastern Mediterranean region, and therefore represents a case study of mélangé formation that involves rift–drift–collision tectonics of restricted marginal basins in the Tethyan realm and beyond.

**Ophiolite geology of the Hellenides**

The NW-trending Neotethyan ophiolites in the Hellenides occur in two distinct zones bounding the Pelagonian ribbon continent (Figure 2(a)). The Vardar Zone ophiolites, also known as the ‘Innermost Hellenic ophiolites’ (Smith 1993) or the ‘Eastern Hellenic ophiolites’, are located east of Pelagonia and are Jurassic–Early Cretaceous in age (Bébien et al. 1986; Mussallam and Jung 1986; Robertson 2002). The ophiolites to the west of the Pelagonian microcontinent, called the ‘Western Hellenic ophiolites’, are nearly coeval or slightly older than those in the Vardar Zone and are spatially associated with Triassic–Jurassic volcano-sedimentary units and mélanges (Smith 1993; Robertson and Karamata 1994; Bortolotti et al. 2005; Dilek et al. 2005; Saccani and Photiades 2005). The Western Hellenic ophiolites in Greece and Albania, their northward continuation into Kosovo and Serbia, and the Dinaric ophiolites in Bosnia and Croatia collectively form
the Pindos Zone ophiolites in the western Balkan Peninsula (Robertson and Karamata 1994; Hoeck et al. 2002; Smith and Rassios 2003; Koller et al. 2006; Dilek et al. 2008). These ophiolites show bidivergent emplacement onto Pelagonia in the east and Apulia in the west (Figure 2(b)).

The root zones of the Pindos and Vardar Zone ophiolites and their possible genetic relations have been a source of debate in discussions of Balkan geology. Some researchers argue that both the Pindos and Vardar Zone ophiolites were derived from a Mesozoic ocean basin located east of the Pelagonian microcontinent, and that the Jurassic ophiolites in the Pindos Zone thus represent far-travelled nappe sheets with their roots in the Vardar Zone (Collaku et al. 1990, 1991; Ricou et al. 1998; Bortolotti et al. 2005; Gawlick et al. 2007; Schmid et al. 2008). These interpretations imply that the Pelagonian microcontinent was not rifted apart from Apulia, and that it was an outlier of the Apulian passive margin at all times throughout the Mesozoic. The alternative and more widely accepted models suggest that the Pelagonian block was an insular continental entity separating the Pindos and Vardar (and/or Maliac) Basins within the Neotethyan realm during much of the Mesozoic (Smith 1993; Robertson and Shallo 2000; Robertson 2002; Stampfli and Borel 2004; Dilek et al. 2005, 2007; Saccani and Photiades 2005). The structure and tectonic evolution of the subophiolitic mélanges in the Pindos Zone provide important constraints on the validity of these different geodynamic models.

Vourinos and Pindos ophiolites: Mesohellenic oceanic slab

The Vourinos and Pindos ophiolites constitute the eastern and western edges, respectively, of a larger Jurassic ophiolitic body, known as the Mesohellenic ophiolite (Rassios and Dilek 2009) in the Western Hellenides (Figure 2(b)). These two ophiolites are exposed >30 km apart, although magnetic and drilling data indicate that they are part of a single mafic–ultramafic slab, which is continuous in the subsurface beneath the Palaeogene–Neogene sedimentary cover of the Mesohellenic Trough (Saccani and Photiades 2004; Rassios and Moores 2006; Rassios and Dilek 2009). This ophiolite belt continues to the NW into Albania (SE Albanian and Mirdita ophiolites) and to the SE into Southern Greece (Figure 1). Both the Vourinos and Pindos ophiolites overlie subophiolitic mélanges displaying some lithological similarities.

The Pindos and Vourinos ophiolites are coeval in age and display suprasubduction-zone affinities (Kostopoulos 1989; Smith and Rassios 2003; Pe-Piper et al. 2004; Saccani and Photiades 2004; Beccaluva et al. 2005; Rassios and Dilek 2009), although they also show major differences in their internal structure and geochemical fingerprints. The Pindos mantle section is harzburgitic to lherzolitic, indicating comparatively fertile mantle compositions (Nicolas and Boudier 2003; Beccaluva et al. 2005; Rassios and Moores 2006).
A nearly 1-km-thick extrusive sequence in Pindos shows MORB to island arc tholeiite (IAT) and boninitic compositions (Capedri et al. 1980; Kostopoulos 1989; Jones and Robertson 1991; Jones et al. 1991; Pe-Piper et al. 2004; Saacani and Photiades 2004; Beccaluva et al. 2005; Dilek and Furnes 2009). The Pindos ophiolite is underlain by the subophiolitic Avdella mélangé (Kostopoulos 1989; Jones and Robertson 1991), which we describe in a later section.

