Available online at www.sciencedirect.com

ScienceDirect

Gondwana Research 11 (2007) 453–475

www.elsevier.com/locate/gr

GR Focus

Suprasubduction zone ophiolite formation along the periphery of Mesozoic Gondwana

Yildirim Dilek [a,*], Harald Furnes [b], Minella Shallo [c]

[a] *Department of Geology, Miami University, Oxford, OH 45056, USA*
[b] *Centre of Geobiology & Department of Earth Science, University of Bergen, 5007 Bergen, Norway*
[c] *Fakulteti i Gjeologjise dhe Minierave, Universiteti Politeknik, Tirana, Albania*

Received 23 December 2006; received in revised form 19 January 2007; accepted 19 January 2007

Abstract

Neotethyan suprasubduction zone ophiolites represent anomalous oceanic crust developed in older host basins during trench rollback cycles and later entrapped in orogenic belts as a result first of trench-passive margin and then continent–continent collisions. The Middle Jurassic Mirdita zone ophiolites in northern Albania constitute a critical transition between the dominantly mid-ocean ridge basalt (MORB)-related Early Jurassic Alpine–Apennine ophiolites in the west and supra-subduction zone (SSZ)-generated Cretaceous Eastern Mediterranean ophiolites in the east. The previously recognized Western- and Eastern-type ophiolites in the Mirdita zone display significant differences in their internal structure and pseudostratigraphy, but their geochemical affinities are more gradational in contrast to the earlier claims that these ophiolites may have formed in different tectonic settings at different times. Crosscutting relations of dike intrusions in the Eastern-type ophiolites indicate changes in the chemistry of magmatic plumbing systems from basaltic to andesitic, dacitic, rhyodacitic, and boninitic compositions through time and from west to east. The chemostratigraphy of the extrusive sequence in the Western-type ophiolites shows that the MORB-like tholeiitic rocks display a significant decrease in their TiO_2 contents and Zr concentrations stratigraphically upward, although their $\varepsilon_{Nd(T)}$ values (+7.3 to +6.9) show minor variation. The basaltic andesites in the upper 100 m of the Western extrusive sequence have island arc tholeiite (IAT)-like chemical characteristics (low-Ti, lower HFSE and HREE distribution, significant LREE depletion and higher Co, Ni, and Cr contents) that signify increased subduction influence in magma/melt evolution. The Eastern-type extrusive rocks range in composition from basaltic andesite to andesite, dacite and rhyodacite stratigraphically upward mimicking the temporal changes in the sheeted dikes, and they display constant Zr (~ 50 ppm) but significantly varying Cr contents. The TiO_2 contents of their pyroxenes are <0.3 wt.%, and their $\varepsilon_{Nd(T)}$ values decrease from +6.5 in the lower parts to ~ +3.1 in the uppermost section of the sequence. Farther east in the extrusive sequence the youngest boninitic lavas and dikes have $\varepsilon_{Nd(T)}$ values between −1.4 and −4.0. These chemical variations through time point to a mantle source increasingly contaminated by subduction-derived aqueous fluids and sediments, which were incorporated into the melt column beneath an extending protoarc–forearc region. Slab retreat and sinking played a major role in establishing asthenospheric upwelling and corner flow beneath the forearc mantle that in turn facilitated shallow partial melting of highly depleted harzburgitic peridotites, producing boninitic magmas. This chemical progression in the Mirdita zone ophiolite volcanism is similar to the temporal variations in magma chemistry documented from very young intraoceanic arcs built on recently generated backarc crust (i.e., South Sandwich arc). The Western and Eastern-type ophiolites in the Mirdita zone are therefore all subduction-related with the subduction zone influence in the lavas increasing stratigraphically upward as well as eastwards, suggesting a west-dipping slab geometry. The Mirdita zone and the Western Hellenic ophiolites in the Balkans were produced within a marginal basin that had evolved between the Apulian and Pelagonian microcontinents, and were subsequently emplaced onto their passive margins diachronously through different collisional processes.

Keywords: Albanian ophiolites; Jurassic oceanic crust; Suprasubduction zone ophiolites; Slab rollback; Chemostratigraphy of extrusive sequences; Neotethys and Gondwana; Boninites; MORB to SSZ transition

---

* Corresponding author. Tel.: +1 513 529 2212; fax: +1 513 529 1542.
E-mail address: dileky@muohio.edu (Y. Dilek).

doi:10.1016/j.gr.2007.01.005

Contents

---

1. Introduction

The Mesozoic peri-Gondwanan ophiolites exposed in the Alpine–Himalayan orogenic belt show an age progression from the Jurassic in the west to the Cretaceous in the east and display structural, geochemical, geochronological, and tectonic evidence for the rift, drift, seafloor spreading, and convergent margin evolution of a series of ocean basins, developed after the breakup of Pangea (Sengör et al., 1984; Robertson et al., 1996; Pamic et al., 2002; Dilek and Flower, 2003; Stampfli and Borel, 2004; Bortolotti and Principi, 2005; Dilek et al., 2005). These ocean basins are inferred to have evolved between Gondwana-derived continental fragments within a larger Neotethyan realm and to have been closed as a result of terminal collisions of the bounding continents (Dewey et al., 1973; Robertson and Dixon, 1984; Dilek and Moores, 1990). The remnants of these ancient basins are represented by Triassic volcanosedimentary units having within-plate alkaline basalt (WPB) to transitional and mid-ocean ridge basalt (MORB) chemical affinities (Pamic, 1984; Dilek and Rowland, 1993; Pe-Piper, 1998; Saccani et al., 2003) and Jurassic–Cretaceous ophiolites showing MORB to calc-alkaline island arc geochemical fingerprints (Capedri et al., 1980; Robinson et al., 1983; Dilek and Thy, 1998; Dilek et al., 1999; Parlak et al., 2000; Al-Ryami et al., 2002; Bortolotti et al., 2002; Saccani and Photiades, 2004). The Jurassic ophiolites in the Alpine–Apennine mountain belt in the west (Fig. 1) commonly display MORB geochemistry (Hébert et al., 1989; Tribuzio et al., 1999; Rampone and Piccardo, 2000), whereas the Late Jurassic–Cretaceous ophiolites in the Tauride–Pontide (Turkey), Zagros (Iran), and Himalayan mountain belts to the east show geochemical affinities characteristic of suprasubduction zone (SSZ) environments (Pearce et al., 1981, 1984; Arvin, 1990; Robinson and Malpas, 1990; Dilek et al., 1999; Hassanipak and Ghazi, 2000; Hébert et al., 2003; Malpas et al., 2003; Parlak et al., 2006). Some of these SSZ ophiolites are spatially and temporally associated with mature magmatic arc sequences indicating their proximity to Andean-type convergent plate margins during their late-stage evolution (i.e., SE Anatolian orogenic system in Turkey, Dilek and Flower, 2003; Parlak et al., 2006; Ladakh and Kohistan in the Himalayas, Srikantia and Razdan, 1980; Sullivan et al., 1993).

The Middle Jurassic ophiolites in the Dinaride–Hellenide mountain belt in the Balkan Peninsula constitute a geographic, geochronologic, and tectonic transition between the Alpine–Apennine and the Anatolian ophiolites. These NNW–SSE-trending ophiolites form a bridge between the ~ E–W-running subparallel ophiolite belts of the Alpine and Anatolian mountain systems (Fig. 1) that have crystallization ages of their intrusive suites ranging from the Late Triassic–Early Jurassic (~ 212–185 Ma, Rampone and Piccardo, 2000, and references therein) to the Late Cretaceous (~ 95–92 Ma for the Tauride ophiolites, Parlak et al., 1996; Okay et al., 1996; Dilek et al., 1999; Onen, 2003), respectively. The Middle Jurassic ophiolites in the Dinaride–Hellenide mountain belt also display in their upper mantle peridotites and crustal units lateral and vertical gradations from MORB to SSZ geochemical affinities (Pamic et al., 2002, and references therein). Therefore, these ophiolites present an ideal laboratory to investigate the geochemical and geodynamic evolution of the Mesozoic peri-Gondwanan oceanic crust in a geographically and tectonically critical transition zone within the Neotethyan realm.

The purpose of this paper is to present a case study of the Middle Jurassic Mirdita ophiolites in Albania (MO in Fig. 1) and to document the mode and nature of the MORB to SSZ geochemical transition in the petrogenetic evolution of their magmas in a Neotethyan marginal basin. We use our new chemostratigraphic data and observations from the extrusive sequences in the Mirdita ophiolites to demonstrate this geochemical transition and its petrogenetic significance. We then discuss the implications of our petrogenetic model for the geodynamic evolution of the Mirdita ophiolites, their coeval counterparts in the Balkan Peninsula, and the restricted marginal basins that developed in the aftermath of the dismantling of the northern edge of western Gondwana. The well-constrained tectonic evolution of the bounding continental fragments (Apulia to the west and Pelagonia to the east), which were rifted off from Gondwana in the Permo-Triassic (Dewey et al., 1973; Stampfli et al., 1991, 2001; Stampfli and Borel, 2004), and the lack of pronounced Alpine deformational and thermal overprint on ophiolitic and continental margin rocks permit us to construct the Mesozoic–early Cenozoic paleogeography of this basin reasonably well. The results of this study and our interpretations are also important for better understanding of temporal and chemical variations in volcanism across infant arc systems, and hence changes in mantle character and dynamics through short time spans above subducting slabs.

2. Ophiolite geology of the Balkan Peninsula

The NNW-trending Neotethyan ophiolites in the Balkan Peninsula occur in two distinct zones bounding the Pelagonian ribbon continent (Fig. 2). 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). Although most of the Vardar Zone ophiolites are highly disrupted and dismembered lacking a coherent ophiolite pseudostratigraphy, some (i.e., Guevgueli, Sithonia) contain sheeted dike complexes suggesting seafloor spreading dynamics during their crustal generation. The geochemistry of their ophiolitic subunits encompasses both MORB and island arc tholeiite (IAT) compositions with local occurrences of boninite (i.e., Evros ophiolite; Bébien et al., 1986; Magganas, 2002).

The Vardar Zone ophiolites separate the Pelagonian microcontinent from the Serbo-Macedonian Zone to the east, which represents the Jurassic–Early Cretaceous active margin of Eurasia (Fig. 2). Middle Jurassic calc-alkaline plutons and extrusive rocks (Chortiatis unit) in the western edge of the Serbo-Macedonian Zone constitute a magmatic arc developed along the southern margin of Eurasia (Schunemann, 1985; Mussallam and Jung, 1986). The Paikon volcanic complex west of both the Chortiatis unit and the Guevgueli ophiolite is interpreted to have developed as a volcanic arc fringing this active margin in the mid to Late Jurassic (De Wet et al., 1989; Bébien et al., 1994; Brown and Robertson, 2004). The active margin tectonics in the eastern part of the Vardar Zone was a result of the subduction of the Vardar Zone ocean floor northeastwards (in present coordinate system) beneath Eurasia during much of the Middle Jurassic through Early Cretaceous. While an active margin tectonics dominated the geodynamic evolution of the eastern part of the Vardar Zone during this time, a passive margin evolution persisted adjacent to Pelagonia to the west following the Triassic rifting episode (Robertson, 2002; Sharp and Robertson, 2006).

The Neotethyan ophiolites to the west of the Pelagonian microcontinent are nearly coeval or slightly older than the ones in the Vardar Zone and are spatially associated with Triassic–Jurassic volcano-sedimentary units and mélanges (Smith, 1993; Robertson and Karamata, 1994; Saccani and Photiades, 2005; Bortolotti et al., 2005). The Western Hellenic ophiolites in Greece and Albania, the Mirdita ophiolites in northern Albania and their northward continuation into Kosovo and Serbia, and the Dinaric ophiolites in Bosnia and Croatia collectively form

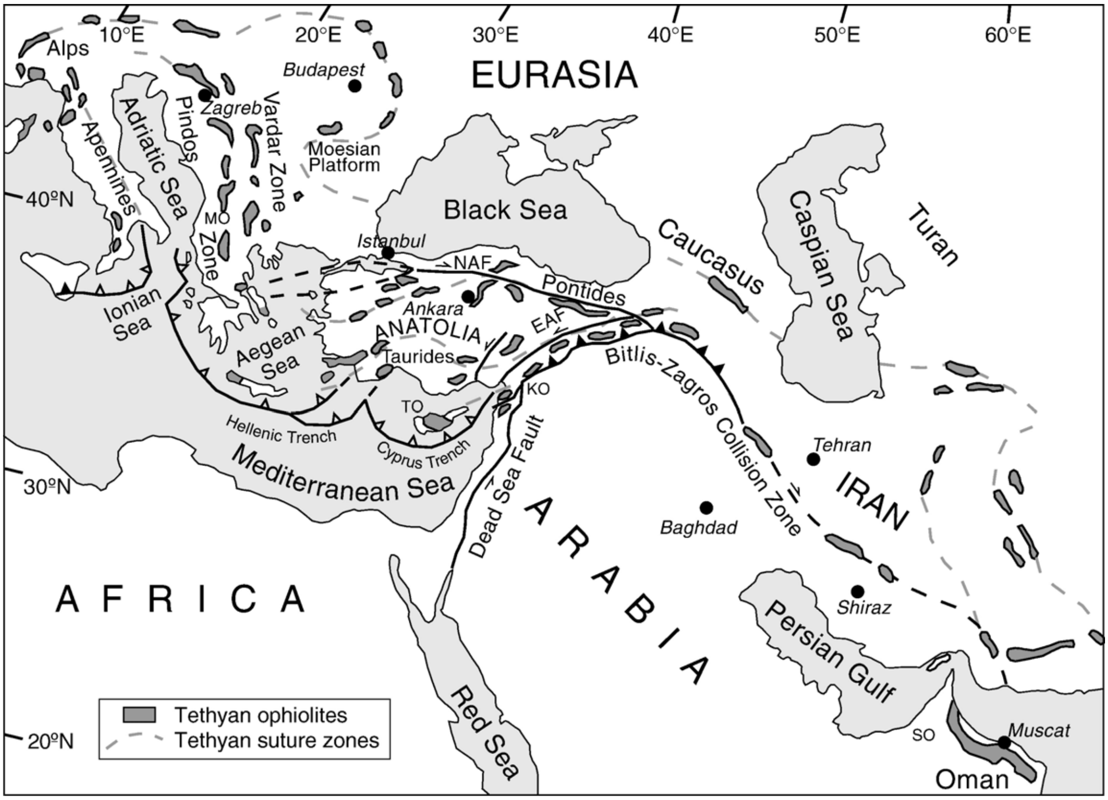


Fig. 1. Simplified tectonic map of the eastern Mediterranean region showing the distribution of the Neotethyan ophiolites and suture zones. Key to lettering: MO — Mirdita ophiolites, KO — Kizildag ophiolite, SO — Semail ophiolite, TO — Troodos ophiolite.

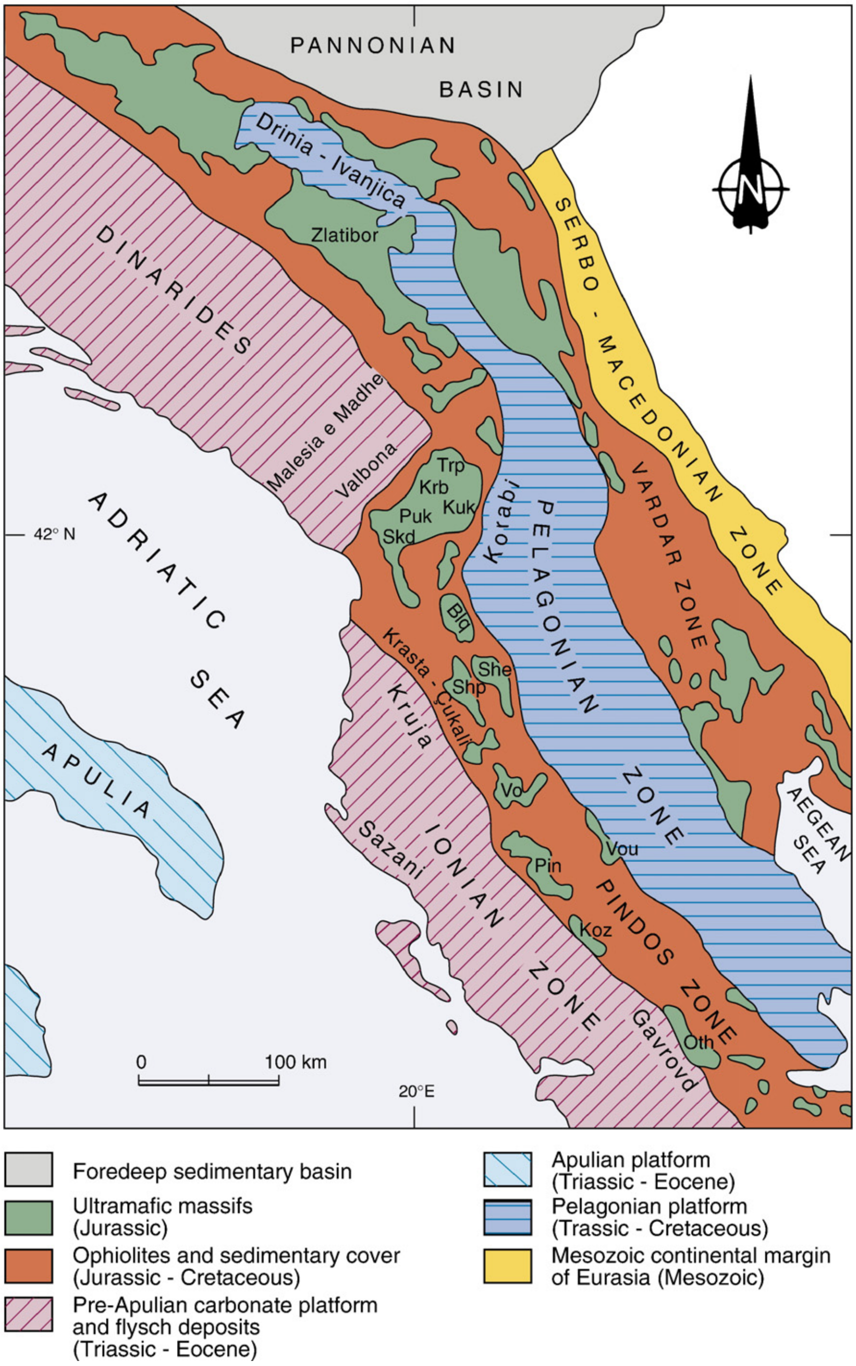


Fig. 2. Simplified geological map of the west-central Balkan Peninsula, showing major tectonic zones and ophiolite occurrences. Key to lettering for different Jurassic ophiolites in the region (from north to south): Trp — Tropoja, Krb — Krrabi, Kuk — Kukesi, Puk — Puke, Skd — Skenderbeu, Blq — Bulqize, Shp — Shpati, She — Shebenik, Vo — Voskopoja, Pin — Pindos, Vou — Vourinos, Koz — Koziakas, Oth — Othris.

the Pindos Zone ophiolites in the Balkan Peninsula. These ophiolites show bidivergent emplacement onto Pelagonia in the east and Apulia in the west (Fig. 2). Similar to their counterparts in the Vardar Zone, they also display geochemical affinities ranging from MORB, IAT, to boninitic compositions (Beccaluva et al., 1984; Shallo et al., 1990; Jones et al., 1991; Bébien et al., 1998; Clift and Dixon, 1998; Pe-Piper and Piper, 2002; Dilek and Flower, 2003), indicating subduction zone involvement in their geodynamic evolution.

