Structural architecture of the sheeted dike complex and extensional tectonics of the Jurassic Mirdita ophiolite, Albania

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A B S T R A C T

The Jurassic Mirdita ophiolite in northern Albania occurs in a ~40 km-wide zone bounded by the passive margins of Apulia (W) and Pelagonia (E). The ~3 km-thick Western Mirdita ophiolite (WMO) contains lherzolitic peridotites and gabbros overlain by basaltic pillow lavas, whereas the ~12 km-thick Eastern Mirdita ophiolite (EMO) represents a Penrose-type oceanic crust with suprasubduction zone affinities. The 1 km-thick sheeted dike complex (SDC) in the EMO shows mutually intrusive relations with the underlying gabbros, is overlain by a 1.1-km-thick extrusive sequence, and records a history of complex seafloor spreading and rift tectonics in a suprasubduction zone environment. Crosscutting relations within the SDC indicate four generations of dike intrusions becoming progressively younger to the east. Early D1 and D2 dikes have basalt and basaltic andesite compositions and NNE and NNW attitudes, respectively, with moderate to gentle dips to the east. They are cut by mineralized, dike-parallel normal faults defining local grabens. Younger D3 dikes display andesitic and boninitic compositions and have WNW strikes with steep dips. These dikes are cut by both dike-parallel and dike-orthogonal faults that form locally well-developed graben structures with extensive epidote and chalcopyrite mineralization. The youngest D4 dikes with 240°–290° orientations occur as isolated swarms intruding earlier dike generations in the eastern part of the SDC, range in composition from quartz–microdiorite to rhyodacite and rhyolite, and are cut by ~NW-oriented faults and shear zones. Changes in dike compositions from basalt and basaltic andesite to andesite, boninite, rhyodacite and rhyolite through time in the SDC are consistent with changes in the lava chemistry stratigraphically upward and eastward in the extrusive sequence, indicating significant chemical variations in melt compositions as the EMO evolved. Development of the SDC and its extensive normal faulting were a result of upper plate extension and rifting in the protoarc–forearc crust caused by rapid slab rollback in the Mirdita basin, reminiscent of the late Cenozoic extensional tectonics of the Izu–Bonin–Mariana system in the Western Pacific. Shifting of dike attitudes to more easterly orientations in later stages of SSZ magmatism signals a gradual change in the spreading direction likely caused by impingement of the clockwise rotating Pacific plate. The SSZ Mirdita basin evolved similarly to the last 100 km of recorded spreading in the West Philippine Basin, where the rotation of the seafloor spreading axis was caused by the incipient collision between the northern part of the Philippine arc with rifted fragments of Eurasia.

1. Introduction

Ophiolites have provided the basis for many of the hypotheses regarding oceanic crust formation, since their recognition as preserved fragments of ancient oceanic lithosphere in the 1960s (Gass, 1968; Miyashiro, 1973; Coleman, 1977; Moores, 1982; Pearce et al., 1984; Dilek et al., 1990; Robertson, 2002; Flower and Dilek, 2003; Garfunkel, 2006; Dilek and Polat, 2008). Ophiolite exposures on land provide a unique opportunity to observe the structural architecture of oceanic crust in four dimensions, specifically spreading-related tectonic structures (faults and shear zones) and those features associated with magmatic plumbing (different dike generations and crosscutting relations) and hydrothermal alteration (veins and vein systems) (Harper et al., 1988; Juteau et al., 1988; Dilek and Eddy, 1992; Dilek et al., 1998). Although the ophiolite-oceanic crust analogy based mainly on structural observations and the seismic velocity structure of oceanic crust has increased our understanding of magmatic, tectonic, and hydrothermal processes at seafloor spreading centers, modern oceanic crust generated at mid-ocean ridges is geochemically quite different from most ophiolites (Dilek, 2003, and references therein for the historical background on this topic). While oceanic crust recovered from modern mid-ocean ridges has MORB chemistry, most ophiolites display silica oversaturated, low-Ti, low-Zr chemistry indicative of supra-subduction zone (SSZ) origin (see Pearce, 2003, for related discussions and history; Miyashiro, 1973; Shervais, 2001).
It is widely believed nowadays that ophiolites have been developed or modified in extensional settings in suprasubduction zone (SSZ) environments where the amount of spreading is controlled by rates of subduction and slab rollback, while the magma supply rates are controlled by local temperature profiles, the lithology of the subducting crust and mantle wedge, and the abundance and nature of fluids. Modern SSZ environments are difficult to examine in 4D because of the limited access and sampling, although ODP studies of the Izu–Bonin–Mariana (IBM) system in the Western Pacific has been extremely productive and insightful to document the mode and nature of extensional tectonics, igneous stratigraphy, and chemical geodynamics in arc–forearc–trench rollback systems (Stern et al., 1989; Arculus et al., 1992; Pearce et al., 1992; Taylor, 1992).