The Vourinos ophiolite comprises a large mantle section of depleted harzburgite and dunite with economically viable chromite bodies, a petrologic Moho, 4–5-km-thick mafic and ultramafic cumulates, sheeted dikes, a thin extrusive sequence consisting mainly of pillow lavas, and a Cretaceous pelagic limestone cover (Jackson et al. 1975; Harkins et al. 1980; Vrahatis and Grivas 1980; Rassios 1981; Rassios et al. 1983; Grivas et al. 1993; Liati et al. 2004; Rassios and Moores 2006; Sharp and Robertson 2006). All lithological units in the Vourinos ophiolite have been tilted or overturned to the west, so that the structural progression of units from top to bottom is from west to east, with the upper mantle peridotites occurring at the easternmost rim of the ophiolite nappe (Figure 3). The Vourinos dikes and lavas are mainly IAT in composition, but boninitic dikes and lavas occur as late-stage magmatic products both in the sheeted dike complex and the extrusive rocks (Rassios and Dilek 2009, and references therein). Around the eastern rim of the

![Figure 3. Geological map of the Vourinos ophiolite. Numbered boxes show subophiolitic mélangé localities that are investigated in detail in this study.](image-url)
Figure 4. Panoramic view (to the north) of the Vourinos ophiolite, its subophiolitic mélangé exposed in the Agios Nikolaos Valley, and the Pelagonian carbonate platform.
ophiolite, the subophiolitic mélange occurs as a discontinuous sliver between the ophiolite and the Pelagonian microcontinent (Figure 3; Jones and Robertson 1991; Ghikas et al. 2007; Rassios and Dilek 2009).

**Vourinos subophiolitic mélange**

A 300–500 m-thick mélange unit occurs structurally underneath the Vourinos ophiolite and on top of the Pelagonian microcontinent (Figure 4), and is exposed discontinuously around the entire margin of the ophiolite. This study has focused on four major localities around the rim of the Vourinos ophiolite, where the representative sections of the Vourinos subophiolitic mélange are exposed. These localities include: (1) the Agios Nikolaos Valley, (2) North of Skoumtsa, (3) Frourio, and (4) the Aliakmonas River Valley (Figure 3).

The Vourinos subophiolitic mélange locally contains numerous blocks and thrust sheets of various rock types, ranging in size from several metres to several kilometres. These subunits are typically less than 100 m thick, and thus the surface expression of the mélange resembles a collection of thin lensoidal blocks and thrust sheets with a strong preferred alignment and imbrication in the direction of ophiolite emplacement to the NE (Figure 5).

Most mélange subunits show an internal fabric (bedding, foliation, or shearing) and the contacts between the subunits are most commonly defined by reverse and thrust faults. Both the contacts and the internal fabric elements in the subunits approximately parallel the dip of the bounding thrust faults of the mélange. The general emplacement direction of the Vourinos ophiolite is to the northeast (Figure 5; Rassios and Moores 2006; Rassios and Dilek 2009), but locally the contractional deformation associated with this northeastward movement has been overprinted by oblique-slip deformation. Along the north–northwestern edge of the ophiolite (Mt. Vourinos, Agios Nikolaos Valley, and North of Skoumtsa), the Vourinos subophiolitic mélange shows mainly contractual deformation with sinistral oblique-slip overprint and duplexing (Figure 6). In the central region (Frourio), the deformation is manifested in major ENE-vergent thrust faults with second-order, conjugate dextral and sinistral oblique-slip faults (Figure 7). Along the southern edge of the ophiolite nappe (Aliakmonas River Valley), the southeast-vergent thrust faults show strong dextral strike-slip components (Figure 8).

The Vourinos subophiolitic mélange consists mainly of two major units, the Agios Nikolaos Formation (ANF) and the Rift Assemblage. Below, we describe the internal structure and stratigraphy of these two mélange units.

**Agios Nikolaos Formation (ANF)**

The ANF, as originally named by Naylor and Harle (1976), is the most extensive subunit of the mélange and can be characterized as a ‘broken formation’. It is a brown, foliated to
schistose mudstone containing pebble-, cobble-, and boulder-size clasts of sandstone (arenite and wacke) mainly composed of quartz and plagioclase grains (Figure 9). The provenance of the sandstone material is interpreted to be the Pelagonian hinterland based on the presence of quartz, feldspars, muscovite, and detrital zircons (Mountrakis 1986; Lips et al. 1998; Most et al. 2001; Anders et al. 2006). The ANF has little or no ophiolitic or Pelagonian carbonate blocks within it; however, the mudstone matrix is locally tectonically mixed with reworked serpentinite mud and silt along shear zones. Most blocks are lensoidal in shape and/or bounded by thrust faults. Both lithologically and structurally, the ANF is analogous to the Lichi Mélange associated with the East Taiwan ophiolite in Taiwan (Liou et al. 1977).