One of the characteristic features of the ophiolites in the Pindos Zone is the occurrence of rather large peridotite massifs overlain directly by various oceanic crustal units, unlike an ideal Penrose-type ophiolite pseudostratigraphy. These peridotites range in composition from spinel lherzolites and plagioclase-spinel lherzolites (i.e., Zlatibor and Sjenicki Ozren in the Dinaric belt, Skenderbeu and Puke in the Mirdita zone) to spinel harzburgites (Kukse and Bulqize in the Mirdita zone) that appear to concentrate in the western and eastern parts of the

Pindos Zone, respectively (Menzies and Allen, 1974; Jackson et al., 1975; Pamic, 1983; Rassios and Smith, 2000; Shallo and Dilek, 2003; Bazylev et al., 2003, 2006). Bazylev et al. (2003, 2006) have argued based on their petrological data and modelling that spinel lherzolites in the Dinaric ophiolites are similar to orogenic lherzolites of subcontinental lithospheric mantle, and that there is a continuous transition from lherzolites with varying degrees of depletion to harzburgites that show mineralogical and textural evidence for refertilization by percolating melts. They have suggested that these harzburgitic peridotites experienced partial melting and refertilization in the presence of elevated water content in a suprasubduction zone setting. A subcontinental origin of lithospheric mantle peridotites has been documented for the Ligurian ophiolites in the Alpine–Apennine ophiolites farther west based on petrological, geochemical, and isotope data (Rampone and Piccardo, 2000; Müntener and Piccardo, 2003, and references therein).

The root zones of the Pindos and Vardar Zone ophiolites and their possible genetic relations have been a source of debate in the discussions of the 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). These interpretations imply that the Pelagonian Zone represents a lower crustal unit exhumed from beneath a >15 km thick ophiolitic tectonic cover, analogous to the metamorphic core complexes in the Aegean region farther south, 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; Saccani and Photiades, 2005). We discuss and evaluate these two alternative models for the origin of the Pindos Zone ophiolites later in the paper.

3. Structure of the Mirdita ophiolites

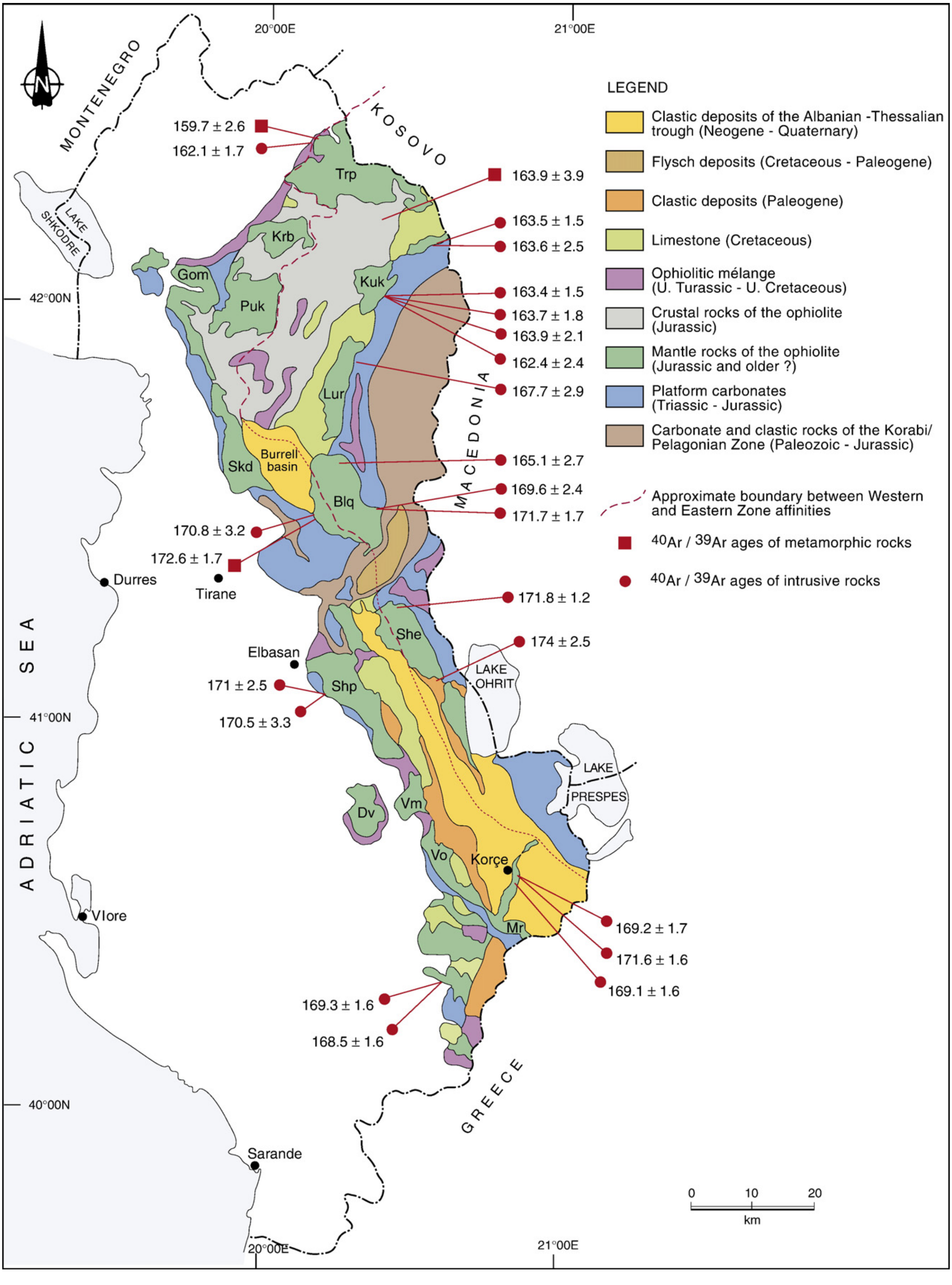
The Pindos Zone ophiolites in southern Albania occur in a NW-trending belt, which makes a sharp 90° turn into a short NE-trending segment in northern Albania before it joins the NW-oriented Dinaric ophiolite belt (Fig. 2). This NE-trending short segment is known as the Mirdita zone in the literature and also corresponds to the Shkoder-Peç lineament on the tectonic map of Albania (Robertson and Shallo, 2000; Bortolotti et al., 2005). This lineament and the Mirdita zone ophiolites sharply truncate the pre-Apulian carbonate platform and flysch deposits in the Dinarides (Malesia e Madhe and Valbona) on the west and the northeasterly turn at the edge of the Korabi–Pelagonian platform carbonates on the east (Fig. 2). Some researchers have suggested that the NE-trending Mirdita zone may represent a paleo-oceanic transform fault zone within the Pindos basin (Robertson and Shallo, 2000).

3.1. South Albanian ophiolites

The Albanian ophiolites south of the Mirdita zone consist mainly of upper mantle peridotites intruded by gabbroic, troctolitic, and basaltic dikes, and overlain by cumulate gabbros (Bébien et al., 1998; Hoeck et al., 2002; Shallo and Dilek, 2003; Dilek et al., 2005). Sheeted dikes are absent in these ophiolites, and gabbros and troctolites are directly overlain in places by basalts and volcanic breccias that are intercalated with, and covered by, sedimentary breccias and conglomerates (Hoeck et al., 2002). Individual ophiolite massifs in this NW-trending belt are commonly several km thick, and are unconformably overlain by Neogene–Quaternary clastic rocks of the Mesohellenic or Albanian–Thessalian trough (i.e., Burrell basin, Korçe basin). Discontinuous exposures of metamorphic rocks, composed of amphibolite, actinolite–chlorite–epidote schist, micaschist, and marble occur along the western and eastern edges of this belt, and they commonly rest on subophiolitic mélanges beneath the ophiolites and/or on serpentinized peridotites (i.e., Boboshtica metamorphics in the Voskopoja peridotite massif and in the Shebenik massif). Commonly several hundred meters in thickness, these metamorphic units have been interpreted by many researchers as metamorphic soles beneath the Albanian ophiolites (Collaku et al., 1991; Bortolotti et al., 1996; Carosi et al., 1996; Vergély et al., 1998; Robertson and Shallo, 2000; Dimo-Lahitte et al., 2001), recording P–T conditions of metamorphism up to 860°–750 °C and 9–19 kbar during their formation at the inception of subduction (Vergély et al., 1998; Dimo-Lahitte et al., 2001). The ^{40}Ar/^{39}Ar ages obtained from the amphibolites in these metamorphic units range from 174 Ma to 165 Ma and are generally older (by ~ 14 m.y.) than their counterparts in the Mirdita zone farther north (Dimo-Lahitte et al., 2001).

3.2. Mirdita zone ophiolites

The ophiolites in the Mirdita zone occur in a ~ 30–40-km-wide belt bounded by the conjugate passive margin sequences of Apulia and Korabi–Pelagonia on the west and the east (Fig. 3; Dilek et al., 2005). The western and eastern parts of this ophiolite belt are occupied by peridotite massifs representing the upper mantle units. The massifs adjacent to the Apulian margin sequences in the west (i.e., Krabbi, Gomsiqe, Skenderbeu) are composed mainly of lherzolites–plagioclase lherzolites, whereas those close to Pelagonia in the east (i.e., Tropoja, Kukesi, Lura) are made of harzburgites with major chromite deposits (Hoxha and Boullier, 1995; Nicolas et al., 1999). The Western lherzolites show a widespread mylonitic fabric caused by low-temperature (~ 1000–800 °C) plastic deformation in lithospheric conditions and spatially associated with melt impregnation patches (Nicolas et al., 1999). These upper mantle rocks are overlain by plastically deformed flaser gabbros. Isotropic gabbros and sheeted dikes are rare to absent in the crustal sections, and the mylonitic peridotites and deformed gabbros are locally directly overlain by basaltic lavas and intruded by diabasic dikes and sills. Nicolas et al. (1999) have reported that the Western lherzolitic peridotites give way into tectonized harzburgites a few km below the lower crustal gabbros.


20°00E
21°00E
N
MONTENEGRO
KOSOVO
MACEDONIA
GREECE
ADRIATIC SEA
LAKE SHKODRE
LAKE OHRIT
LAKE PRESPES
42°00N
41°00N
40°00N
Trp
Krb
Gom
Puk
Kuk
Lur
Burrell basin
Skd
Blq
She
Shp
Dv
Vm
Vo
Korçe
Mr
Durres
Tirane
Elbasan
Vlore
Sarande
159.7 ± 2.6
162.1 ± 1.7
163.9 ± 3.9
163.5 ± 1.5
163.6 ± 2.5
163.4 ± 1.5
163.7 ± 1.8
163.9 ± 2.1
162.4 ± 2.4
167.7 ± 2.9
165.1 ± 2.7
169.6 ± 2.4
171.7 ± 1.7
170.8 ± 3.2
172.6 ± 1.7
171.8 ± 1.2
174 ± 2.5
171 ± 2.5
170.5 ± 3.3
169.2 ± 1.7
171.6 ± 1.6
169.1 ± 1.6
169.3 ± 1.6
168.5 ± 1.6
LEGEND
Clastic deposits of the Albanian -Thessalian trough (Neogene - Quaternary)
Flysch deposits (Cretaceous - Paleogene)
Clastic deposits (Paleogene)
Limestone (Cretaceous)
Ophiolitic mélange (U. Turassic - U. Cretaceous)
Crustal rocks of the ophiolite (Jurassic)
Mantle rocks of the ophiolite (Jurassic and older ?)
Platform carbonates (Triassic - Jurassic)
Carbonate and clastic rocks of the Korabi/ Pelagonian Zone (Paleozoic - Jurassic)
Approximate boundary between Western and Eastern Zone affinities
40Ar / 39Ar ages of metamorphic rocks
40Ar / 39Ar ages of intrusive rocks
0 10 20
km

Based on the differences between the upper mantle peridotites and the internal stratigraphy and chemical compositions of the crustal units, previous studies have recognized the existence of two types of ophiolites in the Mirdita zone (Shallo et al., 1985; Shallo, 1990b; Shallo et al., 1990; Beccaluva et al., 1994; Bortolotti et al., 1996; Bébien et al., 1998; Nicolas et al., 1999; Shallo and Dilek, 2003). The Western-type ophiolites have much thinner crustal sections (~ few km) and show mainly MORB affinities, whereas the Eastern-type ophiolites may reach up to 10–12 km in thickness and show predominantly SSZ geochemical affinities. The boundary between these two types is not well defined because it is an irregular contact (Fig. 3) with the Eastern-type plutonic and hypabyssal rocks being intrusive into the Western-type peridotites and gabbros. However, locally the Eastern-type ophiolitic subunits are juxtaposed tectonically against the Western-type peridotites and gabbros along west-directed, Late Cenozoic reverse and thrust faults (Dilek et al., 2005).

The Western-type ophiolites contain upper mantle peridotites, mafic–ultramafic cumulates and mylonitic gabbros, sparse sheeted dikes, and extrusive rocks that collectively form a ~ 3-km-thick composite sequence. The peridotites include lherzolite–harzburgite, plagioclase lherzolite, plagioclase dunite, and rare amphibole peridotites (olivine hornblendite). The plutonic sequence, which is locally intrusive into and/or overlying the peridotites, consists of olivine gabbro, troctolite, ferrogabbro, gabbro, and rare amphibole gabbro and generally displays an ol-pl-px crystallization order (Beccaluva et al., 1994). Stratiform titanomagnetite deposits and small vein-type Cu–Fe–quartz sulfide ore bodies are locally seen in the gabbroic rocks. Extrusive rocks, composed mainly of massive to pillow lavas and hyaloclastites, form a nearly 600-m-thick sequence and rest directly on serpentinized peridotites and gabbroic rocks along igneous contacts (Dilek et al., 2005; Figs. 4 and 5). These primary contact relations suggest that the lavas were erupted directly on the upper mantle peridotites and lower crustal rocks already exposed on the seafloor. Isolated dikes crosscut these extrusive rocks and feed into different lava flows. These features of the Western-type ophiolites are similar to those reported from slow-spreading modern oceanic lithosphere (Cannat and Casey, 1995, and references therein) and its ancient analogues (Dilek and Eddy, 1992; Alexander and Harper, 1992; Dilek and Thy, 1998; Nicolas et al., 1999; Tribuzio et al., 2000; Müntener and Piccardo, 2003). Normal faults truncate and displace these dikes and discrete lava flows for as much as several meters and are spatially associated with quartz and epidote mineralization (Banerjee et al., 2002; Dilek et al., 2005). Pillow lavas are stratigraphically overlain by 5- to 20-m-thick radiolarian cherts that are late Bajocian–early Bathonian to late Bathonian–early Callovian in age (Marcucci et al., 1994; Marcucci and Prela, 1996).

The Eastern-type ophiolites in the Mirdita Zone commonly include all subunits of a typical Penrose-type ophiolite pseudostratigraphy (Fig. 5) with thicknesses up to 10–12 km (Shallo and Dilek, 2003, and references therein). The peridotite massifs of this type (Tropoja, Kukesi, Lura) are composed of harzburgite tectonite, harzburgite–dunite interlayers, and dunite with extensive chromite deposits. The harzburgites are composed of olivine (~ 80% forsterite), orthopyroxene (~ 17% enstatite), clinopyroxene (<3% diopside), and spinel (~ 2%) (Hoxha and Boullier, 1995). Dunites are massive and composed of olivine, chrome spinel, orthopyroxene, and interstitial clinopyroxene. The chromite lenses and bands within the dunites are intensely folded and displaced along extensional shear zones (Hoxha and Boullier, 1995). The massive dunite in the upper part of the peridotite section is transitional upward into ultramafic cumulates, which consist of olivine clinopyroxenite, wehrlite, olivine websterite, and dunite. This ultramafic cumulate section, which is 0.5 to <2 km-thick, forms a transitional Moho reminiscent of that in the Semail ophiolite (Oman) and the fast-spreading modern oceanic lithosphere (Dilek and Eddy, 1992; Nicolas et al., 1999). The plutonic section in the Eastern-type ophiolites comprises pyroxenite, gabbronorite, gabbro, amphibole gabbro, diorite, quartz diorite, and plagiogranite intrusions. Harzburgite–wehrlite intrusions crosscut the lower crustal rocks in both the Eastern- and Western-type ophiolites (Dilek et al., 2005). The sheeted dikes have mutually intrusive relations with isotropic gabbros, plagiogranites, and quartz diorites, and feed into the overlying pillow lavas.