In this paper we present a detailed study of the internal structure of the sheeted dike complex in the Eastern Mirdita ophiolite (EMO), Albania (Fig. 1), in order to document the mode and nature of extensional tectonics and associated magmatism during formation of the Jurassic protoarc–forearc crust preserved in this ophiolite. We describe the spatial and temporal distribution of different dike generations and their geochemical variations, and discuss the significance of the changes in dike orientations and chemistry through time and space in light of the tectonic evolution of this ophiolite. We then compare the construction of the EMO to the extensional tectonics of the IBM and the West Philippine Basin in the Pacific in order to derive some conclusions about SSZ evolution of oceanic crust.

2. Geology of the Mirdita ophiolite

The majority of the Jurassic ophiolites in Albania occur in a NW-trending belt (Fig. 1), which is bounded by the Krasta–Çukali tectonic zone and the Pre-Apulian Platform to the west and by the Pelagonian Platform to the east (Fig. 2). The Krasta–Çukali tectonic zone consists of Middle Triassic intermediate to basic volcanic rocks stratigraphically and tectonically intermingled with contemporaneous continental shelf, slope and rise sedimentary rocks (Shallo, 1992; Robertson and Shallo, 2000; Dilek et al., 2005, and references therein). The Pelagonian Platform at its western edge includes a Lower–Middle Triassic sandstone–limestone–volcanic rock assemblage, which is overlain by Middle–Upper Triassic to Lower Jurassic shallow-water carbonates interbedded with chert and thin layers of micritic limestone (Shallo, 1992; Dilek et al., 2005). The Triassic volcanic rocks are composed mainly of basalt, with andesite, rhyolite, and trachyte intercalations. The Upper Jurassic pelagic Ammonitico Rosso and thin nodular limestones overlie the shallow-water limestones and pass upward into shale and red radiolarian chert of deep-water sedimentary facies rocks. These rocks are in turn unconformably overlain by Tithonian–Lower Cretaceous turbiditic rocks, debris flow, and olistostromal deposits that contain widespread ophiolitic material. The Krasta–Çukali and Pelagonian zones collectively make up a rifted conjugate passive margin pair bounding the Albanian ophiolites (Dilek et al., 2005).

The Albanian ophiolites within this NW-trending belt (i.e. south of Tirane in Fig. 1) include mainly upper mantle peridotites intruded by gabbroic, troctolitic, and basaltic dikes, and overlain by cumulate gabbros (Dede et al., 1966; Shallo, 1992, 1994; Kodra et al., 1993b; Bébien et al., 1998; Hoeck et al., 2002; Shallo and Dilek, 2003; Bortolotti et al., 2005; Dilek et al., 2005; Koller et al., 2006). Sheeted dikes are rare to 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; Koller et al., 2006). 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, Karçe 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. These metamorphic units have been interpreted by many researchers as metamorphic soles beneath the Albanian ophiolites (Carosi et al., 1996; Collaku et al., 1992; Bortolotti et al., 1996; Vergely 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 (Vergely et al., 1998; Dimo-Lahitte et al., 2001). The 40Ar/39Ar ages obtained from the amphibolites in these metamorphic units range from 174 Ma to 165 Ma and are generally older (by ∼4 m.y.) than their counterparts in the Mirdita zone farther north (Dimo-Lahitte et al., 2001).