In most areas, the ANF has undergone lower greenschist-facies metamorphism, as evidenced by the presence of abundant quartz–sericite–calcite–chlorite in the matrix rocks. Higher grades of metamorphism are seen lower in the structural section near the contact with the Pelagonian platform carbonates, where the ANF becomes a phyllite with a strongly developed foliation (Figure 10) and actinolite– albite–chlorite–epidote mineral assemblages. Phyllitic foliation (cleavage) in the matrix generally dips to the west (SW or NW) with quartz elongation and/or stretching lineation also plunging to the west (Figure 10). Both transposed bedding and phyllitic cleavage are folded around NW–SE-trending fold axes, which plunge at moderate to steep angles in these directions. Tight to isoclinal folds and crenulation folds are commonly overturned to the NE. The sandstone clasts are recrystallized to quartz veins, boudins, and lenses, and are commonly strongly folded and elongated (Figure 9(c)). Adjacent to the Pelagonian microcontinent, the ANF becomes a schist.

**Rift assemblage**

Discrete blocks and thrust sheets of igneous rock assemblages and associated sedimentary rocks are locally abundant within the Vourinos subophiolitic mélange (Figures 6 and 8). The rock types include basaltic lavas, serpentinite breccia, gabbro, dolerite, jasper, ribbon chert, cherty carbonate, metapelitic rocks, and mylonitized pelagic carbonate, as lensoidal or phacoidal bodies typically bounded by thrust faults. However, these lithologies locally have intrusive and/or depositional contacts and/or are interlayered with each other. These blocks occur along the northern and southern margins of the ophiolite, such as North of Skoumtsa, in the Agios Nikolaos Valley, and in the Aliakmonas River Valley, but are not observed at the Frourio locale on the eastern margin of the Vourinos ophiolite (Figure 7). They are tectonically intercalated with the ANF (Figures 6 and 8).

**Volcanic units and associated sedimentary rocks**

Volcanic rocks are widely distributed in the mélange, particularly in the Aliakmonas River Valley, the Agios Nikolaos Valley, and North of Skoumtsa. They occur as large blocks of meta-tuff, pillow lavas, and hyaloclastites, varying in size from 10- to 100-m-long (Figure 11(a,b); Zimmerman 1968; Ross and Zimmerman 1996). The basaltic lava outcrops along the Aliakmonas River are strongly coloured in purple, dark red, pink, and green, and are spatially associated with pink micritic limestone or cherty limestone (Figure 11(c)). Calcite and chlorite fill brittle fractures as secondary minerals. The phyric basaltic lavas contain acicular plagioclase microlites and granular clinopyroxene in a vitrified glassy groundmass. Chlorite occurs as the replacement of olivine. Some of these basaltic lava blocks contain hemipelagic cherty ribbon limestone (1–3 cm thick ribbons)
Figure 6. Geological map of the Agios Nikolaos Valley and structural cross-sections. See text for discussion.
interlayered with siltstone and tuffaceous sandstone (< 0.5 cm thick layers). These rocks are locally strongly folded and recrystallized.

Basaltic lava outcrops in the Agios Nikolaos Valley farther north occur as thin tectonic wedges bounded by thrust faults (Figure 8), similar to the lava units along the Aliakmonas River. However, they do not visually resemble the lavas to the south, and their associated sedimentary units also differ from their counterparts to the south. These volcanic rocks in the north are mostly massive lava flows and are brown to grey-green, aphanitic, and
commonly heavily weathered, although few pillow shapes are still locally discernable. The sedimentary rocks associated with these northern volcanic units are metalliferous red jasper and pelagic limestone. These sedimentary rocks occur either as continuous interlayers or as large (0.5 m long) lenses within the volcanic units. The jasper interlayers are highly folded and crenulated.

Intrusive units and associated sedimentary rocks

The intrusive rock units in the mélangé include gabbro stocks and dolerite dikes that are commonly associated with a serpentinite breccia (Figure 12). They are intrusive into and/or tectonically overlie the Pelagonian carbonate platform units, and are also tectonically intercalated with metapelitic rocks, micritic limestone, and chert. They have been intensely deformed via folding and thrust faulting, but their original contact relationships have largely survived this contractional deformation. Some of the originally intrusive contacts were partly reactivated as thrust faults during emplacement of the Vourinos ophiolite.

Gabbroic and doleritic intrusions are best seen along the Aliakmonas River (Figure 8). They occur structurally at the bottom of the Vourinos subophiolitic mélangé, just above the contact with the intensely deformed and recrystallized Pelagonian platform carbonates and metapelites. This area of the mélangé does not contain the ANF. Gabbroic stocks and doleritic dikes are intrusive into finely foliated phyllite and marble, psammitic schist, and mylonitized micritic limestone that constitute the outermost units of the Pelagonian microcontinent. Locally, the sedimentary and igneous contacts between these rock
units are well preserved. The Pelagonian marble units contain dasycladacean algae, algal oncolites, and loferites, suggesting a neritic to littoral environment of deposition for their protoliths, which ranged in age from Middle Triassic to Upper Jurassic (Zimmerman 1972).