Sheeted dikes are generally moderately to steeply dipping (~ 80°–60°; Fig. 6A), except in places where they have been rotated into more gentle dips (40°–30°) along low-angle normal faults. They are extensively mineralized along these faults and around the late-stage quartz diorite intrusions that are widespread throughout the Eastern-type ophiolites (Figs. 4 and 6B). Dike swarms locally intrude the overlying lava flows causing hydrothermal alteration and mineralization (epidosite and pyrite) in their volcanic host rocks (Fig. 7A). Hydrothermal brecciation and accompanying mineralization are also common along these dike swarms in the extrusive rocks. Epidote, quartz, and pyrite–chalcopyrite mineralization and hydrothermal alteration are common in the sheeted dike rocks hosting these quartz diorite intrusions (Fig. 6B). Both the sheeted dikes and quartz diorites are oriented NNE, parallel to the main trend of the Mirdita Zone (Fig. 4).

Crosscutting relations within the sheeted dike complex reveal several distinct generations of dike formation with different orientations and compositions (Fig. 7B). Diabasic (basaltic) dikes constitute nearly 45% of the sheeted dike complex and represent the earliest dike generation. These dikes are cut by dike-parallel normal faults, which display brecciation and epidosite mineralization (Fig. 7B). Basaltic andesite, andesite, dacite, and quartz diorite–dacite dike swarms are intrusive into these earlier basaltic dikes and are cut by and

Fig. 3. Geological map of the Albanian ophiolites and the surrounding tectonic units. Modified from Dilek et al. (2005). Dashed line depicts the approximate boundary between the Western- and Eastern-type ophiolites, based mainly on the changes in the chemical affinities of the crustal and upper mantle rocks from MORB to SSZ (respectively). ^{40}Ar/^{39}Ar ages (in Ma) of intrusive and metamorphic rocks are from Vergély et al. (1998) and Dimo-Lahitte et al. (2001). Key to lettering for different peridotite massifs (from north to south): Trp — Tropoja, Krb — Krrabi, Gom — Gomsiqe, Puk — Puke, Kuk — Kukesi, Lur — Lure, Skd — Skenderbeu, Blq — Bulqize, She — Shebenik, Shp — Shpati, Dv — Devolli, Vm — Vallamara, Vo — Voskopoja, Mr — Morava.

rotated along normal faults with similar orientations to those in the diabasic dike complex. Younger andesitic to quartz-microdioritic dikes with more easterly orientations crosscut all these earlier dike generations. Late-stage, ENE-striking, steeply dipping boninitic dikes intrude into the pre-existing dike swarms in the eastern part of the sheeted dike complex and are in turn cut and offset by generally E-dipping normal faults (Fig. 7B). These intrusive relations indicate in general a significant change in magma compositions and in the extensional stress regime such that more evolved and highly depleted dike compositions appear to dominate the latest-stage plumbing system beneath the oceanic spreading center. The direction of extension also seems to have rotated from WNW–ESE to NNW–SSE through time during the construction of the Mirdita oceanic crust.

The extrusive sequence in the Eastern-type ophiolites is nearly 1.1 km thick and consists of pillowed to massive sheet flows ranging in composition from basalt and basaltic andesite to andesite, dacite, and rhyodacite in the upper part (Shallo et al., 1987; Shallo, 1990b; Beccaluva et al., 1994; Bortolotti et al., 1996, 2002; Shallo and Dilek, 2003; Saccani et al., 2004). Rare boninitic dikes and lavas in the easternmost parts of the Mirdita zone crosscut and/or overlie the earlier-formed extrusive rocks, indicating that they represent the latest magmatic products in

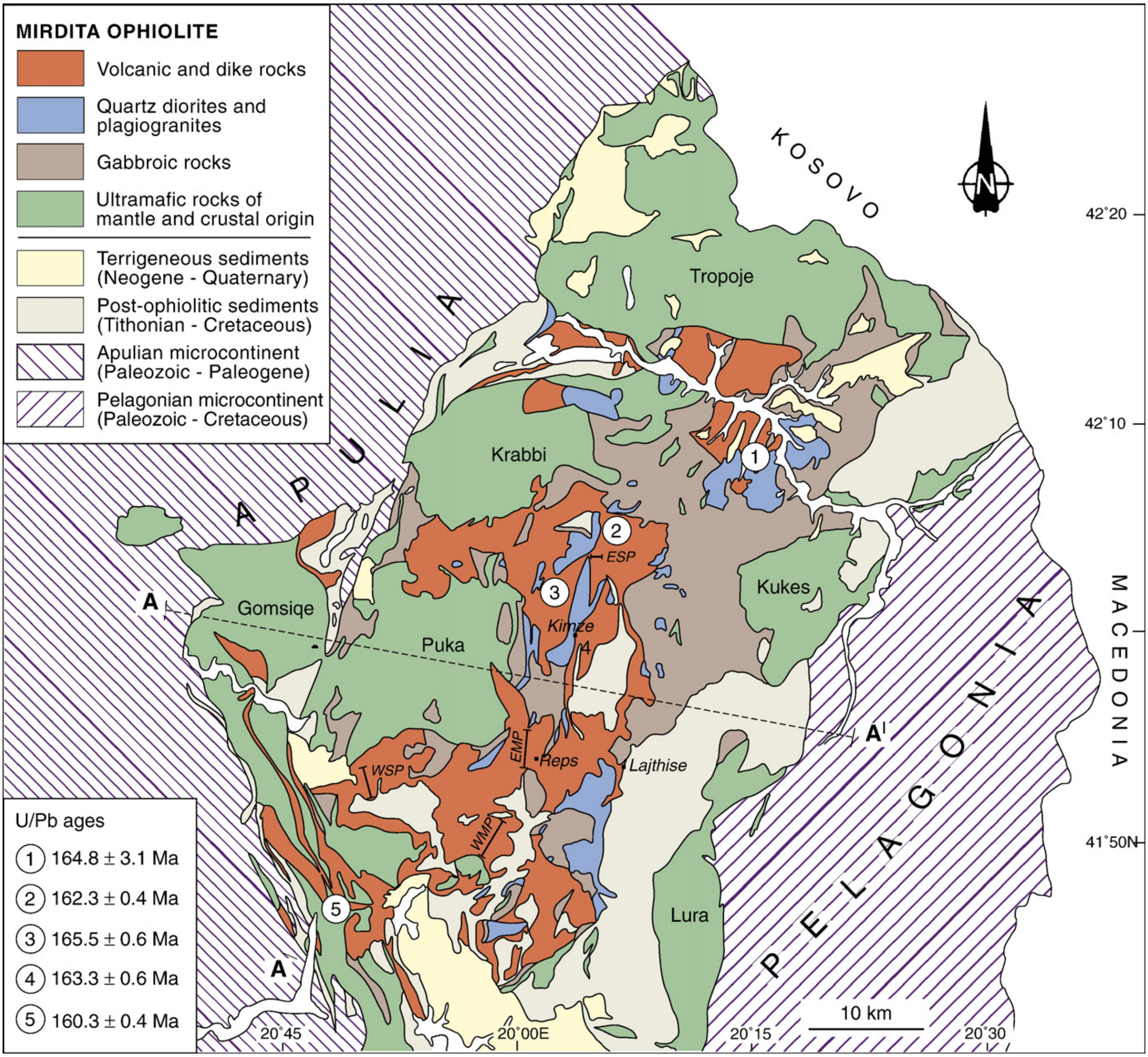


Fig. 4. Geological map of the Mirdita Zone in northern Albania. A–A′ depicts the profile line for the structural cross-section shown in Fig. 5 (modified from ISPGJ-IGJN, 1983, Geological Map of Albania, scale 1:200,000). WMP and EMP represent the western and eastern main profile lines followed during our chemostratigraphic sampling. WSP and ESP refer to western and eastern subprofiles, along which additional systematic sampling of the extrusive and dike rocks was done.

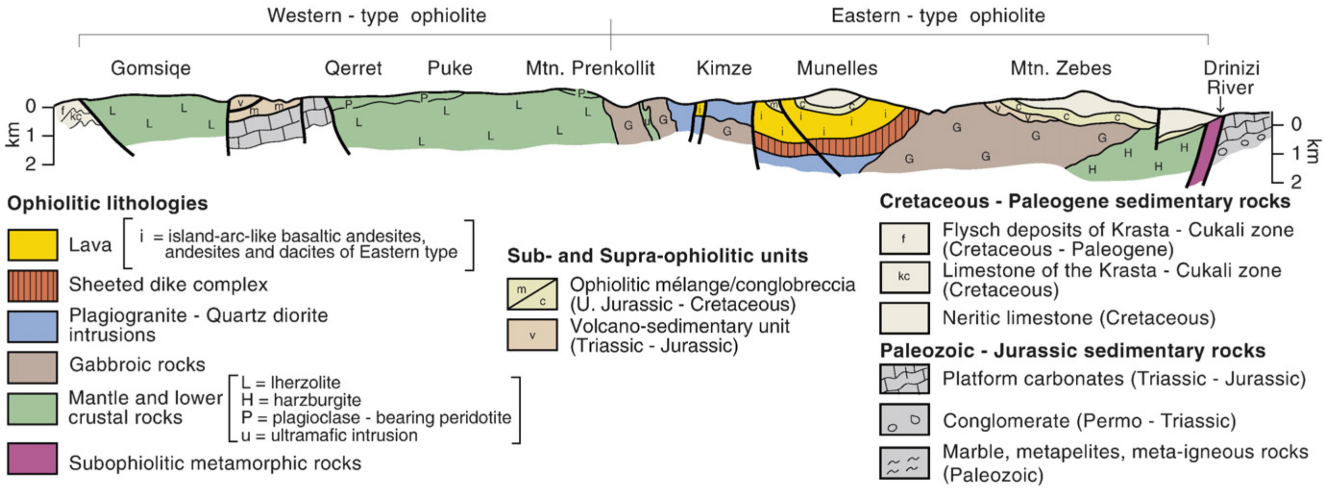


Fig. 5. Structural cross-section across the Mirdita Zone ophiolites and the Apulian and Pelagonian continental margin units. No vertical exaggeration.

crustal accretion of the Eastern-type ophiolites (Dilek et al., 2005). The upper Bathonian–Oxfordian radiolarian cherts stratigraphically overlie the extrusive sequence of the Eastern-type ophiolites (Marcucci et al., 1994; Chiari et al., 1994; Marcucci and Prela, 1996).

4. Geochemical variations in the Mirdita zone ophiolites

4.1. Geochemistry

Extrusive rocks in the Western-type ophiolites consist mainly of high-Ti basalts with MORB affinities (Beccaluva et al., 1994), consistent with the crystallization order and strong Fe–Ti enrichment of the plutonic rocks. The lavas are characterized by a relatively high TiO_2 content (>1.3 wt.%) and Ti/V ratios (24–41), and exhibit relatively abundant high field strength element (HFSE) concentrations (HFSE to N-MORB ratio ~ 1 to 5); their significant light REE (LREE) depletion and 20 to 50 times chondritic abundances for heavy REE (HREE) are typical of N-MORB compositions of Sun and McDonough (1989) (Bortolotti et al., 1996; Bortolotti et al., 2002; Saccani et al., 2004; Beccaluva et al., 2005; this study).

Stratigraphically and structurally upward and farther to the east, the Western-type extrusive rocks include medium-to low-Ti basalts that straddle the boundary between MORB and IAT (Ti/V = 20). These rocks have lower HFSE and HREE concentrations, greater LREE depletion ($La_N/Sm_N = 0.15$–0.28) and higher Co, Ni and Cr contents than the MORB lavas, indicating that they were likely derived from rather primitive magmas (Saccani et al., 2004).

Previous geochemical studies of the basaltic rocks in the Eastern-type ophiolites have shown that they have relatively low TiO_2 (0.3–0.8 wt.%) and low Ti/V ratios (10–20), and lower HFSE (ranging from 0.2 to 0.8; Bortolotti et al., 2002) and HREE contents compared to MORB values of Sun and McDonough (1989) (Saccani et al., 2004; Beccaluva et al., 2005). Low-Ti basaltic andesites higher in the sequence are only slightly depleted in LREE but significantly depleted in HREE (6 to 15 times chondritic abundances) relative to the MORB-like volcanic rocks in the Western-type ophiolites. Very low-Ti basalts and basaltic andesites show significant HFSE and REE depletion and U-shaped chondrite-normalized REE patterns, characteristic of high-Ca boninites (Bortolotti et al., 2002; Dilek and Flower, 2003; Saccani et al., 2004; Beccaluva et al., 2005). Collectively, the Eastern-type extrusive rocks display geochemical evidence for partial melting of progressively more refractory mantle source(s) and variable enrichment of these sources in the most incompatible elements (LREE and LFSE) from subduction-derived fluids (Dilek and Flower, 2003; Beccaluva et al., 2005). The latest-stage boninitic lavas and dikes represent magma compositions derived from higher degrees (up to 30%) of partial melting of a highly refractory harzburgitic source in the sub-arc and/or fore-arc mantle (Dilek and Flower, 2003; Beccaluva et al., 2005). The spatial and temporal relations of the MORB, IAT and boninitic rocks are, therefore, highly important to model the petrogenetic and tectonomagmatic evolution of the Mirdita Zone ophiolites within the geodynamic framework of the region.

4.2. Chemostratigraphy of the extrusive sequences

To better constrain the geochemical variations within and across the Mirdita Zone ophiolites, we undertook a systematic chemostratigraphic study of the extrusive sequences and dikes within the Western- and Eastern-type ophiolites. The majority of our analyzed samples were collected along two profiles, WMP and EMP for the Western and Eastern main profiles, respectively, shown on the geological map in Fig. 4. The volcanic rocks along the WMP consist mainly of pillow lavas with minor sheet flows and hyaloclastic breccias. The extrusive sequence along this profile is ~ 650 m thick and rests directly on serpentinized lherzolites and gabbroic rocks. The basaltic lavas that make up a large part of the sequence are non-amygdaloidal and dominantly aphyric or slightly phyric (~ 90% contain <2% phenocrysts). The pillow lavas in the upper 150 m of the WMP consist of slightly amygdaloidal basaltic andesites.

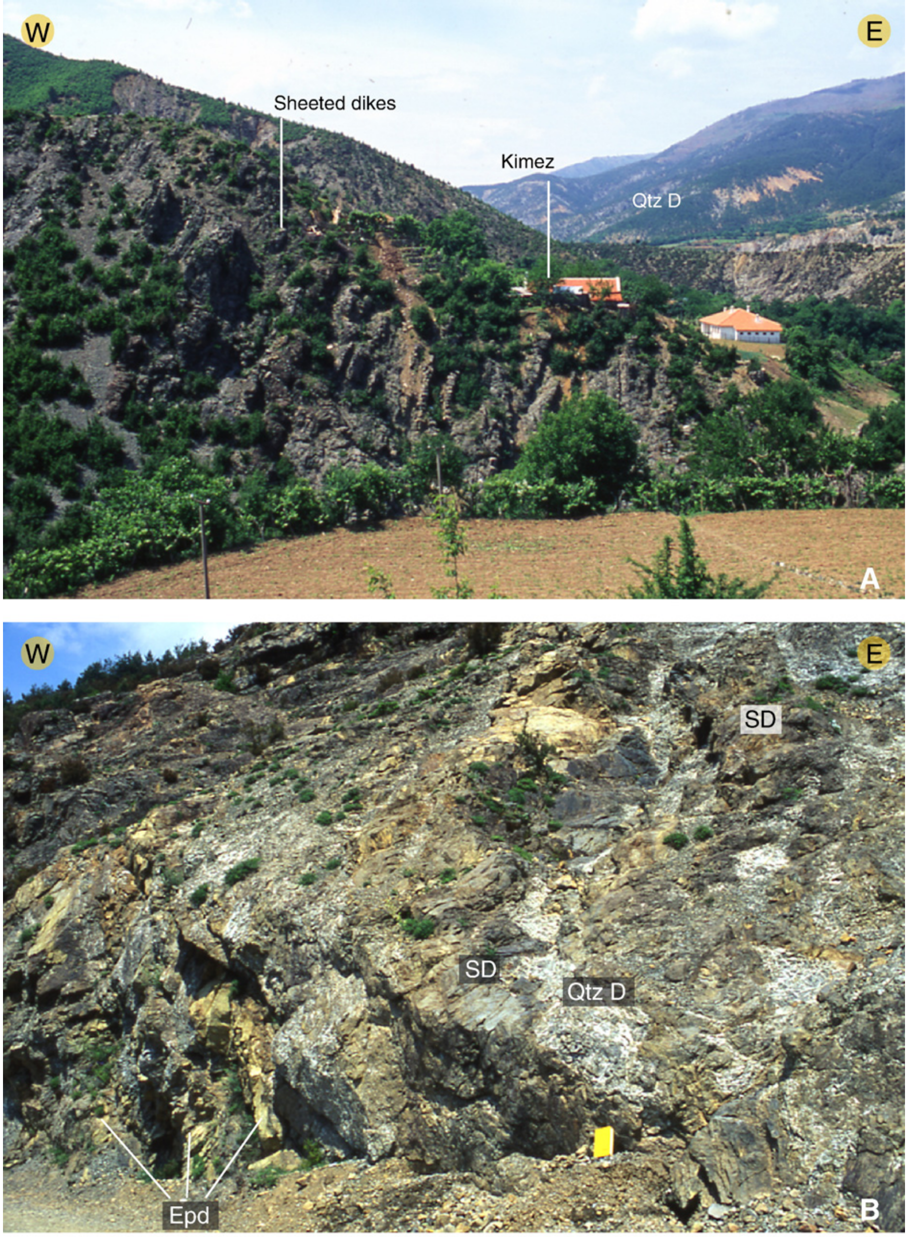


Fig. 6. Field photos of the sheeted dike complex in the central Mirdita Zone near the town of Kimze (A) and the mutual intrusive relations between the diabasic and quartz diorite dikes with associated epidote mineralization (B). Yellow notebook for scale.

These rocks are mostly aphyric, but some slightly phyric ones contain clinopyroxene and plagioclase phenocrysts.