The NW-trending ophiolite belt makes a sharp 90° turn into a short NE-trending segment in northern Albania (Fig. 2), known as the Mirdita zone and corresponding to the Shkodër–Peç lineament (Fig. 1) on the tectonic map of Albania (Kodra et al., 1993a; Robertson and Shallo, 2000; Bortolotti et al., 2005). The ophiolites in the Mirdita zone occur in a ∼40-km-wide belt also bounded by the conjugate passive margin sequences of the Krasta–Çukali and Pelagonia zones on the west and the east (Fig. 2). The western and eastern parts of the Mirdita zone are occupied by upper mantle peridotites with different lithological and chemical compositions (Dilek and Flower, 2003). The peridotite massifs close to the Apulian margin sequences in the

Fig. 1. Distribution of the Jurassic Tethyan ophiolites in the Balkan Peninsula. The Mirdita ophiolite occurs in a NE-trending zone (north of Tirane) between the NW–SE-running Dinaride and Hellenic ophiolites. Key to lettering: EMO — Eastern Mirdita ophiolite, SPL — Shkodër–Peç lineament.
west (i.e. Krabbi, Puka, Gomsiqe) consist mainly of lherzolites — plagioclase lherzolites, whereas those near Pelagonia in the east (i.e. Kukesi, Lura, Bulqize) are composed of harzburgites with major chromite deposits (Nicolas et al., 1999; Hoxha and Boullier, 1995). Nicolas et al. (1999) have reported that the lherzolitic peridotites in the west are also underlain by tectonized harzburgites.

The Mirdita zone has been interpreted to have two distinct ophiolite types based on the differences between the upper mantle peridotites and the internal stratigraphy and chemical compositions of crustal units (Shallo et al., 1985; Shallo et al., 1990; Beccaluva et al., 1994; Bortolotti et al., 1996; Tashko, 1996; Bébien et al., 1998; Nicolas et al., 1999; Robertson and Shallo, 2000; Bébien et al., 2000; Bortolotti et al., 2002; Shallo and Dilek, 2003; Saccani et al., 2004; Dilek et al., 2008). The thinner Western Mirdita ophiolite (WMO) shows mainly MORB affinities, and the nearly 10–12 km-thick Eastern Mirdita ophiolite (EMO) displays MORB to island arc tholeiite (IAT) geochemical affinities (Saccani et al., 2004; Beccaluva et al., 2005). Structural and geochemical studies by Dilek et al. (2008) have shown that these two ophiolite types are both laterally (from west to east) and vertically transitional in time and space, although the original igneous contacts have been locally modified by late Cenozoic, collisional thrust faults (Dilek et al., 2005).

The WMO consists of lherzolitic peridotites, mafic-ultramafic cumulates and mylonitic gabbros, rare sheeted dikes, and extrusive rocks that collectively form a ~3-km-thick ophiolite sequence characteristic of Hess-type oceanic crust (Dilek, 2003). Plutonic rocks include olivine gabbro, troctolite, ferrogabbro, gabro, and plagiogranite, and are locally intrusive into and/or overlying the peridotites. Extrusive
rocks form a nearly 600-m-thick sequence composed mainly of massive to pillow lavas and hyaloclastites resting directly on serpentinized peridotites and gabbroic rocks along igneous contacts (Dilek et al., 2005). Isolated dike intrusions crosscut and feed into different lava flows. These dikes and the overlying lava flows are cut by normal faults showing throws as much as several meters and quartz–epidote mineralization (Banerjee et al., 2002; Dilek et al., 2005). Late Bajocian–early Bathonian to late Bathonian–early Callovian age, 5- to 20-m-thick radiolarian cherts overlie the extrusive rocks in the WMO (Marcucci et al., 1994; Marcucci and Prela, 1996).