The gabbroic intrusions here are typically less than 100 m thick, with weakly foliated to submylonitic fabric parallel to the NE-oriented strike of the outcrop. They appear as lozenge-shaped, highly sheared intrusive bodies with significant grain size change in short distances. Mylonitic high-T foliation in the gabbros is folded and crosscut by discrete narrow mylonitic shear zones. Strong mineral lineation and the fold axes of parasitic z-folds in these local shear zones all plunge to the west (~270°). These gabbroic intrusions are cut by numerous subparallel doleritic dikes (Figure 12(b)), which also extend into the adjacent ultramafic breccia outcrops. Gabbro and dolerite rocks show pervasive secondary alteration and lower amphibolite facies metamorphism evidenced by extensive replacement of pyroxene by hornblende and actinolite. Some gabbro outcrops have been completely altered to serpentinite, chlorite, and oxidized ferromagnesian minerals. Epidosite is also common, occurring as thick bands parallel to the foliation, or as disseminated individual grains.

Serpentinite

There are two types of reworked serpentinite types in the Vourinos mélangé. The first one strongly resembles the serpentined harzburgite in the upper mantle section of the Vourinos ophiolite in terms of its mineralogical and textural features, and still contains relict pyroxene and olivine crystals although highly sheared. This sheared serpentinite is found directly beneath the ophiolite or as rare thrust sheets within the ANF. It was derived mainly from the Vourinos ophiolite during its tectonic emplacement, which locally incorporated blocks of highly sheared harzburgite into the mélangé.

The second type of reworked serpentinite bears no resemblance to peridotite rocks from the ophiolite. It is black and contains rounded to angular clasts of serpentinite cemented together by secondary serpentine and carbonate minerals. Outcrops of this serpentinite are typically found in a structurally lower position in the mélangé (Figure 8), near the contact with the mylonitized carbonates and metapelitic rocks of the Pelagonian microcontinent. All these rocks are strongly deformed with refolded folds, thrust imbrication, and z-type parasitic folds. Stretching lineations in the mylonitized metapelitic schists trend ~80° with westerly plunges. Fold axes of the z-folds are locally subvertical and the shear sense indicators suggest a component of dextral strike–slip deformation (Figure 8).

Similar serpentinite breccia occurrences have been reported from the Gödene Zone of the Antalya Complex in SW Turkey (Figure 1), where foliated and reworked serpentinites...
Figure 10. Equal-area lower-hemisphere stereoplots of various fabric elements in the Vourinos mélangé. (a) North of the Skoumtsa section: Black circles, poles to phyllitic foliation; open circles, poles to quartz elongation and/or stretching lineation; red arrows, poles to fold axes in the phyllite. (b) Froupio section: Black circles, poles to phyllitic foliation. (c) Aliakmon River Section: black circles, poles to phyllitic foliation; black stars, poles to doleritic dikes; black arrows, poles to quartz elongation and/or stretching lineation. See text for discussion.
Figure 11. Field occurrence of lava units within the Vourinos subophiolitic mélangé. (a) Basaltic pillow lava block in a pebbly mudstone–phyllite of the ANF in Mt Vourinos northwest of the Agios Nikolaos Valley. Pillow lavas are mostly aphyric, green-brown in colour. (b) Pillow lava block from the Aliakmonas River Valley, with purple-pink coloured, visible pillows. (c) Close-up image of lava flows in (b) showing thin beds of pink chert interlayers between the lava flows. ANF, Agios Nikolaos Formation; CHRT, chert; LV, basaltic lava.
are tectonically intercalated with Upper Triassic volcanic–sedimentary passive margin assemblages (Marcoux 1976; Robertson and Woodcock 1981; Dilek and Rowland 1993). Anastomosing lenses of fault-bounded serpentinite bodies in the Gödene Zone also include lozenges of gabbro, dolerite, and harzburgite, and are spatially associated with mafic pillow lavas, volcanic breccias, Upper Triassic pelagic limestones, and radiolarites. Dilek and Rowland (1993) interpreted the Gödene Zone as part of the rifted continental margin of the Tauride carbonate platform (or microcontinent).