The volcanic sequence along the EMP, which is located ~ 5–7 km NNE of the WMP (Fig. 4), is about 1.1 km-thick and overlies a sheeted dike complex along a transitional zone consisting of lavas intruded by dike swarms and microgabbros. The upper part of this sequence is overlain by several tens of meters of red chert, intercalated with black shales. The lower 400 m of the sequence consists of non-amygdaloidal to slightly amygdaloidal basaltic andesites. Stratigraphically upward and between 400 m and 650 m above the base of the extrusive sequence the rocks consist of a mixture of pillow lavas (dominant), massive sheet flows, pillow breccias and hyaloclastites, all of which are basaltic andesite in composition. These lavas are moderately to highly amygdaloidal. Farther up between 650 m and 700 m, moderately amygdaloidal, basaltic andesite pillow lavas occur. From 700 m to the top of the extrusive sequence, massive sheet flows dominate with minor occurrences of pillow lavas and pillow breccias. These rocks are mostly non- to highly amygdaloidal andesite with minor amounts of basalt and dacite. The phenocrysts in the andesites consist of plagioclase and clinopyroxene, whereas in the dacites the phenocryst phases include plagioclase, quartz, hornblende, and clinopyroxene.

We present major and trace element analyses of a representative suite of lavas and dikes from the Western- and Eastern-type ophiolites in Table 1. The full data set (also including Nd-isotope data) and a more comprehensive petrological discussion of these rocks are presented elsewhere (Dilek

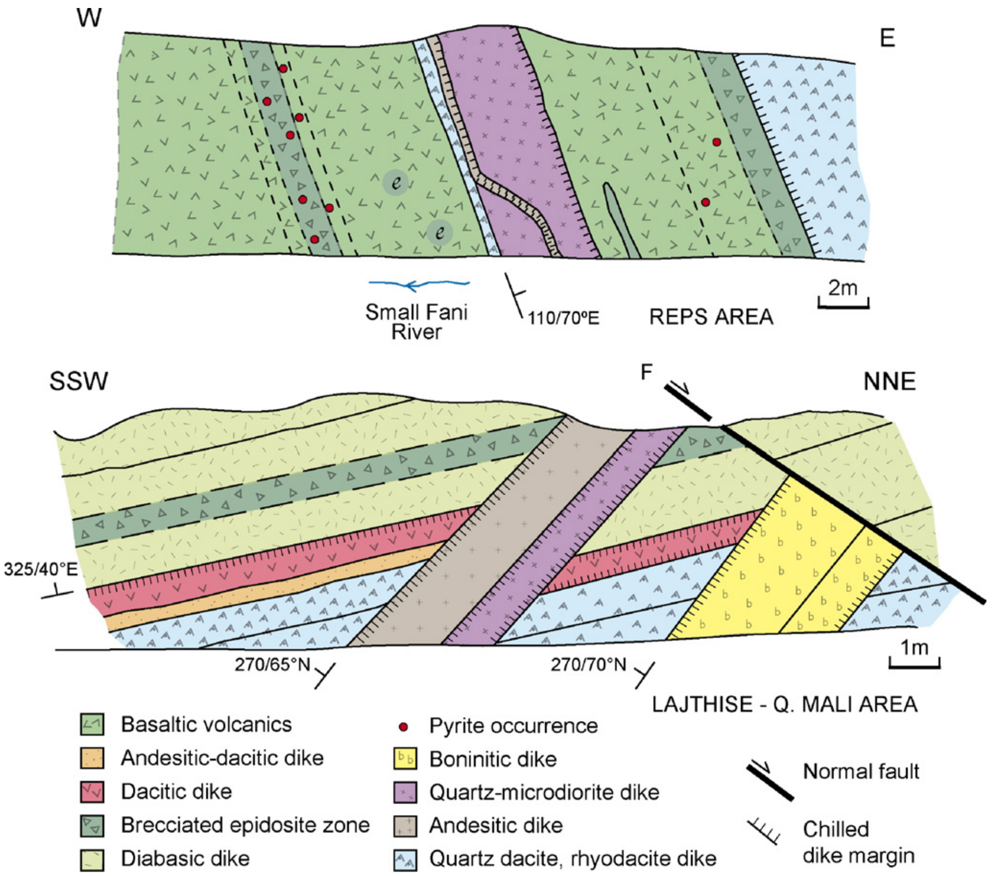


Fig. 7. Roadcut sections of the sheeted dike complex of the Eastern-type ophiolites in the Reps (A) and Lajthisë-Q.Mali (B) areas. These locations are marked on Fig. 4.

et al., in preparation). However, in the following section and on the diagrams in Figs. 8–12, we discuss all our geochemical data collected from the WMP and EMP.

Fig. 8 is a SiO_2 versus FeO^t/MgO plot of the lavas and dikes from the WMP and EMP. All the Western-type dikes and lavas plot in the tholeiitic field, but the Eastern-type dikes and lavas straddle the tholeiitic–calc–alkaline boundary. Most of the dikes and lavas in the WMP have a narrow range of SiO_2 (47–50 wt.%), whereas those along the EMP have a much wider range of SiO_2 (52–70 wt.%) (Fig. 8). Nearly 60% of the WMP basalts are classified as Fe–Ti basalts using the criteria of $FeO^t/MgO > 1.75$ and $TiO_2 < 2$ wt.% (Melson et al., 1976; Sinton et al., 1983).

Fig. 9 shows the distribution of the analyzed rocks on a Zr/TiO_2 versus SiO_2 discrimination diagram. These samples can be classified as sub-alkaline basalts, andesite/basaltic andesites, rhyodacite/dacites, and rhyolites. The lavas and dikes of the Western-type ophiolites plot predominantly in the sub-alkaline basalt field, whereas those of the Eastern-type ophiolites are predominantly basaltic andesites/andesites with a few samples of rhyodacitic/dacitic and rhyolitic compositions.

In Fig. 10, we present all our data in three different discrimination diagrams (TiO_2–V, Zr–Zr/Y and Y–Cr) that are especially useful in the evaluation of various geodynamic environments in which magmatic rocks are generated. In all these discrimination diagrams, the magmas of the Western-type ophiolites display a predominant MORB affinity, although with a detectable subduction zone influence as indicated by the occurrence of typical island arc-type basalts in these ophiolites. The lavas and dikes of the Eastern-type ophiolites, on the other hand, plot nearly all in the island arc and boninitic fields, with some minor occurrences in the MORB field.

Fig. 11 shows chondrite-normalized REE diagrams of a suite of representative lava and dike samples from the Western- and Eastern-type ophiolites. The REE patterns of both the Western- and Eastern-types range from rather flat to LREE-depleted. Although the lavas and dikes of the Eastern-type ophiolites are considerably more differentiated than those of the Western-type, they are nevertheless more depleted with respect to the REEs. However, Sample 90-Al-00 (boninitic dike) shows a distinct convex-down pattern typical of boninites.

Interpreting the chemostratigraphic evolution of the magmatic rocks of the Mirdita ophiolites, we have considered the variations of Zr, Y, P_2O_5 and TiO_2 of the lava samples collected along the WMP and EMP, together with the $\varepsilon_{Nd\ (T=160\ Ma)}$ values of the lavas, dikes and gabbroic rocks from the three sub-areas shown in Fig. 12A. Based on the crosscutting relations of different dike generations and on the stratigraphy of the extrusive rocks along the profiles, we have determined that the rocks become progressively younger from SW to NE in the study area (from Sub-area #1 toward #3). Starting at the bottom of the WMP (#1 in the gray field along the geochemical curve)

Table 1
Geochemical analyses of representative samples of lavas and dikes from the western and eastern part of the Mirdita ophiolite

Rock type	Western-type lavas		Western-type dikes		Eastern-type lavas				Eastern-type dikes			
	Basalt	Basalt	Basalt	Basalt	Basalt	B.and.	Andesite	Dacite	Boninite	B.and.	Andesite	Rhyolite
Sample	44-Al-00	40-Al-00	35-Al-00	55-Al-01	28-Al-00	11-Al-00	YDKA99-2	YDKA99-8	90-Al-00	116-Al-01	48-Al-00	80-Al-00
SiO_2	48.18	48.70	49.92	47.54	52.95	56.37	57.71	67.48	53.21	55.92	61.82	74.61
TiO_2	1.54	3.55	2.24	0.62	0.84	0.49	0.45	0.44	0.12	0.48	1.07	0.44
Al_2O_3	14.66	12.51	13.16	15.86	15.22	14.55	13.71	11.61	10.35	16.25	13.75	11.68
FeO^t	13.29	16.04	14.37	8.82	11.04	9.10	9.13	6.06	8.87	10.34	12.01	6.35
MnO	0.21	0.24	0.21	0.16	0.15	0.16	0.10	0.12	0.15	0.17	0.05	0.07
MgO	7.05	4.76	5.45	9.54	5.99	6.84	3.41	0.83	15.56	5.09	1.28	0.74
CaO	10.02	8.54	9.61	12.88	5.67	4.75	5.62	5.12	9.28	4.39	4.03	1.41
Na_2O	2.16	3.02	3.03	1.05	3.76	3.86	5.43	1.71	0.05	4.42	4.79	4.69
K_20	0.18	0.37	0.04	0.05	0.18	0.05	0.13	0.57	0.01	0.17	0.03	0.09
P_2O_5	0.11	0.37	0.17	0.02	0.06	0.03	0.03	0.08	0.01	0.04	0.28	0.07
L.O.I	3.31	1.95	2.26	3.21	3.25	3.53	n.a	n.a	1.81	2.13	0.95	0.87
SUM	100.71	100.05	100.46	99.74	99.11	99.73	95.72	93.73	99.42	99.44	100.06	101.02
Sc	49.7	46.4	43.2	37.4	41.1	38.8	35.0	20.7	51.8	44.2	23.4	20.8
V	400	448	339	251	318	237	336	13	191	269	7	10
Cr	84	41	66	470	37	86	18	n.d	1319	28	6	7
Co	65	66	61	46	56	50	n.a	n.a	56	52	50	27
Ni	47	32	42	215	27	44	5	3	410	26	2	2
Cu	80	58	53	101	102	81	100	29	5	112	n.d	n.d
Zn	123	153	97	64	77	76	65	89	35	64	19	19
Rb	2	n.d	n.d	1	n.d	n.d	1.6	14.5	1	1	n.d	1
Sr	92	126	73	90	79	44	25	70	21	47	66	54
Y	43	91	59	21	26	13	10	33	4	19	103	57
Zr	91	284	150	36	61	43	24	60	21	36	147	53
Nb	0.74	5.49	1.29	0.06	0.69	0.65	0.89	1.09	0.58	0.47	2.99	0.96
Cs	0.03	0.02	n.d	0.01	0.03	0.02	0.04	2.06	0.01	0.05	n.d	0.01
Ba	5	11	3	5	12	10	7	50	3	9	4	9
La	1.95	9.47	3.39	0.41	1.72	1.18	1.16	3.54	1.19	1.11	6.12	4.11
Ce	6.65	27.69	11.50	1.24	4.12	2.87	2.58	8.59	2.18	2.66	16.74	9.62
Pr	1.23	4.45	2.10	0.30	0.71	0.45	0.35	1.20	0.24	0.39	2.79	1.34
Nd	7.68	23.93	12.45	2.25	4.36	2.53	1.84	6.46	0.93	2.16	16.31	7.17
Sm	3.52	8.69	5.34	1.33	2.01	1.12	0.73	2.70	0.27	1.00	6.93	2.87
Eu	1.32	2.86	2.00	0.61	0.75	0.43	0.26	0.87	0.10	0.39	2.26	0.80
Gd	5.16	11.51	7.49	2.35	3.10	1.66	1.03	3.91	0.34	1.70	10.04	4.03
Tb	1.04	2.16	1.47	0.49	0.61	0.34	0.22	0.77	0.07	0.35	1.94	0.82
Dy	7.09	14.34	9.79	3.51	4.29	2.42	1.59	5.36	0.56	2.51	13.09	5.73
Ho	1.55	3.07	2.13	0.76	0.94	0.53	0.36	1.21	0.14	0.60	2.88	1.31
Er	4.32	8.64	5.90	2.16	2.69	1.54	1.08	3.46	0.44	1.73	8.10	3.79
Tm	0.62	1.24	0.86	0.32	0.40	0.23	0.17	0.52	0.08	0.27	1.17	0.58
Yb	3.89	7.67	5.34	2.03	2.57	1.48	1.13	3.40	0.55	1.82	7.31	3.73
Lu	0.61	1.20	0.82	0.31	0.41	0.23	0.19	0.56	0.10	0.29	1.16	0.61
Hf	2.38	6.81	3.78	0.77	1.46	0.84	0.76	1.87	0.25	0.73	4.73	1.93
Ta	0.06	0.44	0.11	n.d	0.05	0.05	0.08	0.09	0.05	0.03	0.20	0.06
Pb	0.45	0.92	0.21	0.01	0.35	0.54	0.40	5.00	0.26	0.44	0.11	0.24
Th	0.11	0.38	0.15	n.d	0.16	0.18	0.26	0.98	0.42	0.25	0.53	1.20
U	0.04	0.17	0.05	n.d	0.07	0.05	0.10	0.45	0.25	0.18	0.15	0.52

Abbreviations: B. and. = basaltic andesite; n.a = not analysed; n.d = not detected; L.O.I = loss on ignition.

and moving stratigraphically upward, there are pronounced changes in the concentrations of Zr, Y, P_2O_5 and TiO_2 contents of the analyzed lava samples. Up to a stratigraphic level of ca. 500 m above the base of the stratigraphic column, the Zr content varies between 100 and 300 ppm but then continuously decreases further upward to 50 ppm at the stratigraphic top of the profile (Fig. 12B). The Zr content through the EMP (#2 in the gray field along the geochemical curve) is remarkably constant (between 30 to 50 ppm), even though the lava compositions range from basaltic andesite to dacite in the extrusive sequence here (Fig. 12B). Throughout the WMP and EMP lava sequences the variations in the concentrations of Y, P_2O_5 and TiO_2 follow that of Zr (Fig. 12B).

The $\varepsilon_{Nd(T=160\ Ma)}$ values show only small variations (+7 to +6.9) through the lava pile of the WMP, but the highest values (> +7) occur in the lower 300 m of the profile. The gabbros on which the pillow lavas of the WMP (#1) rest show, however, even higher ε_{Nd} values (> +7.5), and a basaltic dike intruding these gabbros and the lherzolitic peridotites exhibits the highest value of +8.0 (Fig. 12B). The $\varepsilon_{Nd(T=160\ Ma)}$ values are around

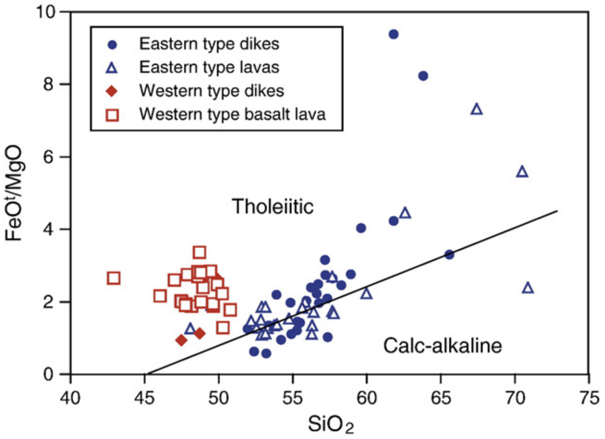


Fig. 8. SiO_2 versus FeO^t/MgO diagram of the lavas and dikes from the Western- and Eastern-type ophiolites. The boundary between tholeiitic and calc-alkaline rock types is from Miyashiro (1974). Some of the lava flows of the upper part of the volcanic sequence of the Eastern ophiolites contain quartz-bearing amygdales, and in some of the samples (lavas and dikes of both WO and EO) there are thin quartz-filled fractures. We have avoided these samples in the diagram.

+6.5 in the lower 800 m of the EMP (#2), highly variable (+6.5 to +5) between 800 and 1050 m, and show a value of ~ +3 in the uppermost sample at 1100 m above the base of the section (Fig. 12B). Thus, we see a systematic drop in the $\varepsilon_{Nd(T=160\ Ma)}$ values upward in the lava column here and much lower in comparison to the lower part of the WMP. Farther to the northeast (Sub-area #3), the intrusive rocks again display lower $\varepsilon_{Nd(T=160\ Ma)}$ values with the gabbros around − 1.4 and the late-stage boninitic dikes as low as −4.0 (Fig. 12B).

An important feature of the chemostratigraphy of the WMP is the change in the geochemistry of the lavas in the upper 100 m of the profile from MORB-like to IAT-like affinities. We emphasize that there is no evidence of a structural break within the depositional sequence of lavas in the stratigraphic column at this point (i.e., no major faults or unconformities). Thus, this chemical transition clearly demonstrates that the change from the MORB-type Western ophiolites to IAT-type Eastern ophiolites within the Mirdita Zone is not only a geographical (west to east), but also a stratigraphic phenomenon. This relationship is in contrast with some of the previous interpretations and models suggesting that the subduction-related Eastern-type ophiolites were built upon a pre-existing MORB-type oceanic crust (i.e., Western-type ophiolites; Robertson and Shallo, 2000; Bortolotti et al., 2002; Dilek and Flower, 2003; Bortolotti et al., 2005). The model of an intra-oceanic subduction zone (whether westward or eastward dipping) to explain the juxtaposition of the older MOR- and the younger SSZ-type ophiolites, as previously proposed (Shallo, 1992; Robertson and Shallo, 2000; Bortolotti et al., 2002, 2005), is difficult to support in light of the present data. Such interpretations imply that the MORB-like lavas of the WMP were erupted long before the SSZ lavas of the EMP, and that there was a major hiatus between the construction of the two ophiolite types. Our data and observations are incompatible with these interpretations. Indeed, our new zircon dates from a number of plagiogranite and quartz-diorite intrusions in both the Western- and Eastern-type ophiolites show rather similar ages clustered tightly between 160 Ma and 165 Ma (Fig. 4; Dilek et al., 2001). These age relations indicate that there were no significant time differences between the magmatic construction and accretion of the Western- and Eastern-type ophiolites in the Mirdita Zone.