The EMO represents a typical Penrose-type ophiolite pseudostratigraphy (Dilek, 2003) complete with sheeted dikes and a nearly 1.1-km-

Fig. 3. Field occurrence of sheeted dikes. (A) Moderately to gently dipping basaltic dikes feeding into the lowermost lava flows within the extrusive sequence. (B) Moderately dipping and highly sheared basaltic D1 dikes on the left are intruded and crosscut by meter-wide, subvertical basaltic andesitic D2 dikes. (C) NW-striking, thick D2 dikes crosscutting thinner, N–S-striking D1 dikes; both dikes are cut by a gently-dipping normal fault (marked by the arrow). (D) Steeply NE-dipping, most prevalent basaltic andesite (D2) dikes. (E) Basaltic andesite D2 dikes (161°, 75°NE) with gabbro screens (white color) are cut by dike-parallel normal faults and shear zones, which are in turn cut and offset by SW-dipping low-angle brittle faults (hammer is resting on one of these late faults).
Fig. 4. Outcrop maps of different dike generations within the sheeted dike complex. A. NNE-striking and WNW-dipping basaltic D1 dikes are intruded by NNW-striking, basaltic andesitic D2 dikes. Dikes range in width from 0.5 m to 1.5 m. Both dike generations are crossect by moderately dipping F3 faults. B. NW-striking, basaltic andesite D2 dikes are intruded by isolated, steeply dipping andesitic D3 dikes and moderately SE-dipping rhyodacitic and rhyolitic D4 dikes. C. Strongly brecciated D2 dikes are intruded by NW-striking andesitic D3 dikes toward the eastern end of the sheeted dike complex near Spac. Brecciation is mostly related to faulting and shearing. D. In the central part of the sheeted dike complex, D1 and D2 dike generations are intruded by mostly andesitic D3 dikes. D2 and D3 sheeted dikes are crossect by NW- and SE-dipping F3 faults, which locally formed intense brecciation and cataclastic shear zones. Both dike generations and faults form locally well defined extensional graben structures associated with widespread epidote and chalcopyrite mineralization. E. In the east-central part of the sheeted dike complex, basaltic andesitic D2 dikes include gabbro–microgabbro screens and are crossect extensively by dike-parallel, moderately NE- and SW-dipping normal faults and shear zones (F2). D2 dikes, gabbro screens and F2 faults are intruded by boninitic D3 dike swarms. Some D3 dikes were emplaced along the pre-existing faults and shear zones, and some were deformed along the re-activated F2 faults.
Fig. 5. Lower-hemisphere stereonet plots of dike generations in the sheeted dike complex. Upper row, from left to right: Contour diagram of the poles to all dikes measured in this study. The two maxima in the northern quadrants indicate predominantly NW- and NNE-striking dikes. D1 through D4 dike generations represent progressively younger dike intrusions (based on crosscutting relations) with different geochemical compositions and show a shift from more northerly to more westerly orientations with generally northerly dips. Rhyolitic D4 dikes are more common in the eastern part of the sheeted dike complex. Lower row, from left to right: F1 and F2 faults are dike-parallel normal faults forming local graben structures with epidote and chalcopyrite mineralization. F3 faults are NNE–WSW-striking ad moderately- to gently-dipping faults that are commonly oblique to perpendicular to D2 and D3 dike generations. NNW-oriented, latest-stage F4 faults dip moderately to steeply to the NE or SW and crosscut the youngest and highly differentiated D4 dikes at nearly perpendicular to oblique faults.
Table 1

Geochemical analyses of representative samples of lavas and dikes from the Western (WMO) and Eastern (EMO) Mirdita ophiolite, Albania

<table>
<thead>
<tr>
<th>Sample</th>
<th>WMO Lavas</th>
<th>WMO dikes</th>
<th>EMO lavas</th>
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<tr>
<td></td>
<td>Basalt</td>
<td>Basalt</td>
<td>Basalt</td>
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<tr>
<td>44-Al-00</td>
<td>48.18</td>
<td>48.70</td>
<td>50.23</td>
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<td>40-Al-00</td>
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<td>55-Al-00</td>
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<td>62.49</td>
<td>64.52</td>
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<tr>
<td>62-Al-00</td>
<td>63.39</td>
<td>67.48</td>
<td>69.54</td>
</tr>
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| Abbreviation: Bas. ande. = basaltic andesite; Dac. = Dacite; n.a. = not analyzed; n.d. = not detected; L.O.I. = loss on ignition.