**Metamorphic sole unit**

Thin, discontinuous exposures of high-grade metamorphic rocks occur between the subophiolitic mélangé and the overlying Vourinos ophiolite (Figures 7 and 8). Best examples of these metamorphic thrust sheets are found on the Zavordas Road and Frourio, where a few metres- to 20-m-thick amphibolite, garnet-micaschist, and quartzite are exposed structurally beneath the Vourinos peridotites (Zimmerman 1972; Ghikas 2007; Myhill 2009). The contacts between these amphibolite and the mélange units are invariably faulted and sharp, but the crenulation cleavage, tight to isoclinal and overturned folds, and microfaults all show east-directed tectonic transport similar to those in the overlying peridotites and the underlying mélange units.

Typical peak-metamorphic mineral assemblages in the Zavordas amphibolites include hornblende–ferropargasite–plagioclase–garnet–sphene–ilmenite–quartz, with retrogressive chlorite, biotite, and phengite rimming hornblende and infilling fractures in garnet (Myhill 2009). Peak temperatures of 670°C (±35°C) for the Zavordas garnet–hornblende pairs and 770 ± 100°C for the Frourio garnet micaschists have been obtained from the Vourinos subophiolitic metamorphic rocks (Myhill 2009). 40Ar/39Ar dating of the Vourinos amphibolites has revealed a cooling age of 171 ± 4 Ma (Spray 1984; Spray et al. 1984). Moores (1969) and Spray and Roddick (1980) interpreted the high-grade rocks beneath the Vourinos ophiolite as a metamorphic sole. The geochemistry of the metabasic rocks in the Vourinos sole indicates both MORB and WPB affinities (Spray and Roddick 1980; Jones and Robertson 1991), similar to the trace-element compositions of the metalavas in the rift assemblage units within the structurally lowermost part of the mélange (see below).

**Neogene cover of the Vourinos mélange**

Both the Vourinos ophiolite and the subophiolitic mélange are unconformably overlain by a lower Miocene conglomerate (Tsotyli Conglomerate) of the Palaeogene–Neogene sedimentary sequence of the Mesohellenic Trough (Figure 13). This matrix-supported and poorly sorted conglomerate consists almost entirely of ophiolitic material, and the clast size ranges from greater than 1 m to cm scale (Figure 13). A regional compressional episode in the late Miocene (Vamvaka et al. 2006) produced several SW-dipping thrust faults, tectonically stacking the conglomerate, the ophiolite, and the mélange along
Figure 13. Panoramic roadcut image of the Miocene Tsoyli conglomerate, subophiolitic mélange, and serpentinitized peridotite of the Vourinos ophiolite. Clasts in the conglomerate are made entirely of ophiolitic material and range in size from more than 1 m to cm scale. (a) and (b) depict the close-up photos of the contact relations among these three units. (a) Miocene conglomerate rests unconformably on both the serpentinitized peridotite and the mélange (ANF). Serpentinite is in thrust contact with the ANF. (b) The unconformity is reactivated as an east-vergent thrust fault. Both the conglomerate and the ANF have been imbricated along NE-vergent thrust faults farther east in this outcrop.
northeast-vergent thrust faults (Figure 13). These late Cenozoic thrust faults parallel the orientation of the older emplacement faults and the foliation planes in sheared peridotites and serpentinites in the ophiolite. Locally, the original depositional contact between the conglomerates and the Vourinos mélange was also activated as a thrust fault (Figure 13).

**Geochemistry of the rift lavas in the Vourinos mélange**

A detailed geochemistry and petrogenetic history of the rift lavas and dikes in the Vourinos mélange is presented elsewhere (Dilek et al. in preparation). We report here the relevant geochemical features of these metabasic rocks. The metalavas in the mélange straddle the boundary between the tholeiitic and calc-alkaline fields on the AFM diagram, and overlap compositionally with the Triassic lavas from Albania and southern mainland Greece (Figure 14(a); Pe-Piper 1998; Saccani et al. 2003; Monjoie et al. 2008). Two main groups of basaltic lavas, high-Ti and low-Ti, have been recognized within the rift assemblage. The high-Ti group lavas show WPB to MORB geochemical signatures, whereas low-Ti group lavas display an IAT affinity, suggesting a subduction zone influence in their melt evolution (Figure 14(b,c)). The incompatible element-enriched high-Ti group lavas are likely to have been derived from an E-MORB mantle source in a rift tectonic environment (Dilek et al. in preparation). The geochemical features of the low-Ti group lavas suggest that the enriched mantle source was influenced by subduction zone-derived fluids (Dilek et al. in preparation). We interpret this subduction zone influence as an inheritance from earlier Palaeotethyan subduction events in the region that produced the late Palaeozoic continental arc magmatism in the Rhodope, Strandja, and Sredna Gora zones in today’s eastern Greece and Bulgaria (Pe-Piper 1998; Bonev and Dilek 2010).