Our detailed work on the structural and chilling relationships within the sheeted dike complex of the Eastern-type ophiolites (Shallo, 1995; Dilek et al., 2005; this study) shows a progression of magma compositions from basaltic to quartz dioritic (and rhyodacitic) and lastly to boninitic types through time (Fig. 7). This progression corresponds roughly with the lava chemostratigraphy of the EMP. Furthermore, if the progressively decreasing ε_{Nd} values are a function of age as a result of an increasingly contaminated mantle source, the boninitic dikes and lavas of the Eastern-type ophiolites are among the youngest rocks within the Mirdita Zone.

In summary, our geochemical data from the two main profiles (WMP and EMP), as well as from the sheeted dikes and dike swarms within the Eastern-types ophiolites and dikes and lavas from the Western-type ophiolites, collectively suggest that all magmatic components of the Mirdita zone ophiolites were influenced by subduction zone processes. This inference has also been documented by some of the previous studies (Bébien et al., 1998; Beccaluva et al., 2005). Our chemostratigraphic data show unequivocally that the subduction zone influence in magma chemistry increases stratigraphically upward as well as

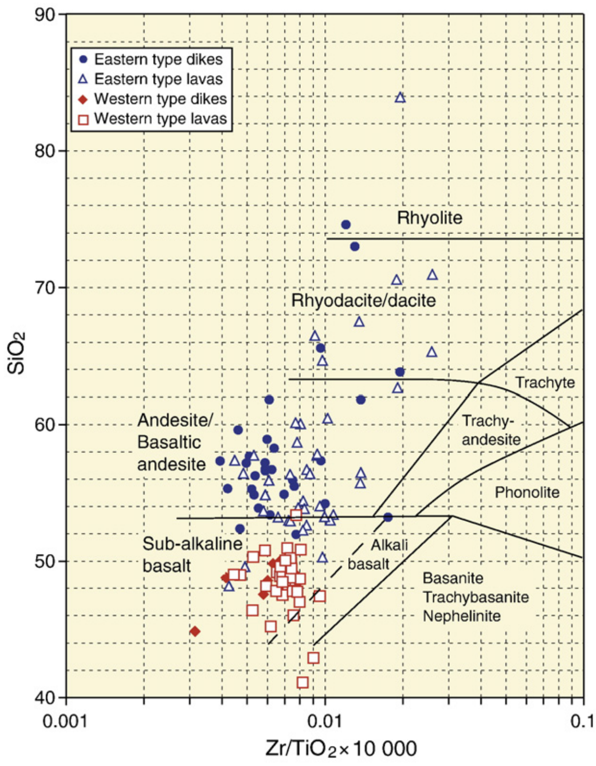


Fig. 9. Geochemical classification of the lavas and dikes from the Western- and Eastern-type ophiolites using the $Zr/TiO_2 \times 10{,}000$ versus SiO_2 diagram of Winchester and Floyd (1977).

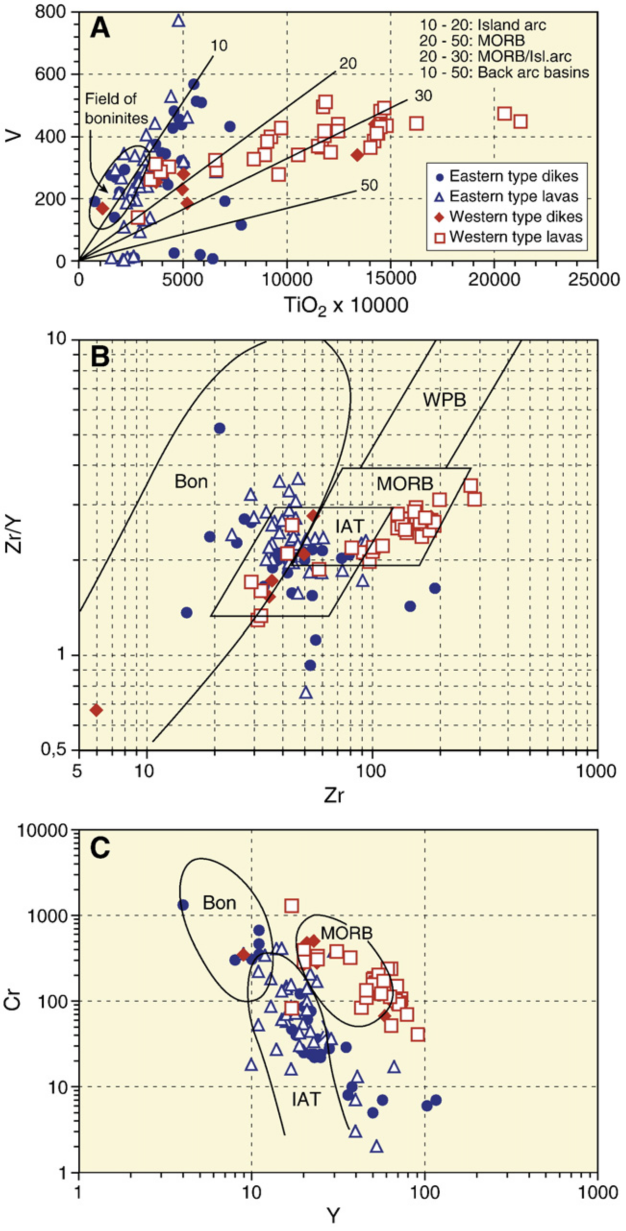


Fig. 10. TiO_2–V (A), Zr–Zr/Y (B), and Y–Cr (C) discriminant diagrams. MORB = mid-ocean ridge basalts, IAT = island arc tholeiites, WPB = within-plate basalts, Bon = boninites. See Pearce (2003) for further references to these discriminant diagrams.

eastwards in the Mirdita zone. This spatial and temporal progression in magma evolution must have been strongly controlled by the geodynamic evolution of the Pindos Zone ophiolites in the Balkan Peninsula.

5. Petrogenesis of the Mirdita zone ophiolites

The structural architecture and the internal stratigraphy of the passive margin sequences bounding the Mirdita zone ophiolites adjacent to the Apulian and Pelagonian microcontinents suggest that these lithostratigraphic units developed as conjugate continental margins during the early Mesozoic, following the Middle to Late Triassic continental breakup (Dilek and Flower, 2003; Dilek et al., 2005). The Triassic volcanic rocks and dikes having within-plate alkaline basalt (WPB) to transitional and MORB chemistry occur in tectonic intercalations within west- and east-directed thrust sheets beneath the Mirdita zone ophiolites (Shallo, 1990a). Similar Triassic rift volcanic rocks and associated hemipelagic rocks are spatially associated with the Western Hellenic ophiolites farther south in the Pindos Zone (Jones and Robertson, 1991; Pe-Piper, 1998; Saccani et al., 2003). Although no Triassic oceanic rocks have yet been documented in this area, some researchers have suggested that Triassic MORB-type crust may represent the early stages of the evolution of Neotethyan basin development in the eastern Mediterranean region (Malpas et al., 1993; Dilek and Flower, 2003; Saccani et al., 2003; Garfunkel, 2006).

The suprasubduction zone evolution of the Albanian ophiolites in the Pindos Zone was a result of the collapse of a Triassic–Early Jurassic ocean basin between the Apulian and Pelagonian microcontinents (Dilek et al., 2005, and references therein). The bidivergent nature of ophiolite emplacement onto the Apulian and Pelagonian continental margins resulted from this collapse and the subsequent inversion of the pre-existing ocean floor and rift structures. Although the majority of the high-grade metamorphic units beneath the Albanian ophiolites may represent true "metamorphic soles", those (>169 Ma) older than the igneous ages (~ 165–160 Ma) of the ophiolites and resting structurally on top of the peridotites (i.e., in Shpati, Shebenik, Voskopoja, and Morava massifs) may have been related to frictional shear heating and/or dynamothermal metamorphism associated with the rise of isothermal surfaces during lithosphere thinning, initial rifting and continental breakup (Fig. 13A). Hall (1984) has previously suggested a similar model for the peri-Arabian ophiolites and their "metamorphic soles" in the eastern Mediterranean region. These high-grade metamorphic rocks in lower crustal depths may have been subsequently exhumed during rifting, and the older Ar ages may have been locked in as a result of this crustal exhumation. Thus, the Middle Jurassic Albanian ophiolites appear to have developed in an older and wider ocean basin, following the initial collapse and consumption of its floor as a result of intra-oceanic subduction (Dilek and Flower, 2003; Dilek et al., 2005; Garfunkel, 2006).

The igneous stratigraphy and geochemistry of the Mirdita Zone ophiolites suggest that their magmas were evolved from mantle sources that were highly heterogeneous as a result of varying degrees of previous partial melting and associated depletion events, and of enrichment by various trace elements due to the addition of slab-derived fluids carrying a subduction component. The space and time relations of the MORB, IAT, and boninitic magmatism provide the most critical constraints for the petrogenetic evolution of these ophiolites. Those models, which assume an older MORB-type crustal formation of the Western-type ophiolites, envision an east-dipping (in present coordinate system) subduction zone beneath an already operating mid-ocean ridge system (Bortolotti et al., 1996, 2002). With the establishment of the subduction zone, MORB/IAT basalts and IAT to boninitic magmas were produced from partial melting of relatively hot, repeatedly depleted peridotites in a suprasubduction mantle wedge. The previously formed MORB oceanic crust and its peridotites were likely impregnated by subduction-derived magmas (to form, for example, boninitic dikes and lavas). On the other hand, some alternative models assume that the MORB-like Western-type ophiolites may have formed in a back-arc spreading environment at more advanced stages of a west-dipping subduction zone and far away from the subducting slab so that lherzolite mantle diapirs rising beneath the back-arc spreading center(s) were unaffected by subduction-derived fluids (Saccani et al., 2004; Beccaluva et al., 2005). The IAT basaltic to andesitic, dacitic volcanic rocks, sheeted dikes and mafic intrusions formed, in this model, from magmatism triggered from ascending mantle diapirs and related melting beneath an infant arc. Slab rollback and sinking during continued subduction caused increasing asthenospheric diapirism from the arc axis to the forearc region. This in turn resulted in shallow partial melting of the highly depleted (after IAT melt extraction) and refractory harzburgites producing boninitic magmas (Beccaluva et al., 2005). This model envisions much younger MORB magmatism that produced the Western-type ophiolites in this suprasubduction zone setting.

Our field observations and chemostratigraphic results suggest, however, a magmatic progression from MORB to IAT to boninitic affinities through time (albeit very short time span) and from west to east within the Mirdita zone. Therefore, our preferred petrogenetic model differs from those outlined above, although it resembles the general outline of the life cycle of suprasubduction zone ophiolites as suggested earlier by Shervais (2001). Because of the occurrence of highly evolved andesitic, dacitic to rhyodacitic volcanics and dikes and boninitic rocks in the Eastern-type ophiolites and the unequivocal geochemical evidence for subduction zone influence in their formation, we rule out the models and interpretations that suggest a mid-ocean ridge origin of the Albanian ophiolites in a restricted Tethyan basin (i.e., Nicolas et al., 1999; Moores et al., 2000; Fig. 13B). These models envision tectonically (historically) conditioned and highly heterogeneous mantle sources, which were progressively tapped into to form the oceanic crust with differing geochemical fingerprints, as the basin widened due to seafloor spreading. It is difficult to explain via these models where the fluids and water came from to cause the melting of refractory mantle sources. Diapiric upwellings that promote decompressional melting of hydrated refractory mantle wedge in a suprasubduction zone setting are needed in order to get increasingly more boninitic magmas through time (Dilek and Flower, 2003; Flower and Dilek, 2003; Garfunkel, 2006); the non-subduction mid-ocean ridge models of ophiolite generation do not provide a satisfactory explanation for the source of these upwellings, fluids, and additional heat.

We prefer, instead, a progressive evolution of MORB to IAT to boninitic magmas above a west-dipping subduction zone, which was experiencing rapid slab retreat (Fig. 13C) after its establishment. The metamorphic sole rocks with ages around 168–165 Ma and recording *P*–*T* conditions of ~ 9–19 kbar and ~ 860°–750° likely formed at the inception of this subduction zone (Fig. 13C). This is consistent with those widely accepted models suggesting that metamorphic soles commonly form at the inception of oceanic subduction beneath the hot mantle of the hanging wall (Wakabayashi and Dilek, 2003, and references therein). Slab rollback faster than the convergence rates resulted in extension in the upper plate (Dilek and Flower, 2003; Garfunkel, 2006) that helped produce a well-developed sheeted dike complex in the Eastern-type ophiolites. The continued westward subduction facilitated increasing rates of subduction of oceanic sediments that in turn played a major role in mantle enrichment by non-conservative and incompatible elements (Plank and Langmuir, 1998). A progressive decrease in the ε_{Nd} values with increasing SiO_2 contents eastward within the Mirdita Zone ophiolites is consistent with this interpretation (Fig. 13C). We envision a melting column above a retreating slab in which mixing of upwelling mantle diapirs occurred with the influx of fertile mantle and incompatible element-enriched fluids and subducted sediments, and the resulting magmas further evolved via fractional crystallization in crustal to sub-crustal magma chambers beneath an extending protoarc–forearc system (Fig. 13C). This evolutionary mode of the nascent ‘Mirdita arc’ is analogous to the poly-phase petrogenetic evolution of the Timor–Tanimbar ophiolite in eastern Indonesia (Ishikawa et al., 2007) and is similar to the petrogenesis of the

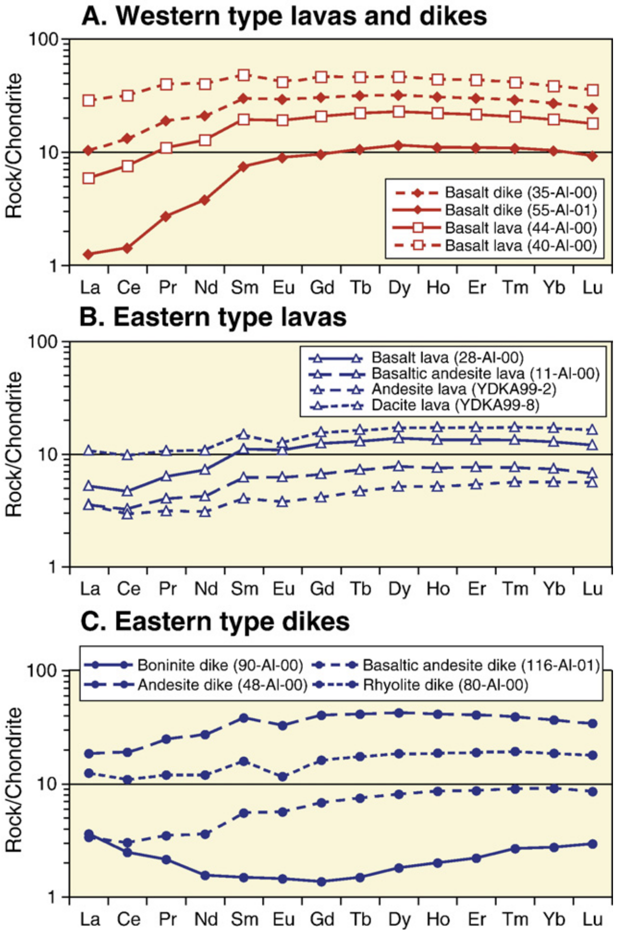


Fig. 11. Chondrite-normalized REE patterns of representative lava and dike samples from the Western- and Eastern-type ophiolites. Chondrite values are from Haskin et al. (1968).

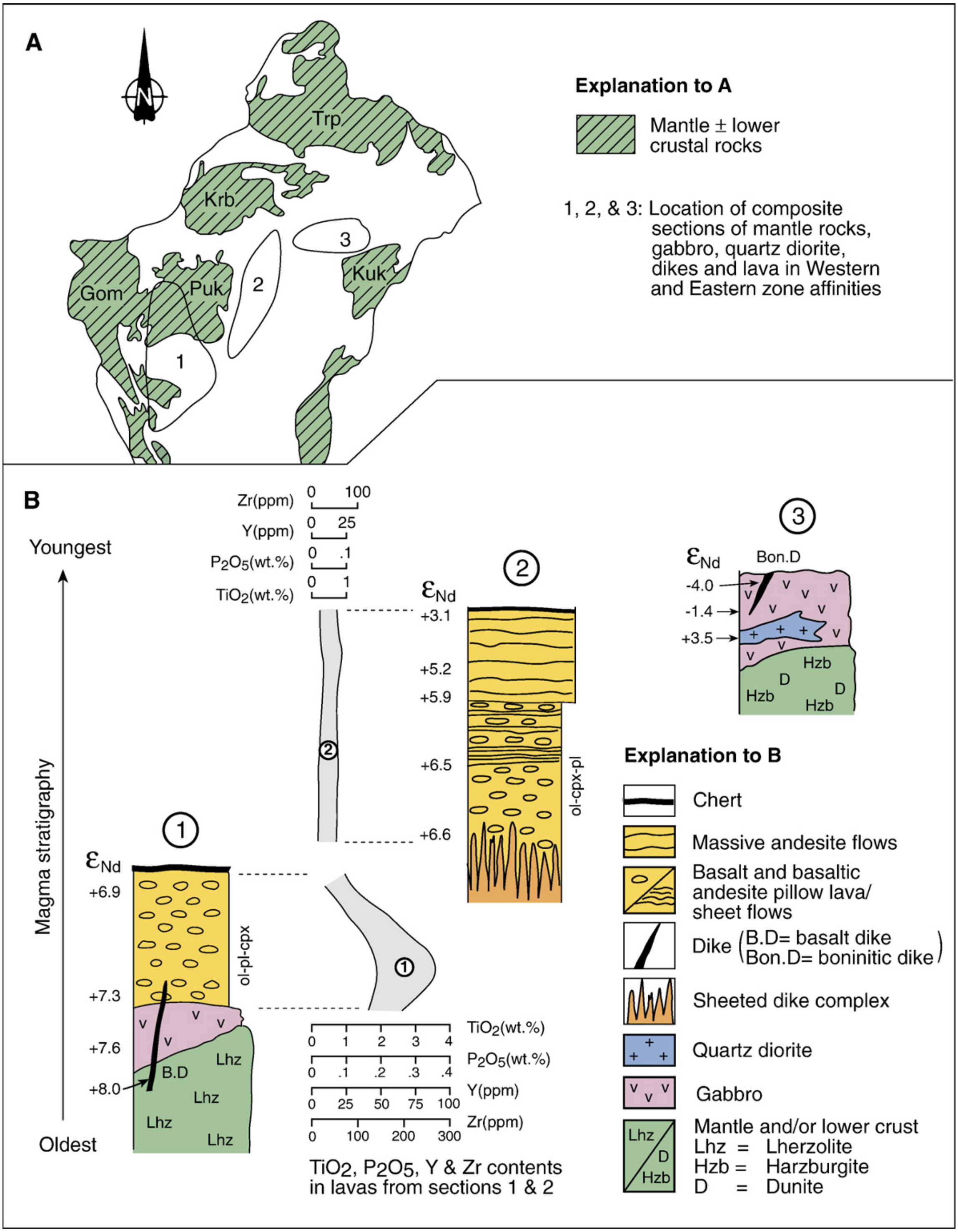


Fig. 12. Chemostratigraphy of the extrusive sequences in the Western- and Eastern-type ophiolites as measured along the profiles in locations 1, 2 and 3 (shown in A). See text for discussion.

tholeiitic to calc-alkaline series volcanic rocks of the intraoceanic South Sandwich arc in the South Atlantic Ocean (Pearce et al., 1995; Leat et al., 2003). Constructed on a recently formed backarc oceanic crust, the geochemical evolution of the South Sandwich arc magmas has been affected mainly by the addition of subducted sediments and aqueous fluids into the previously depleted mantle sources above the slab (Leat et al., 2003). The amount of added sediment component and the degree of mantle depletion are interpreted to have controlled the formation of tholeiitic and calc-alkaline magma series, with the calc-alkaline types having the higher sediment input. Our findings from the SSZ ophiolites in the Mirdita zone are consistent with these observations from the young intraoceanic arc in the South Sandwich Islands.