3. Internal structure of the sheeted dike complex

The sheeted dike complex (SDC) comprises a nearly 10-km-wide section of mutually intrusive sub-parallel dikes (Fig. 3). We examined 922 dikes along a 71-km-segment of the SDC in the EMO between the towns of Reps and Spaç (Fig. 2). This transect included a complete cross-section of the sheeted dike complex from the dike–gabbro boundary upward to the contact between the dikes and the extrusive sequence. The dike–gabbro boundary is marked by a transition zone displaying mutually intrusive relations between dikes and the uppermost isotropic gabbros, quartz diorites, and plagiogranites. The boundary between the sheeted dikes and the extrusive sequence is complex with dikes locally feeding into various levels of pillow and sheet lavas.

We have identified four dike generations based on their cross-cutting relations and structural and compositional features. Nearly 15% of the dikes have doubly chilled margins. The rest of the dikes show one-sided chilled margins, and the majority of these dikes have mutually intrusive relations with isotropic gabbros, plagiogranites, and quartz diorites, and feed into the overlying pillow lavas (Fig. 3). The internal structure of the sheeted dike complex is presented in the next section below.

The ~1 km thick extrusive sequence in the EMO is composed of pillowed to massive sheet flows ranging in composition from basalt and basaltic andesite at the bottom to andesite, boninite, rhyodacite and rhyolite in the upper part (Shallo et al., 1987; Shallo, 1990, 1995; Beccaluva et al., 1994; Bortolotti et al., 1996; Bortolotti et al., 2002; Shallo and Dilek, 2003; Saccani et al., 2004; Dilek et al., 2007, 2008). Pillowed to massive sheet flows in some areas are enriched in silica with lavas occupying the graben centers.
generally display chilled zones on their eastern margins. The first and second dike generations, labeled D1 and D2 respectively, are composed primarily of grey to blue-green, andesite dikes are mostly aphyric with a groundmass consisting of epidotized plagioclase, amphibole (variably altered to chlorite), minor clinopyroxene and Fe-oxides, and less commonly quartz. Rare phenocrysts consist of moderate-phyric (7% phenocrysts) to highly-phyric (∼75%) dacite and dacitic andesite dikes. These dikes range in width from 60 cm to 3 m and in vertical extent from ∼40 cm, with doubly chilled, irregular margins. This dike generation is cut by NW-oriented, dike-orthogonal normal faults (F4) and shear zones (Fig. 4B–C and Fig. 5). D4 dikes make up the youngest dike generation within the SDC, have easterly orientations between 240° and 290° with steep dips (∼75°); Fig. 5), range in composition from quartz dacite and dacitic rhyodacite to rhyolite. These dikes broadly correspond to Shallo’s (1995) description of fourth generation dikes described as quartz–dactite and dactic–rhyodacitic dikes. These fine-grained dikes commonly occur as single dikes, isolated intrusions, or small dike swarms throughout the dike complex (Fig. 4B–C). D4 dikes typically have widths of 20–40 cm, with doubly chilled, irregular margins. This dike generation is cut by N–NW-oriented, dike-perpendicular faults (F4) and shear zones (Fig. 4B–C and Fig. 5). Dactite and rhyolitic dikes are aphyric to moderately phyrty (∼7% phenocrysts) to highly-phyry (∼20% phenocrysts). Phenocrysts in these dikes rocks are made of clinopyroxene, orthopyroxene, and plagioclase.