**Regional tectonics of the Vourinos mélange**

In order to understand the regional geology of the Vourinos subophiolitic mélange within the tectonic framework of the Western Hellenides and the Pindos Basin, it is important to compare it with its counterpart on the west, the Avdella mélange (Figure 2(b)). The Avdella mélange contains abundant clasts ranging in size from 1 cm to 2 km (Kostopoulos 1989; Jones and Robertson 1991). Major components of this mélange include thick shallow turbidite and detrital sequences, and olistostromal blocks composed of Triassic basaltic lavas (Pe-Piper 1982), Jurassic lavas, dolerite, gabbro, and serpentinitized peridotites of an ophiolitic origin, Upper Triassic ‘ammonitico rosso’, pelagic limestone, Triassic and Jurassic radiolarian cherts, and metamorphic sole rocks (i.e. amphibolite, greenschist, and micaschist). Volcanoclastic turbidites and debris flows, composed in many localities of ophiolite-derived detritus, occur both as blocks within the mélange and make up relatively coherent sequences within the mélange stratigraphy. These lithologies range in age from Mid-Triassic to Upper Jurassic. The mélange matrix is heterogeneous (Kostopoulos 1989), and is composed of shale, mudstone, and terrigenous sandstone (Kostopoulos 1989; Ross and Zimmerman 1996). This polygenetic composition is reminiscent of the lithological make-up of other subophiolitic mélanges farther south in the Hellenic ophiolite belt, such as the Pagondas and Komi Leibadi mélanges of Crete (Scherreiks 2000).

The Avdella and Vourinos subophiolitic mélange bear many lithological similarities and occupy analogous tectonic positions beneath the western and eastern margins of the Mesohellenic oceanic slab (respectively). However, they differ significantly regarding
their internal structural architecture and the processes involved in their formation. The Avdella mélange contains blocks of rocks associated with the initial rifting of Pelagonia and Apulia, as well as with the development of a mature carbonate platform (pre-Apulian platform), the deposition of thick shallow-marine turbidite and detrital sequences (shelf and slope deposits of the pre-Apulian passive margin), and the emplacement of the Pindos ophiolite (Jones and Robertson 1991; Rassios et al. 2009). With this association, the Avdella mélange can be characterized as a ‘block-in-matrix’ type, polygenetic mélange, the evolution of which involved both sedimentary and tectonic processes (Raymond 1984). The Avdella mélange was emplaced westwards onto the Cretaceous–Eocene shelf and turbidite deposits of the pre-Apulian platform (Rassios et al. 2009).

The Vourinos mélange, by contrast, is not a chaotic, ‘block-in-matrix’ mélange. It consists mainly of tectonic imbricates of a pebbly mudstone (ANF) with

Figure 14. (a) AFM diagram showing the geochemical affinity of the rift lavas in the Vourinos mélange (after Irvin and Baragar 1971). (b) Zr vs. Zr/Y diagram (after Pearce and Norry 1979). (c) MnO–P₂O₅–TiO₂ diagram (after Mullen 1983). (d) Ti vs. V diagram (after Shervais 1982). Samples of rift-related basalts from the Albanides (data from Monjoie et al. 2008) and southern mainland Greece are also included for comparison (see text for discussion). Light green (left-facing blank) triangles, OIB samples (Triassic) from the Albanides (Monjoie et al. 2008); green (right-facing filled) triangles, BAB samples from Albanides and Othrys ophiolite in Greece (Monjoie et al. 2008); purple blank rhombs, rift lavas from the Vourinos mélange; purple filled triangles, Triassic basaltic lavas from the Argolis Peninsula (Saccani et al. 2003); green (top-facing, blank) triangles, basaltic lavas from the Hellenides (Pe-Piper 1998).
Pelagonia-derived detrital material, and a Triassic rift assemblage including serpentinite breccia, meta-gabbro, dolerite dikes, pillow lavas, and chert. Many of these tectonically incorporated blocks show their own internal fabric features (i.e. bedding, foliation, and pre-existing folding) overprinted by shearing and folding associated with the emplacement of the Vourinos ophiolite and the subsequent eastward imbrication of the ophiolite, mélangé, and the overlying Mesohellic sedimentary cover in the late Cenozoic (Rassios and Dilek 2009; Vamvaka et al. 2010). The ANF is derived almost exclusively from mudstone and sandstone formed in a depocentre that developed west of Pelagonia following the early episode of continental rifting in the Mid-Triassic (Zimmerman 1968; Naylor and Harle 1976; Ghikas et al. 2007). The rift assemblage represents the incipient rift sequence of the western continental margin of the Pelagonian microcontinent.

We interpret these igneous lithologies and associated sedimentary units collectively as ‘rift assemblages’ that formed during the initial rifting of the Pelagonian microcontinent from Apulia in the Late Triassic–Jurassic and prior to the onset of seafloor spreading in the Pindos Basin. Olistostromal blocks or olistoliths are not present in the Vourinos subophiolitic mélangé, and blocks of either the ophiolite or the Pelagonian carbonate platform are rare to be absent within it. The Vourinos mélangé, therefore, can be best described as a tectonic mélangé (Raymond 1984).