6. Root zones of the Mirdita ophiolites in the Balkan Peninsula

The petrotectonic model presented here supports the Pindos Zone origin of the Albanian ophiolites and hence implies that these and other Western Hellenic ophiolites are relatively parautochthonous in their present tectonic configurations, rather than being far-travelled nappe systems. Fig. 14 depicts two alternative geodynamic models for the Albanian and Western Hellenic ophiolites: the Pindos Zone versus Vardar Zone origin. In the first model, the suprasubduction zone ophiolites with MORB to IAT to boninitic geochemical gradations in space and time (from west to east) form above a west-dipping subduction zone within an older host basin, which evolved between the Apulian and Pelagonian microcontinents (Fig. 14.2A); Dilek et al., 2005, and this study). With continued subduction of this older ocean floor the Pelagonian passive margin finally arrived at the trench, and the ensuing trench–continent collision resulted in the emplacement of the SSZ ophiolites eastwards onto the Pelagonian margin in the Late Jurassic (Fig. 14.3A). This tectonic scenario is analogous to the ongoing collision of the Banda Arc with the continental margin of Australia in the Indonesia region and to the emplacement of the heterogeneous Banda Sea oceanic crust onto the Australian passive margin (Harris, 2006). The Eastern-type ophiolites in the Mirdita Zone and the Vourinos ophiolite farther south in Greece are unconformably overlain by Upper Jurassic–

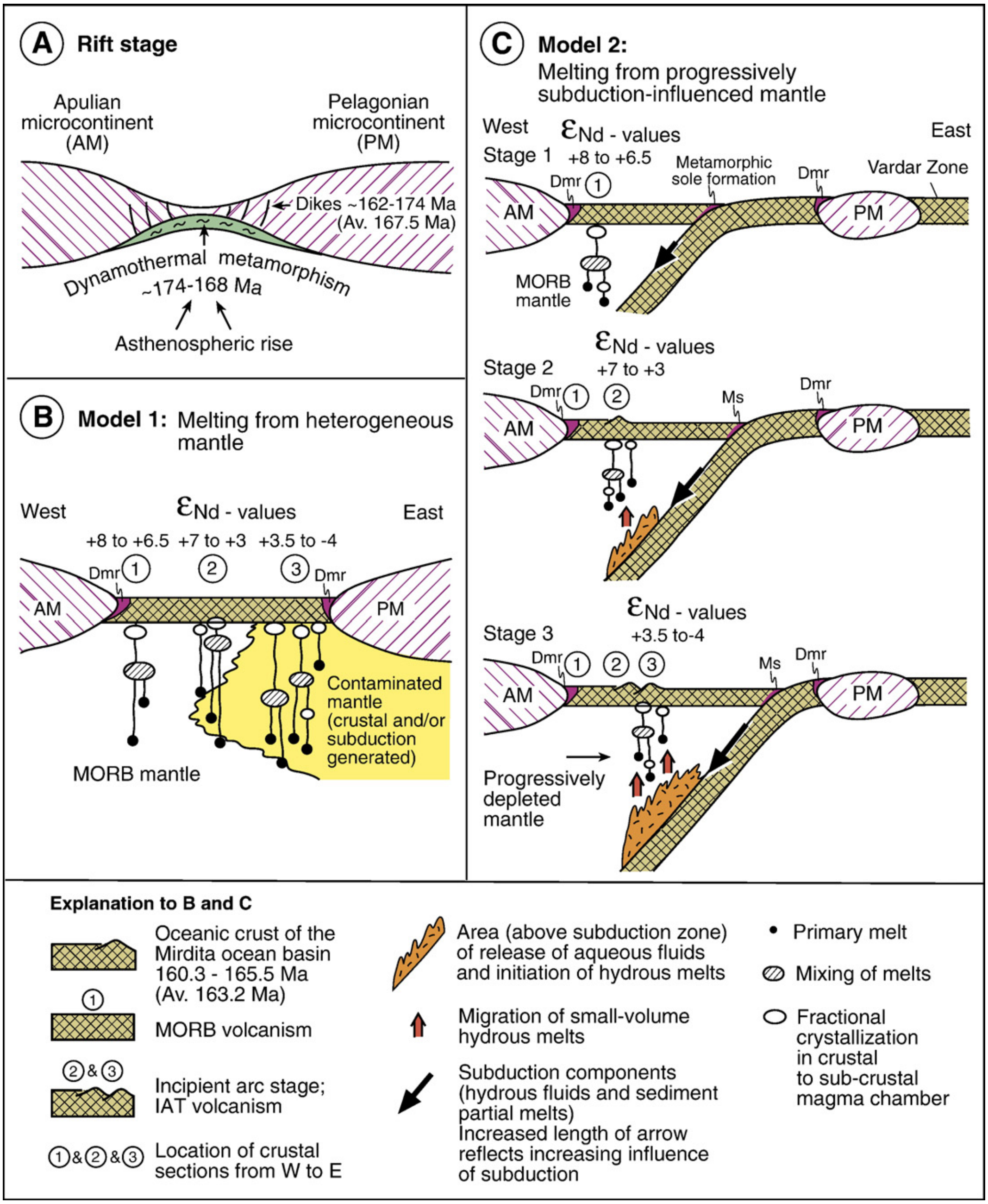


Fig. 13. Petrotectonic model for the evolution of the Mirdita Zone ophiolites. See text for explanation and discussion. Dmr = Dynamothermal metamorphic rocks, Ms = Metamorphic sole.

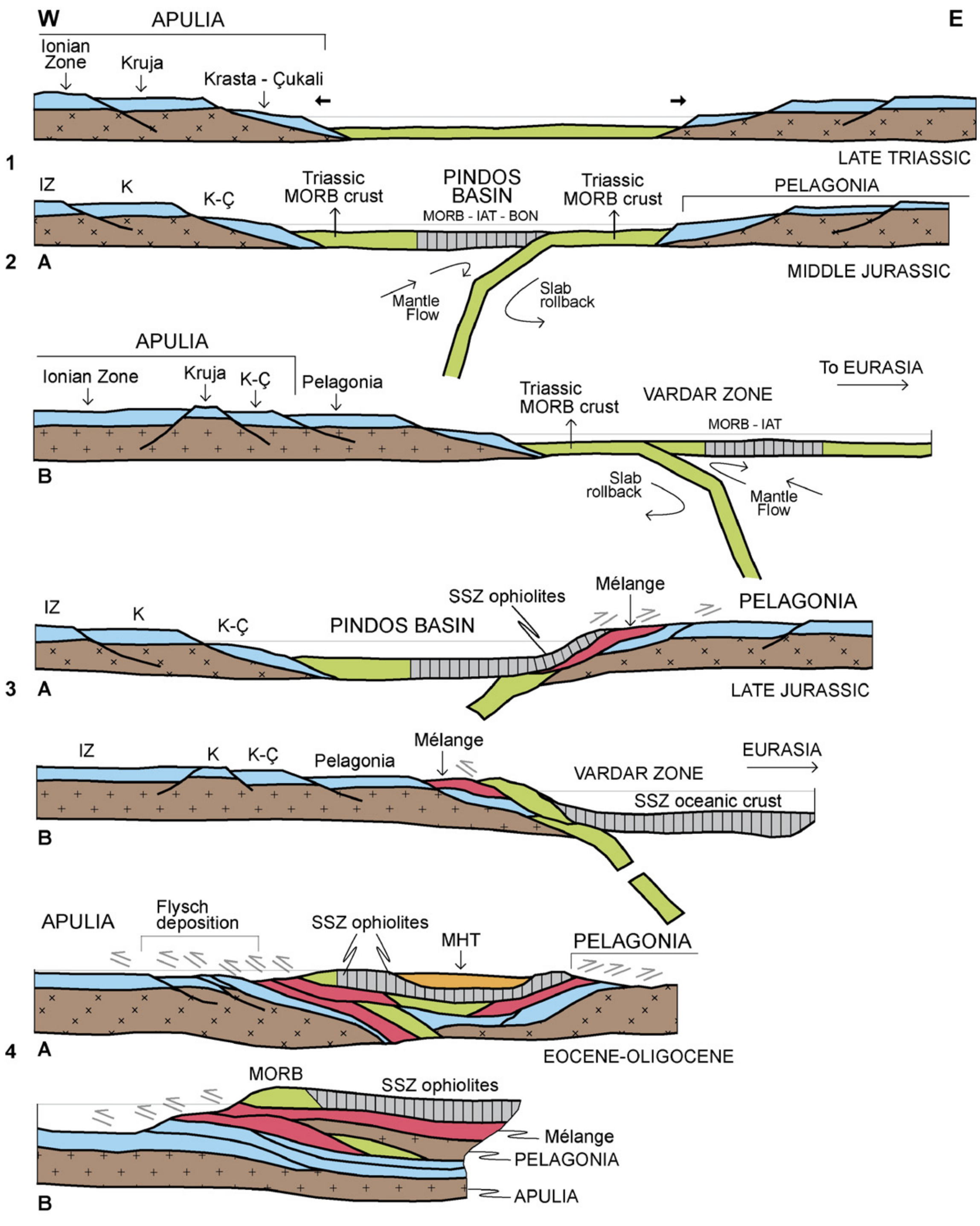


Fig. 14. Alternative models for the geodynamic evolution and the root zones of the Albanian ophiolites. Diagrams in A versions depict the Pindos root zone of the Albanian ophiolites (Dilek et al., 2005, this study), whereas those in B versions depict the purported Vardar root zone as proposed by Bortolotti et al. (2005). See text for discussion. MHT refers to the Mesohellenic trough.

Lower Cretaceous slope to deep-water carbonate rocks of a transgressive sequence (Pichon and Lys, 1976; Robertson and Shallo, 2000; Sharp and Robertson, 2006), providing an important time constraint for the emplacement age of the ophiolites. The westward deepening of this cover sequence (into pelagic rocks) points to the existence once of a still deep ocean to the west of the Pelagonian continental margin at this time. Furthermore, the stratigraphic evidence from the Apulian side indicates that passive margin conditions along Apulia appear to have continued until the early Tertiary (Meço and Aliaj, 2000).

The oblique NE convergence of Apulia with respect to fixed Eurasia and their collision in the early Paleogene caused Apulia to underplate Eurasia and the subsequent westward emplacement of the relict ocean floor of the Pindos basin onto the Apulian passive margin (Fig. 14.4A; Doutsos et al., 1993; Meço and Aliaj, 2000; Dilek et al., 2005). The SSZ ophiolites and the relict oceanic rocks

(Triassic?–Jurassic) overrode the Apulian passive margin along W-directed thrust faults, and the deformation front propagated westwards into the Krasta–Çukali, Kruja, and Ionian Zones (Fig. 14.4A). Flysch deposits accumulated within foreland-migrating flexural basins, and thin-skinned thrust packages developed over the Apulian basement and toward the peri-Adriatic trough to the west during the Eocene–Oligocene. We interpret the proto Mesohellenic trough (MHT) to be a terrestrial remnant of the Pindos Ocean that evolved as a piggy-back basin until the onset of extensional tectonics in the region around the Early to Middle Miocene (Dilek et al., 2005; Dumurdzanov et al., 2005).

The geodynamic models that suggest a Vardar root zone of the Albanian and Western Hellenic ophiolites assume a single Neotethyan ocean basin in the Mesozoic Balkans (Fig. 14.2B; Collaku et al., 1992; Bortolotti et al., 2005). In these models, Pelagonia has been interpreted to have been attached to Apulia at all times and the ophiolite emplacement to have occurred westward onto the eastern margin of Pelagonia in the Late Jurassic (Fig. 14.3B). However, this is incompatible with the stratigraphic relations from the Apulian and Pelagonian continental margin units. Deep-water conditions of the Middle Jurassic passive margin sequences of Apulia indicate that there had to be a basin to its east reaching abyssal depths (rather than Pelagonia) by 175 Ma. Furthermore, the Apulian and Pelagonian continental margins seem to have experienced different marine conditions throughout the Mesozoic (Dilek et al., 2005, and references therein), unlike what we would expect from a contiguous continental block. Finally, the existence of well-preserved rift-drift volcano-sedimentary units along both margins of the Pindos Zone ophiolites and the continuous sedimentary record of the Triassic through Upper Jurassic–Lower Cretaceous platform carbonates of the Pelagonian microcontinent support the separate basins interpretation and are incompatible with the far-travelled nappe origin of the Pindos zone ophiolites.

In the Vardar Zone model, the westward imbrication of the ophiolites, sub-ophiolitic mélanges, and continental margin units throughout the Eocene–Oligocene is envisioned to have produced a thick orogenic crust, with Pelagonia deeply buried beneath a >15 km of tectonic cover (Fig. 14.4B; Bortolotti et al., 2005). Bortolotti et al. (2005) interpret the current Pelagonian continental fragment as part of an exhumed lower crust, reminiscent of the metamorphic core complexes in the Aegean region. Much of the Pelagonian platform carbonates exposed along the margins are made of low-temperature metamorphic rocks (Dilek and Rassios, unpublished data) and are overlain on the Albanian side by an unmetamorphosed Barremian ophiolitic conglobreccia, suggesting that these units were never buried to lower crustal depths. Therefore, we think that the far-travelled nappe origin of the Albanian ophiolites derived from the Vardar Zone can be ruled out. Instead, we envisage the Pindos and Vardar oceans to be separate basins that evolved as restricted marginal basins adjacent to a larger, Pacific-type Neotethyan Ocean. The geodynamic evolution of these marginal basins was to a large extent controlled by the relative motions of the bounding continental fragments, Apulia and Pelagonia, which were rifted away from Gondwana in the Triassic (Stampfli and Borel, 2004; Dilek et al., 2005; Robertson, 2006).

7. Conclusions

Neotethyan suprasubduction zone ophiolites that developed along the periphery of the Mesozoic Gondwana represent the remnants of an anomalous oceanic crust produced in a protoarc–forearc setting. Following the continental breakup of the northern edge of Gondwana in the Triassic, a series of ocean basins floored with MORB crust were opened between the Gondwana-derived ribbon continents (i.e., Pelagonia, Apulia, Tauride platform), and their geodynamic evolution was controlled by the relative motions of the bounding continental fragments. The collapse of these basins via intra-oceanic subduction resulted in the generation of new oceanic crust in the upper plate, which was undergoing tectonic and magmatic extension keeping pace with the trench-slab rollback. The production of this nascent arc–forearc crust was commonly a short-lived event (~ 10–15 m.y.), terminated by the collision of a passive continental margin with the trench.

Our chemostratigraphic study of the extrusive sequences and dike rocks of the Jurassic Mirdita ophiolites in Albania shows that their magmas evolved from MORB to IAT to boninitic compositions stratigraphically upward and from west to east across the width of the ophiolite zone. This geochemical progression through time and space was a result of various degrees of melting of a highly heterogeneous and repeatedly depleted mantle source, which was modified by slab-derived fluids and sediments. The systematic decrease in the $\varepsilon_{\mathrm{Nd}(T)}$ values with increasing silica contents of extrusive rocks in this gradation suggests increased rates of sediment input (via subduction) into the sub-arc mantle. Rapid slab rollback and associated extension in the arc–forearc region caused increasing asthenospheric diapirism and corner flow toward the forearc mantle, resulting in shallow partial melting of the highly refractory harzburgites producing boninitic magmas. Systematic documentation of lateral and stratigraphic (vertical) variations in the lava geochemistry in SSZ ophiolites may hence be an effective tool to constrain subduction polarities in ancient marginal basins.

Based on the geochemical evolution of the Mirdita Zone ophiolites and on the structure and stratigraphy of the bounding passive margins of the Apulian and Pelagonian microcontinents, we infer that the Middle Jurassic ophiolites in the Pindos Zone in the Balkan Peninsula were derived from a basin that evolved between these two continental fragments. The ophiolites were emplaced first onto the Pelagonian margin in the east during the Late Jurassic and then onto the Apulian margin in the west in the early Paleogene. This geodynamic scenario is consistent with the regional tectonic constraints on the relative motions of Apulia (Adria) and Africa with respect to Eurasia and rules out a far-travelled nappe origin of the Mirdita and Western Hellenic ophiolites from the Vardar Zone farther east in the Balkans.

Acknowledgments

This study was funded by a NATO Science Programme research grant (EST.CLG-97617) and the Miami University Committee on Faculty Research. We wish to thank the directors of the Albanian Geological Survey (M. Zaçay and H. Beshku) for their logistical support during our fieldwork, and our Albanian colleagues (S. Bushati, E. Gjani, A. Meshi, I. Milushi, and A. Vranaj) for providing us with valuable information and discussions on the geology of Albania. Constructive and thorough journal reviews by John Wakabayashi and two anonymous referees helped us improve our presentation and interpretations in the paper. We thank Professor Santosh for inviting us to contribute this study as a Focus Article in Gondwana Research.

References

Alexander, R.J., Harper, G.D., 1992. The Josephine ophiolite: an ancient analogue for slow- to intermediate-spreading oceanic ridges. In: Parson, L.M., Murton, B.J., Browning, P. (Eds.), Ophiolites and their Modern Oceanic Analogues. Geological Society of London Special Publication, vol. 60, pp. 3–38.

Al-Ryami, K., Robertson, A.H.F., Xenophontos, C., Danelian, T., Dixon, J.E., 2002. Origin and emplacement of the Late Cretaceous Baer–Bassit ophiolite and its metamorphic sole in NW Syria. Lithos 65, 225–260.

Arvin, M., 1990. Petrology and geochemistry of ophiolites and associated rocks from the Zagros suture, Neyriz, Iran. In: Malpas, J., Moores, E.M., Panayiotou, A., Xenophontos, C. (Eds.), Ophiolites, Oceanic Crustal Analogues. Proceedings of the Symposium “Troodos 1987”. The Geological Survey Department, Nicosia, Cyprus, pp. 351–365.

Banerjee, N.R., Muehlenbachs, Dilek, Y., 2002. Petrography and geochemistry of epidosites from the Mirdita ophiolite, Albania. 1st International Symposium of the Faculty of Mines (ITU) on Earth Sciences and Engineering, 16–18 May 2002, Istanbul Turkey, vol. 136.

Bazylev, B.A., Karamata, S., Zakariadze, G.S., 2003. Petrology and evolution of the Brezovica ultramafic massif, Serbia. In: Dilek, Y., Robinson, P.T. (Eds.), Ophiolites in earth history. Geological Society of London Special Publication, vol. 218, pp. 91–108.

Bazylev, B., Popevic, A., Kononkova, N., Simakin, S., 2006. Spinel and plagioclase peridotites of Sjenicki Ozren massif (Dinaridic ophiolite belt): petrology and origin. Proceedings of International Symposium, Mesozoic Ophiolite Belts of Northern Part of the Balkan Peninsula, 31 June–6 June 2006, Belgrade–Banja Luka, pp. 5–7.

Bébien, J., Dubois, R., Gauthier, A., 1986. Example of ensialic ophiolites emplaced in a wrench zone: Innermost Hellenic ophiolite belt (Greek Macedonia). Geology 14, 1016–1019.

Bébien, J., Platevoet, B., Mercier, J., 1994. Geodynamic significance of the Paikon Massif in the Hellenides: contribution of the volcanic rock studies. Bulletin of the Geological Society of Greece XXX/1, 63–67.

Bébien, J., Shallo, M., Manika, K., Gega, D., 1998. The Shebenik massif (Albania): a link between MOR and SSZ-type ophiolites. Ofioliti 23, 7–15.

Beccaluva, L., Ohnenstetter, D., Ohnenstetter, M., Paupy, A., 1984. Two magmatic series with island arc affinities within the Vourinos ophioliote. Contributions to Mineralogy and Petrology 85, 253–271.

Beccaluva, L., Coltorti, M., Premti, I., Saccani, E., Siena, F., Zeda, O., 1994. Mid-ocean ridge and supra-subduction affinities in the ophiolitic belts from Albania. Ofioliti 19, 77–96.

Beccaluva, L., Coltorti, M., Saccani, E., Siena, F., 2005. Magma generation and crustal accretion as evidenced by supra-subduction ophiolites of the Albanide–Hellenide Subpelagonian zone. Island Arc 14, 551–563.

Bortolotti, V., Principi, G., 2005. Tethyan ophiolites and Pangea break-up. Island Arc 14, 442–470.

Bortolotti, V., Kodra, A., Marroni, M., Mustafa, F., Pandolfi, L., Principi, G., Saccani, E., 1996. Geology and petrology of ophiolitic sequences in Mirdita region (Northern Albania). Ofioliti 21, 3–20.

Bortolotti, V., Marroni, M., Pandolfi, L., Principi, G., Saccani, E., 2002. Interaction between mid-ocean ridge and subduction magmatism in Albanian ophiolites. Journal of Geology 110, 561–576.

Bortolotti, V., Marroni, M., Pandolfi, L., Principi, G., 2005. Mesozoic to Tertiary tectonic history of the Mirdita ophiolites, northern Albania. Island Arc 14, 471–493.

Brown, S.A.M., Robertson, A.H.F., 2004. Evidence for the Neotethys ocean rooted in the Vardar Zone: evidence from the Voras Mountains, NW Greece. Tectonophysics 381, 143–173.

Cannat, M., Casey, J.F., 1995. An ultramafic lift at the Mid-Atlantic Ridge: successive stages of magmatism in serpentinized peridotites from the 15°N region. In: Visers, R.L.M., Nicolas, A. (Eds.), Mantle and Lower Crust Exposed in Oceanic Ridges and in Ophiolites. Kluwer Academic Publishers, Dordrecht, pp. 5–34.

Capedri, S., Venturelli, G., Bocchi, G., Dostal, J., Garuti, G., Rossi, A., 1980. The geochemistry and petrogenesis of an ophiolite sequence from Pindos, Greece. Contributions to Petrology and Mineralogy 74, 189–200.

Carosi, R., Cortesogno, L., Gaggero, L., Marroni, M., 1996. Geological and petrological features of the metamorphic sole from the Mirdita nappe, northern Albania. Ofioliti 21, 21–40.

Chiari, M., Macucci, M., Prela, M., 1994. Mirdita Ophiolite Project: 2. Radiolarian assemblages in the cherts at Fushe Arrez and Shebaj (Mirdita area, Albania). Ofioliti 19, 313–318.

Clift, P.D., Dixon, J.E., 1998. Jurassic ridge collapse, subduction initiation and ophiolite obduction in the southern Greek Tethys. Eclogae Geologicae Helvetiae 91, 128–138.

Collaku, A., Cadet, J.-P., Melo, V., Vranaj, A., Bonneau, M., 1990. Sur l’allochtonie des zones internes albanais: Mise en evidence de fenetre a l’arriere de la nappe ophiolitique de la Mirdita (Albanie). Comptes Rendus de L’Academie des Sciences de Paris 311, 1251–1258.

Collaku, A., Bonneau, M., Cadet, J.-P., Kienast, J.-R., 1991. La semelle métamorphique infra-ophiolitique de la nappe de Mirdita, son métamorphisme inverse et ses relations avec la série volcano-sédimentaire (region de Lura, Albanie septentrionale). Comptes Rendus de l’Academie des Sciences de Paris 313, 251–258.

Collaku, A., Cadet, J.-P., Bonneau, M., Jolivet, L., 1992. L’edifice structural de l’Albanie septentrionale: Des elements de réponse sur les modalité de la mise en place des ophiolites. Bulletin de la Societe Géologique de France 163, 455–468.

Dewey, J.F., Pitman, W.C., Ryan, W.B.F., Bonnin, J., 1973. Plate tectonics and the evolution of the Alpine System. Geological Society of America Bulletin 84, 3137–3180.

De Wet, A.P., Miller, J.A., Bickel, M.J., Chapman, H.J., 1989. Geology and geochronology of the Arnea, Sithonia and Ouranoupolis intrusions, Chaldiki peninsula, Northern Greece. Tectonophysics 161, 65–79.

Dilek, Y., Eddy, C.A., 1992. The Troodos (Cyprus) and Kizildag (S. Turkey) ophiolites as structural models for slow-spreading ridge segments. Journal of Geology 100, 305–322.

Dilek, Y., Flower, M.F.J., 2003. Arc-trench rollback and forearc accretion: 2. A model template for ophiolites in Albania, Cyprus, and Oman. In: Dilek, Y., Robinson, P.T. (Eds.), Ophiolites in Earth History. Geological Society of London Special Publication, vol. 218, pp. 43–68.

Dilek, Y., Moores, E.M., 1990. Regional tectonics of the Eastern Mediterranean ophiolites. In: Malpas, J., Moores, E.M., Panayiotou, A., Xenophontos, C. (Eds.), Ophiolites, Oceanic Crustal Analogues. Proceedings of the Symposium “Troodos 1987”. The Geological Survey Department, Nicosia, Cyprus, pp. 295–309.

Dilek, Y., Rowland, J.C., 1993. Evolution of a conjugate passive margin pair in Mesozoic southern Turkey. Tectonics 12, 954–970.

Dilek, Y., Thy, P., 1998. Structure, petrology and seafloor spreading tectonics of the Kizildag ophiolite, Turkey. In: Mills, R.A., Harrison, K. (Eds.), Modern Ocean Floor Processes and the Geological Record. Geological Society of London Special Publication, vol. 148, pp. 43–69.

Dilek, Y., Thy, P., Hacker, B., Grundvig, S., 1999. Structure and petrology of Tauride ophiolites and mafic dike intrusions (Turkey): implications for the Neo-Tethyan ocean. Geological Society of America Bulletin 111, 1192–1216.

Dilek, Y., Furnes, H., Shallo, M., Mortensen, J.K., 2001. Structure, petrology, and geochronology of the Albanian ophiolites and their tectonic evolution within the Neotethyan orogenic belt. EUG XI, European Union of Geosciences, Strasbourg, France. Journal of Conference Abstracts 6 (1), 321.

Dilek, Y., Shallo, M., Furnes, H., 2005. Rift-drift, seafloor spreading, and subduction tectonics of Albanian ophiolites. International Geology Review 47, 147–176.

Dimo-Lahitte, A., Monié, P., Vergély, P., 2001. Metamorphic soles from the Albanian ophiolites: petrology, ^{40}Ar/^{39}Ar geochronology, and geodynamic evolution. Tectonics 20, 78–96.

Doutsos, T., Pe-Piper, G., Boronkay, K., Koukouvelas, 1993. Kinematics of the central Hellenides. Tectonics 12, 936–953.

Dumurdzanov, N., Serafimovski, T., Burchfiel, B.C., 2005. Cenozoic tectonics of Macedonia and its relation to the South Balkan extensional regime. Geosphere 1, 1–22.

Flower, M.F.J., Dilek, Y., 2003. Arc-trench rollback and forearc accretion: 1. A collision-induced mantle flow model for Tethyan ophiolites. In: Dilek, Y., Robinson, P.T. (Eds.), Ophiolites in Earth History. Geological Society of London Special Publication, vol. 218, pp. 21–41.

Garfunkel, Z., 2006. Neotethyan ophiolites: formation and obduction within the life cycle of the host basins. In: Robertson, A.H.F., Mountrakis, D. (Eds.), Tectonic Development of the Eastern Mediterranean Region. Geological Society of London Special Publication, vol. 260, pp. 301–326.

Hall, R., 1984. Ophiolites: figments of oceanic lithosphere. In: Gass, I.G., Lippard, S.J., Shelton, A.W. (Eds.), Ophiolites and Oceanic Lithosphere. Geological Society of London Special Publication, vol. 13, pp. 393–403.

Harris, R., 2006. Rise and fall of the Eastern Great Indonesian arc recorded by the assembly, dispersion and accretion of the Banda Terrane, Timor. Gondwana Research 10, 207–231.

Haskin, L.A., Haskin, M.A., Frey, F.A., Wildeman, T.R., 1968. Relative and absolute terrestrial abundances of the rare earths. In: Ahrens, L.H. (Ed.), Origin and distribution of the elements. Pergamon Press, New York, pp. 889–912.

Hassanipak, A.A., Ghazi, A.M., 2000. Petrology, geochemistry and tectonic setting of the Khoy ophiolite, northwest Iran: implications for Tethyan tectonics. Journal of Asian Earth Sciences 18, 109–121.

Hébert, R., Serri, G., Hekinian, R., 1989. Mineral chemistry of ultramafic tectonites and ultramafic to gabbroic cumulates from the major oceanic basins and Northern Apennine ophiolites (Italy): a comparison. Chemical Geology 77, 183–207.

Hébert, R., Huot, F., Wang, C., Liu, Z., 2003. Yarlung Zangbo ophiolites (Southern Tibet) revisited: geodynamic implications from the mineral record. In: Dilek, Y., Robinson, P.T. (Eds.), Ophiolites in Earth History. Geological Society of London Special Publication, vol. 218, pp. 165–190.

Hoeck, V., Koller, F., Meisel, T., Onuzi, K., Kneringer, E., 2002. The Jurassic South Albanian ophiolites: MOR- vs. SSZ-type ophiolites. Lithos 65, 143–164.

Hoxha, M., Boullier, A.-M., 1995. The peridotites of the Kukës ophiolite (Albania): structure and kinematics. Tectonophysics 249, 217–231.

Ishikawa, A., Kaneko, Y., Kadarusman, A., Ota, T., 2007. Multiple generations of forearc mafic–ultramafic rocks in the Timor–Tanimbar ophiolite, eastern Indonesia. Gondwana Research 11, 200–217.

ISPGJ-IGJN, 1983, Geological Map of Albania, scale 1:200000. Tirana, Albania.

Jackson, E.D., Green II, H.W., Moores, E.M., 1975. The Vourinos ophiolite, Greece: cyclic units of lineated cumulates overlying harzburgite tectonite. Geological Society of America Bulletin 86, 390–398.

Jones, G., Robertson, A.H.F., 1991. Tectono-stratigraphy and evolution of the Mesozoic Pindos Ophiolite and related units, Northwestern Greece. Journal of the Geological Society of London 148, 267–288.

Jones, G., Robertson, A.H.F., Cann, J.R., 1991. Genesis and emplacement of the supra-subduction zone Pindos ophiolite, northwestern Greece. In: Peters, T.J., Nicolas, A., Coleman, R.G. (Eds.), Ophiolite genesis and evolution of the oceanic lithosphere. Kluwer Academic Publishing, Dordrecht, pp. 771–799.

Leat, P.T., Smellie, J.L., Millar, I.L., Larter, R.D., 2003. Magmatism in the South Sandwich arc. In: Larter, R.D., Leat, P.T. (Eds.), Intra-Oceanic Subduction Systems: Tectonics and Magmatic Processes. Geological Society of London Special Publication, vol. 219, pp. 285–313.

Magganas, A.C., 2002. Constraints on the petrogenesis of Evros ophiolite extrusives, NE Greece. Lithos 65, 165–182.

Malpas, J., Calon, T., Squires, G., 1993. The development of Late Cretaceous microplate suture zone in SW Cyprus. In: Prichard, H.M., Alabaster, T., Harris, N.B.W., Neary, C.R. (Eds.), Magmatic Processes and Plate Tectonics. Geological Society of London Special Publication, vol. 76, pp. 177–195.

Malpas, J., Zhou, M.-F., Robinson, P.T., Reynolds, P.H., 2003. Geochemical and geochronological constraints on the origin and emplacement of the Yarlung Zangbo ophiolites, Southern Tibet. In: Dilek, Y., Robinson, P.T. (Eds.), Ophiolites in Earth History. Geological Society of London Special Publication, vol. 218, pp. 191–206.

Marcucci, M., Prela, M., 1996. The Lumi i zi (Puke) section of the Kalur cherts: radiolarian assemblages and comparison with other sections in northern Albania. Ofioliti 21, 71–76.

Marcucci, M., Kodra, A., Pirdeni, A., Gjata, Th., 1994. Radiolarian assemblage in the Triassic and Jurassic cherts of Albania. Ofioliti 19, 105–115.

Meço, S., Aliaj, Sh., 2000. Geology of Albania. Beiträge zur Regionalen Geologie der Erde, Gebrüder Borntraeger, Berlin–Stuttgart, Germany. 246 p.

Melson, W.G., Vallier, T.L., Wright, T.L., Bryerly, G., Nelson, J., 1976. Chemical diversity of abyssal volcanic glass erupted along the Pacific, Atlantic, and Indian Ocean seafloor spreading centers. In: Sutton, G., Manghari, M.H., Moberly, R. (Eds.), The Geophysics of the Pacific Ocean Basin and Its Margins. Geophysical Monograph, vol. 12, pp. 351–367.

Menzies, M., Allen, C., 1974. Plagioclase lherzolite-residual mantle: relationships within two eastern Mediterranean ophiolites. Contributions to Mineralogy and Petrology 46, 454–487.

Miyashiro, A., 1974. Volcanic rock series in island arcs and active continental margins. American Journal of Science 274, 317–327.

Moores, E.M., Kellogg, L.H., Dilek, Y., 2000. Tethyan ophiolites, mantle convection, and tectonic “historical contingency”: A resolution of the “ophiolite conundrum”. In: Dilek, Y., Moores, E.M., Elthon, D., Nicolas, A. (Eds.), Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program. Geological Society of America Special Paper, vol. 349, pp. 3–12.

Müntener, O., Piccardo, G.B., 2003. Melt migration in ophiolitic peridotites: the message from Alpine–Apennine peridotites and implications for embryonic ocean basins. In: Dilek, Y., Robinson, P.T. (Eds.), Ophiolites in Earth History. Geological Society of London Special Publication, vol. 218, pp. 69–89.

Mussallam, K., Jung, D., 1986. Petrology and geotectonic significance of sialic rocks preceeding ophiolites in the eastern Vardar Zone, Greece. Tschermak’s Mineralogische und Petrographische Mitteilungen 35, 217–242.

Nicolas, A., Boudier, F., Meshi, A., 1999. Slow spreading accretion and mantle denudation in the Mirdita ophiolite (Albania). Journal of Geophysical Research 104, 15155–15167.

Okay, A.I., Satir, M., Maluski, H., Siyako, M., Monie, P., Metzger, R., Akyüz, S., 1996. Paleo- and Neo-Tethyan events in northwest Turkey: geological and geochronological constraints. In: Yin, A., Harrison, M.T. (Eds.), Tectonics of Asia. Cambridge University Press, pp. 420–441.