**Origin of the Vourinos mélangé and implications for the Mesohellenic ophiolite**

The internal structure and origin of the Vourinos mélangé are important not only for its own provenance and tectonic history, but also for the root zone and the geodynamic evolution of the overlying Vourinos ophiolite, which shares its geological history. Because the Vourinos subophiolitic mélangé and all its subunits display lithologies and fabric elements consistent with an origin within the Pindos Basin and with tectonic accretion beneath an eastward-advancing ophiolite nappe, the Vourinos ophiolite itself must be rooted in the Pindos Basin. This interpretation rules out the Vardar Zone origin of the Vourinos ophiolite (and hence the Mesohellenic oceanic slab) and its underlying mélangé.

The ANF originated as a mudstone–sandstone unit deposited in a continental rise setting west of the newly formed Pelagonian continental margin during the Late Triassic–Early Jurassic. The sediment was derived from the interior of Pelagonia, where the Palaeozoic and Precambrian schists and gneisses of its basement were exposed (Yarwood and Dixon 1977; Mountrakis 1986; Koroneos et al. 1993; Schermer 1993; Lips et al. 1998; Most et al. 2001; Mposkos et al. 2001; Anders et al. 2006). The lava blocks in the mélangé have WPB to E-MORB geochemical signatures, consistent with their continental rift origin (Pe-Piper 1998; Saccani et al. 2003; Dilek et al. in preparation). These extrusive rocks are also in depositional contacts with marine sedimentary rocks including hemipelagic chert and limestone.

Nearly, all blocks in the Vourinos mélangé are oriented with their long axis parallel to the strike of faults bounding the mélangé between the ophiolite and the Pelagonian margin. Ductile and brittle deformation structures observed within the mélangé, such as folds, foliation, mylonitic and cataclastic shear zones, and brittle thrust faults, are all parallel to the deformation structures within the lower sections of the overlying Vourinos ophiolite (Figure 5). Mylonitic bands and shear zones within the mélangé blocks and the matrix are generally parallel to each other and to the direction of NE thrusting. In all locales within the Vourinos mélangé, the general direction of tectonic transport is eastwards. Recrystallized limestone and metapelitic rocks of the Pelagonian microcontinent structurally beneath the Vourinos ophiolite and mélangé show east-vergent, tight to
isoclinal folds that are commonly overturned to the east. Tectonic models for the root zone and emplacement of the Vourinos ophiolite must, therefore, also include this information.

The Vourinos subophiolitic mélange represents a parautochthonous oceanic assemblage – it was formed in an ocean basin at the western edge of the Pelagonian continent; it is now situated along a suture zone between the Vourinos ophiolite, which is a remnant of the Pindos oceanic lithosphere, and the western edge of the Pelagonian microcontinent. Hence, the Mesohellenic oceanic slab is also a parautochthonous unit. Therefore, a far-travelled nappe origin of the Mesohellenic ophiolite rooted in the Vardar Zone east of Pelagonia is not supported by our observations and tectonic model.

Tectonic history of the Pindos Basin and formation of the Vourinos mélange

Apulia and Pelagonia were part of the northern edge of Gondwana in the latest Permian–Early Triassic. Extension during the Late Triassic caused rifting of Apulia and Pelagonia and formation of the rift assemblage now preserved in the structurally lower section of the Vourinos mélange (Figure 15(a,b)). Deposition of mudstone and sandstone, precursor to the ANF, occurred in the rift basin at this time. Detrital sediments of this incipient rift basin were derived from the crystalline basement of the Pelagonian microcontinent. As the rift–drift tectonics of the Pindos Basin evolved and the passive margin of the Pelagonian microcontinent fully developed, the ANF was deposited in the continental rise environment of this Pelagonian passive margin (Figure 15(c)).

In the mid-Jurassic (175–165 Ma), the Pindos Basin started collapsing via intra-oceanic subduction (Figure 15(d)) as a result of a collision-driven regional compressive stress regime in the Tethyan realm farther east (Dilek et al. 2005, 2007). As subduction continued and began to rollback to the east, suprasubduction-zone oceanic crust formation in the Pindos Basin evolved in an east-facing infant arc–forearc environment (Saccani and Photiades 2004; Beccaluva et al. 2005; Dilek et al. 2005, 2008). Mafic and ultramafic rocks in the Mesohellenic ophiolite show, in general, a west-to-east MORB to SSZ to boninitic progression in chemical affinity (Smith and Rassios 2003; Pe-Piper et al. 2004; Beccaluva et al. 2005; Dilek et al. 2008), suggesting progressive depletion of the mantle wedge peridotites through repeated melting episodes during SSZ oceanic crust evolution. The arrival of the Pelagonian continental margin at the trench started an episode of arc–continent collision in the Late Jurassic–Early Cretaceous that terminated the subduction rollback cycle and magmatism (Figure 15(e)). The Vourinos ophiolite was then displaced from its igneous environment of formation and was tectonically accreted onto the western edge of Pelagonia along an ENE-directed lithospheric-scale thrust fault.

By the Early Cretaceous, the west-dipping subduction in the Pindos Basin was halted by the collision and partial subduction of Pelagonia, and the Vourinos ophiolite (eastern half of the Mesohellenic oceanic slab) was thrust over the Pelagonian microcontinent, along with imbricate thrust sheets of the ANF (continental rise deposits) and the rift assemblage units in this structurally descending order (Figure 15(f)). The western half of the Pindos Basin remained open, and passive margin conditions along the Apulian margin to the west persisted until early Tertiary time (Meço and Aliaj 2000; Dilek et al. 2005).

Figure 15. Tectonic model for the formation and evolution of the Pindos Basin. See text for discussion. A and P in continental blocks refer to Apulia and Pelagonia, respectively. X and o refer to post-collisional strike-slip components of deformation within the Mesohellenic Trough and in the Pelagonian hinterland (x, away; o, towards). WPB, within-plate basalt.
Continued continental convergence between Apulia and Pelagonia caused underplating of the Apulian continental margin beneath the Pindos Basin during the latest Mesozoic–Early Palaeogene. The western half of the Mesohellenic ophiolite slab, the Pindos ophiolite, was then detached and thrust over the Apulian margin, tectonically accreting and overriding rift-related rocks and turbidite deposits along the western margin of the basin (Figure 15(f)). This sequence of events along the eastern margin of Apulia during the latest Cretaceous–Eocene developed the Avdella mélange.

Throughout the early Cenozoic, Pelagonia and Apulia underwent oblique continental collision, creating regional E–W crustal-shortening and broad-dextral deformation in a NW–SE-trending zone in the Pelagonian hinterland (Dilek et al. 2005). As the Pindos basin contracted due to this collision and the Pindos ophiolite overrode the Apulian continental margin, west-directed thrust faults propagated through the Apulian carbonate platform (Figure 15(g)), flysch deposits accumulated within foreland-migrating flexural basins, and thin-skinned thrust packages developed over the Apulian basement during the Eocene–Oligocene. The remnant Pindos Basin gradually transitioned from a marine-dominated environment to a coastal, deltaic, and finally terrestrial alluvial depocentre – the Mesohellenic Trough. The Mesohellenic Trough was bounded and compartmentalized by oblique-slip normal faults that created sub-basins, which were subsequently filled by Miocene–Pliocene sediments (Figure 15(g); Vamvaka et al. 2006).

Conclusions

The Triassic–Jurassic Vourinos subophiolitic mélange consists of passive margin units and rift assemblages that formed prior to the onset of seafloor spreading in the Pindos Basin. The phyllitic matrix of the ANF was originally deposited as a pebbly mudstone and sandstone on the continental rise setting of the rifted Pelagonian margin, and was then deformed and metamorphosed during ophiolite emplacement. Clasts and blocks supported by the phyllitic matrix were mostly derived from the crystalline basement of the Pelagonian microcontinent. Igneous rocks of the rift assemblage are locally intrusive into the recrystallized limestone and metapelites of the Pelagonian margin and have WPB to MORB compositions. Original igneous and sedimentary contacts are well preserved in the rift assemblage. The continental rise deposits and the rift assemblages were imbricated along east-directed thrust sheets during the emplacement of the Vourinos ophiolite onto the Pelagonian margin in the Middle–Late Jurassic. The internal structure and the evolutionary history of the Vourinos mélange represent a tectonic mélange character. The Triassic–Cretaceous Avdella mélange beneath the Pindos ophiolite to the west has a longer, polyphase history of development, and can be described as a block-in-matrix, polygenetic mélange, whose evolution involved both sedimentary and tectonic processes.

The shear sense indicators in the mélange units, the lower structural sections of the Vourinos ophiolite, and the Pelagonian continental margin rocks consistently show top-to-the-ENE shearing associated with the ENE tectonic transport during the initial stages of closure of the Pindos Basin. This tectonic phase was marked by ophiolite emplacement. These structural observations, coupled with the existence of the parautochthonous igneous and sedimentary rift units along the western margin of Pelagonia, rule out those interpretations and models suggesting the westward tectonic transport of the Vourinos ophiolite and its subophiolitic mélange from the Vardar Zone to the east of Pelagonia. The Pindos ophiolite and the Avdella mélange beneath it were displaced westwards and emplaced onto the pre-Apulian platform carbonates as a result of the oblique collision between Eurasia and Apulia later in the Eocene.
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