Onen, A.P., 2003. Neotethyan ophiolitic rocks of the Anatolides of NW Turkey and comparison with Tauride ophiolites. Journal of the Geological Society of London 160, 947–962.

Pamic, J., 1983. Consideration on the boundary between lherzolite and harzburgite subprovinces in the Dinarides and Hellenides. Ofioliti 8, 153–164.

Pamic, J., 1984. Triassic magmatism of the Dinarides in Yugoslavia. Tectonophysics 109, 273–307.

Pamic, J., Tomljenovic, B., Balen, D., 2002. Geodynamic and petrogenetic evolution of Alpine ophiolites from the central and NW Dinarides: an overview. Lithos 65, 113–142.

Parlak, O., Delaloye, M., Bingöl, E., 1996. Geochemistry and mineralogy of post-metamorphic dike emplacement in the Mersin ophiolite (Southern Turkey): new age constraints from ^{40}Ar/^{39}Ar geochronology. Terra Nova 8, 585–592.

Parlak, O., Hoeck, V., Delaloye, M., 2000. Supra-subduction zone origin of the Pozanti–Karsanti ophiolite (S. Turkey) deduced from whole rock and mineral chemistry of the gabbro cumulates. In: Bozkurt, E., Winchester, J.A., Piper, D.A. (Eds.), Tectonics and Magmatism in Turkey and the Surrounding Area. Geological Society of London Special Publication, vol. 173, pp. 219–234.

Parlak, O., Hoeck, V., Kozlu, H., Delaloye, M., 2006. Oceanic crust generation in an island arc tectonic setting, SE Anatolian Orogenic Belt (Turkey). Geological Magazine 141, 583–603.

Pearce, J.A., 2003. Supra-subduction zone ophiolites: the search for modern analogues. In: Dilek, Y., Newcomb, S. (Eds.), Ophiolite Concept and the Evolution of Geological Thought. Geological Society of America Special Paper, vol. 373, pp. 269–293.

Pearce, J.A., Alabaster, T., Shelton, A.W., Searle, M.P., 1981. The Oman ophiolite as a Cretaceous arc–basin complex: evidence and implications.

Philosophical Transactions of the Royal Society of London (Series A), vol. 300, pp. 299–317.

Pearce, J.A., Lippard, S.J., Roberts, S., 1984. Characteristics and tectonic significance of supra–subduction zone ophiolites. In: Kokelaar, B.P., Howells, M.F. (Eds.), Marginal Basin Geology. Geological Society of London Special Publication, vol. 16, pp. 77–89.

Pearce, J.A., Baker, P.E., Harvey, P.K., Luff, I.W., 1995. Geochemical evidence for subduction fluxes, mantle melting and fractional crystallization beneath the South Sandwich arc. Journal of Petrology 36, 1073–1109.

Pe-Piper, G., 1998. The nature of Triassic extension-related magmatism in Greece: evidence from Nd and Pb isotope geochemistry. Geological Magazine 135, 331–348.

Pe-Piper, G., Piper, D.J.W., 2002. The igneous rocks of Greece, the anatomy of an orogen. Beiträge zur Regionalen Geologie der Erde, Gebrüder Borntraeger, Berlin–Stuttgart, Germany. 573 pp.

Pichon, J.F., Lys, M., 1976. Sur l'éxistance d'une série du Jurassic supérieur a Cretacé inférieur surmont les ophiolites dans les collines de Krapa (Massif de Vourinos, Grece). Comptes Rendus de l'Academie de Sciences (Série D) 282, 523–526.

Plank, T., Langmuir, C.H., 1998. The chemical composition of subducting sediment and its consequences for the crust and mantle. Chemical Geology 145, 325–394.

Rampone, E., Piccardo, G.B., 2000. The ophiolite–oceanic lithosphere analogue: new insights from the Northern Apennines (Italy). In: Dilek, Y., Moores, E.M., Elthon, D., Nicolas, A. (Eds.), Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program. Geological Society of America Special Paper, vol. 349, pp. 21–34.

Rassios, A., Smith, A.G., 2000. Constraints on the formation and emplacement age of western Greek ophiolites (Vourinos, Pindos, and Othris) inferred from deformation structures in peridotites. In: Dilek, Y., Moores, E.M., Elthon, D., Nicolas, A. (Eds.), Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program. Geological Society of America Special Paper, vol. 349, pp. 473–483.

Ricou, L.-E., Burg, J.-P., Godfriaux, I., Ivanov, Z., 1998. Rhodope and Vardar: the metamorphic and the olistostromic paired belts related to the Cretaceous subduction under Europe. Geodinamica Acta 11, 285–309.

Robertson, A.H.F., 2002. Overview of the genesis and emplacement of Mesozoic ophiolites in the Eastern Mediterranean Tethyan region. Lithos 65, 1–67.

Robertson, A.H.F., 2006. Contrasting modes of ophiolite emplacement in the Eastern Mediterranean region. In: Robertson, A.H.F., Mountrakis, D. (Eds.), Tectonic Development of the Eastern Mediterranean Region. Geological Society of London Special Publication, vol. 260, pp. 235–261.

Robertson, A.H.F., Dixon, J.E., 1984. Introduction: aspects of the geological evolution of the Eastern Mediterranean. In: Dixon, J.E., Robertson, A.H.F. (Eds.), The Geological Evolution of the Eastern Mediterranean. Geological Society of London Special Publication, vol. 17, pp. 1–74.

Robertson, A.H.F., Karamata, S., 1994. The role of subduction–accretion processes in the tectonic evolution of the Mesozoic Tethys in Serbia. Tectonophysics 234, 73–94.

Robertson, A.H.F., Shallo, M., 2000. Mesozoic–Tertiary evolution of Albania in its regional Eastern-Mediterranean context. Tectonophysics 316, 197–254.

Robertson, A.H.F., Dixon, J.E., Brown, S., Collins, A., Morris, A., Pickett, E., Sharp, I., Ustaömer, T., 1996. Alternative tectonic models for the Late Palaeozoic–Early Tertiary development of Tethys in the Eastern Mediterranean region. In: Morris, A., Tarling, D.H. (Eds.), Palaeomagnetism and Tectonics of the Mediterranean Region. Geological Society of London Special Publication, vol. 105, pp. 239–263.

Robinson, P.T., Malpas, J., 1990. The Troodos ophiolite of Cyprus: new perspectives on its origin and emplacement. In: Malpas, J., Moores, E.M., Panayiotou, A., Xenophontos, C. (Eds.), Ophiolites, Oceanic Crustal Analogues. Proceedings of the Symposium "Troodos 1987". The Geological Survey Department, Nicosia, Cyprus, pp. 13–26.

Robinson, P.T., Melson, W.G., O'Hearn, T., Schmincke, H.-U., 1983. Volcanic glass compositions of the Troodos ophiolite, Cyprus. Geology 11, 400–404.

Saccani, E., Photiades, A., 2004. Mid-ocean ridge and supra-subduction affinities in the Pindos ophiolites (Greece): implications for magma genesis in a forearc setting. Lithos 73, 229–253.

Saccani, E., Photiades, A., 2005. Petrogenesis and tectonomagmatic significance of volcanic and subvolcanic rocks in the Albanide–Hellenide ophiolitic mélanges. Island Arc 14, 494–516.

Saccani, E., Padoa, E., Photiades, A., 2003. Triassic mid-ocean ridge basalts from the Argolis Peninsula (Greece): new constraints for the early oceanization phases of the Neo-Tethyan Pindos basin. In: Dilek, Y., Robinson, P.T. (Eds.), Ophiolites in Earth History. Geological Society of London Special Publication, vol. 218, pp. 109–127.

Saccani, E., Beccaluva, L., Coltorti, M., Siena, F., 2004. Petrogenesis and tectono-magmatic significance of the Albanide–Hellenide ophiolites. Ofioliti 29, 77–95.

Schunemann, M., 1985. Contributions of the geology, geochemistry and tectonics of the Chortiatis Series metamorphic calc-alkaline suite, Chalkidiki, northern Greece, PhD Thesis, University of Hamburg, Germany, 165.

Sengör, A.M.C., Yilmaz, Y., Sungurlu, O., 1984. Tectonics of the Mediterranean Cimmerides: nature and evolution of the western termination of Paleo-Tethys. In: Dixon, J.E., Robertson, A.H.F. (Eds.), The Geological Evolution of the Eastern Mediterranean. Geological Society of London Special Publication, vol. 17, pp. 77–112.

Shallo, M., 1990a. Ophiolitic melange and flyschoidal sediments of the Tithonian–Lower Cretaceous in Albania. Terra Nova 2, 476–482.

Shallo, M., 1990b. Volcanic glasses of the Albanian ophiolitic belts. In: Malpas, J., Moores, E.M., Panayiotou, I., Xenophontos, C. (Eds.), Ophiolites, Oceanic Crustal Analogues. . Proceedings of the Symposium "Troodos 1987". The Geological Survey Department, Nicosia, Cyprus, pp. 271–278.

Shallo, M., 1992. Geological evolution of the Albanian ophiolite and their platform periphery. Geologische Rundschau 81 (3), 681–694.

Shallo, M., 1995. Volcanics and sheeted dikes of the Albanian SSZ ophiolite. Buletini i Shkencave Gjeologjike 1, 99–118.

Shallo, M., Dilek, Y., 2003. Development of the ideas on the origin of Albanian ophiolites. In: Dilek, Y., Newcomb, S. (Eds.), Ophiolite Concept and the Evolution of Geological Thought. Geological Society of America Special Paper, vol. 373, pp. 351–364.

Shallo, M., Kote, Dh., Vranaj, A. and Premti, I., 1985. Ophiolitic magmatism of Albania (in Albanian): Scientific Report, Tirana, Albania. Tirana, Albania, Arkivi Qendror i Gjeologjise, 362 p.

Shallo, M., Kote, D., Vranaj, A., 1987. Geochemistry of the volcanics from ophiolitic belts of Albanides. Ofioliti 12, 125–136.

Shallo, M., Kodra, A., Gjata, K., 1990. Geotectonics of the Albanian ophiolites. In: Malpas, J., Moores, E.M., Panayiotou, A., Xenophontos, C. (Eds.), Ophiolites, Oceanic Crustal Analogues, Proceedings of the Symposium "Troodos 1987". The Geological Survey Department, Nicosia, Cyprus, pp. 165–170.

Sharp, I.R., Robertson, A.H.F., 2006. Tectonic–sedimentary evolution of the western margin of the Mesozoic Vardar Ocean: evidence from the Pelagonian and Almopias zones, northern Greece. In: Robertson, A.H.F., Mountrakis, D. (Eds.), Tectonic Development of the Eastern Mediterranean Region. Geological Society of London Special Publication, vol. 260, pp. 373–412.

Shervais, J.W., 2001. Birth, death, and resurrection: the life cycle of suprasubduction zone ophiolites. Geochemistry, Geophysics, Geosystems (G^3) 2 (Paper# 2000GC000080).

Sinton, J.M., Wilson, D.S., Christie, D.M., Hey, R.N., Delaney, J.R., 1983. Petrologic consequences of rift propagation on oceanic spreading ridges. Earth and Planetary Science Letters 62, 193–207.

Smith, A.G., 1993. Tectonic significance of the Hellenic–Dinaric ophiolites. In: Prichard, H.M., Alabaster, T., Harris, N.B.W., Neary, C.R. (Eds.), Magmatic processes and plate tectonics. Geological Society of London Special Publication, vol. 76, pp. 213–243.

Srikantia, S.V., Razdan, M.L., 1980. The ophiolite–sedimentary belt of the Indus tectonic zone of the Ladakh Himalaya. Its stratigraphic and tectonic significance. In: Panayiotou, A. (Ed.), Ophiolites, Proceedings International Ophiolite Symposium, Cyprus 1979. Geological Survey Department, Nicosia, Cyprus, pp. 430–443.

Stampfli, G.M., Borel, G., 2004. The TRANSMED transects in space and time: constraints on the paleotectonic evolution of the Mediterranean domain. In: Cavazza, W., Roure, F.M., Spakman, W., Stampfli, G.M., Ziegler, P.A. (Eds.), The TRANSMED Atlas. The Mediterranean Region from Crust to Mantle. Springer–Verlag Berlin–Heidelberg, pp. 53–90.

Stampfli, G., Marcoux, J., Baud, A., 1991. Tethyan margins in space and time. Palaeogeography, Palaeoclimatology, Palaeoecology 87, 373–410.

Stampfli, G.M., Borel, G., Cavazza, W., Mosar, J., Ziegler, P.A., 2001. The paleotectonic Atlas of the Peritethyan Domain (CD-ROM). European Geophysical Society.

Sullivan, M.A., Windley, B.F., Saunders, A.D., Haynes, J.R., Rex, D.C., 1993. A palaeogeographic reconstruction of the Dir Group: evidence for magmatic arc migration within Kohistan, N. Pakistan. In: Treloar, P.J., Searle, M.P. (Eds.), Himalayan Tectonics. Geological Society of London Special Publication, vol. 74, pp. 139–160.

Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of ocean basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), Magmatism in the Ocean Basins. Geological Society of London Special Publication, vol. 42, pp. 313–346.

Tribuzio, R., Tiepolo, M., Vannucci, R., Bottazzi, P., 1999. Trace element distribution within the olivine-bearing gabbros from the Northern Apennine ophiolites (Italy): evidence for post-cumulus crystallization in MOR-type gabbroic rocks. Contributions to Mineralogy and Petrology 134, 123–133.

Tribuzio, R., Tiepolo, M., Vannucci, R., 2000. Evolution of gabbroic rocks of the Northern Apennine ophiolites (Italy): comparison with the lower oceanic crust from modern slow-spreading ridges. In: Dilek, Y., Moores, E.M., Elthon, D., Nicolas, A. (Eds.), Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program. Geological Society of America Special Paper, vol. 349, pp. 129–138.

Vergély, P., Dimo, A., Monie, P., 1998. Datation des semelles metamorphiques ophiolitiques d'Albanie par la methode ^{40}Ar/^{39}Ar: Consequences sur le mecanisme de leur mise en place. Comptes Rendus de l'Académie des Sciences 326, 717–722.

Wakabayashi, J., Dilek, Y., 2003. What constitutes "emplacement" of an ophiolite?: mechanisms and relationship to subduction initiation and formation of metamorphic soles. In: Dilek, Y., Robinson, P.T. (Eds.), Ophiolites in Earth History. Geological Society of Special Publication, vol. 218, pp. 427–448.

Winchester, J.A., Floyd, P.A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chemical Geology 20, 325–343.

Yildirim Dilek is a Professor of Tectonics in the Department of Geology and a Harrison Scholars Professor at Miami University (USA). He is the Editor of the *Geological Society of America Bulletin* and an Associate Editor of *Geology* (USA), *Journal of the Geological Society of London* (U.K.), and *Island Arc* (Japan). He received his PhD from the University of California-Davis (1989), worked as a Senior Research Fellow (1989–90) at the Getty Conservation Institute (Los Angeles, CA), and taught at Vassar College (New York) until 1996. He was a visiting Professor at the University of Bergen, Norway (1996), and the University of Tsukuba, Japan (2003, 2005). He has worked in the Mediterranean region (mainly in Albania, Greece, Cyprus, Turkey) for 20 years studying ophiolites, suture zones, and collision tectonics. The focus of his research is mostly on the structure, petrology, and tectonics of modern oceanic crust and ophiolites, post-collisional igneous complexes in orogenic belts, and metamorphic core complexes. He has also worked extensively in the western U. S. Cordillera, Northern Appalachians, Norwegian Caledonides, Caucasus Mountains, Arabian–Nubian Shield, and Central Asian orogenic belts. He is currently investigating the structure and tectonics of the Nankai accretionary prism off southern Japan. He is an expert scientist for the NATO Science for Peace Programme and a member of the United States Science Advisory Committee.

Harald Furnes is a Professor of Geochemistry in the Department of Earth Science at the University of Bergen (Norway). He received his PhD from the University of Oxford (U.K.) in 1978 and subsequently joined the faculty in Bergen. He participated in two Norwegian research expeditions in Antarctica in 1976/77 and 1984/85. He has worked extensively on the volcanology, petrology, and geochemistry of recent to ancient volcanic rocks and ophiolites in the Norwegian Caledonides, Iceland, Greenland, South Africa, Australia, and the Eastern Mediterranean region, and of modern oceanic crust developed along the Mid-Atlantic Ridge, the East Pacific Rise, and the Costa Rica Rift. His current research focuses on the bioalteration of modern and ancient oceanic crust (particularly Precambrian rocks older than 2.5 Ga). His research team leads the interdisciplinary studies of the geomicrobiology and bioalteration of Archean greenstone belts and ophiolites in search of the diverse geological and geochemical evidence for microbial life in the early Earth.

Minella Shallo is a retired Professor of Geology from the Tirana Polytechnic University in Albania. He received his BSc from the University of St. Petersburg, Russia, in 1961 and his PhD from the Tirana University in 1982. He has served as the Chair of the Department of Geology of Albania in the Institute of Geological Research between 1978 and 1989, the chair of the Department of Geological Sciences in the Polytechnic University between 1989 and 1998, and a member of the Head Council of the Albanian Geological Survey between 1997 and 2002. He was a visiting Professor at the University of Edinburgh in 1992 (UK), the University of Paris–Sud (France) in 1998, and Miami University in 2001. He has investigated the geology, petrology, geochemistry, and ore deposits of the Jurassic ophiolites in Albania and in the Balkan Peninsula for over 40 years and has published the results of these studies in the Albanian and international scientific journals; his detailed mapping and field-oriented studies of the Albanian ophiolites and different tectonic zones were instrumental in the production of the Geological Map of Albania (published in 1983 and revised in 2002), the Tectonic Map of Albania (published in 1999), and the Metallogenic Map of Albania (published in 1999). A member of the European Union of Geosciences and the International Association of Volcanology and Chemistry of the Earth's Interior, Professor Shallo currently divides his time between Albania and the USA, where he lives with his family.