Younger third generation dikes (D3) are composed primarily of andesite and porphyritic boninites that crosscut earlier D1 and D2 basaltic and basaltic andesitic dikes (Fig. 4E). These D3 dikes occur in isolated dike swarms with WNW orientations and high angle (60°–75°) dips (Fig. 5). They range in width from 60 cm to 3 m with one- and two-sided chilled margins. They are cut by dike-parallel, mineralized normal faults (F2), defining locally well developed structural grabens (Fig. 5) and displaying throws of a few meters or less. Dike-orthogonal normal faults (F3) crosscutting D3 dikes tend to strike 060°–080° with dips of 35°–50°, locally becoming listric with depth (Fig. 5). Andesitic dikes in the sheeted dike complex are mostly aphyric with a groundmass composed of plagioclase (alterated to smectite), quartz, pale-green amphibole, fine-grained Fe-oxide, zeolite, and chlorite. Rare phenocrysts consist of plagioclase and clinopyroxene. Boninitic dikes range from aphyric to moderately-phyric (∼7% phenocrysts) to highly-phyric (∼20% phenocrysts). Phenocrysts in these dike rocks are made of clinopyroxene, orthopyroxene, and plagioclase.
Late-stage quartz diorite plutons and stocks crosscut all dike generations within the SDC and dikes emanating from these plutons are intruded upward along fault zones and shear zones. Hydrothermal alteration around these plutons is widespread, locally extending over 100 m in width and the dikes of the SDC are almost completely recrystallized to epidotites within these alteration zones. Extensive veining and sulfide (chalcopyrite) mineralization occurs spatially associated with these alteration zones.

4. Geochemical progression within the EMO crustal section

We have done systematic geochemistry of the representative dike generations within the sheeted dike complex and lava flows in the extrusive sequence of the EMO in order to document the progressive evolution of ophiolitic magmas through time. We also compared the geochemistry of the EMO dikes and lavas to that of the WMO dikes and lavas. A more comprehensive coverage of the chemical analyses of the upper crustal rocks in the Mirdita ophiolite is available in Dilek et al. (2008). The analytical techniques and procedures used for major- and trace-element analyses are also described in Dilek et al. (2008). We present the major- and trace-element analyses of a representative suite of lavas and dikes from the WMO and EMO in Table 1. The majority (~75%) of the analyzed samples have L.O.I. contents <4%, indicating very little to moderate alteration. Evaluating the major- and trace-element geochemical data from all analyzed rock samples from the Mirdita ophiolite, Dilek et al. (2008) considered L.O.I. values against all the elements but found no correlation that would indicate enrichment or depletion with variable L.O.I. Therefore, we infer that element mobility during alteration and metamorphism did not affect original element concentrations in our analyzed dike samples significantly.

The WMO dikes and lavas are represented mainly by MORB-type tholeiitic, subalkaline basalts with a narrow SiO$_2$ range of 47–50 wt%, whereas the WMO dikes and lavas are characterized by island arc tholeiitic (IAT) and boninitic rocks ranging in composition from basalt and basaltic andesite to andesite, dacite, rhyodacite, and rhyolite with a much wider range of SiO$_2$ between 50 and 70 wt.% (Fig. 6). This compositional range and progression of the EMO dikes is consistent with our grouping of different dike generations (D1–D4) based on their crosscutting relations in the field. The WMO dikes (mainly equivalent of our D1 dike generation) and lavas display a predominant MORB affinity with a detectable subduction zone influence, as indicated by the occurrence of typical island arc-type (IAT) basalts among them (Fig. 7). However, the EMO dikes and lavas plot nearly all in the island arc and boninitic fields (D2 through D4 dikes), with some minor occurrences in the MORB field (mainly D1 dikes; Fig. 7). The chondrite-normalized REE patterns of both the WMO and EMO dikes and lavas range from rather flat to LREE-depleted; they are also both depleted with respect to the REEs, although the EMO lavas and dikes are considerably more differentiated than those of the WMO (Fig. 8). The representative basaltic andesite dike having the lowest REE contents among the EMO dike groups shows a REE composition typical of MORB/IAT basalts of Saccani et al. (2004) and the intermediate Ti and Zr basalts of Hoeck et al. (2002) from the South Albanian ophiolites. The EMO also includes dikes with high-Mg andesitic compositions showing a distinct convex-down pattern typical of boninites (Fig. 8).

The EMO dike groups are characterized by depletion in Ta, Nb, and high-field strength elements (HFSE) (Fig. 9). Basaltic andesite dikes show HFSE values ranging from 0.4 to 0.8 times N-MORB composition and strong negative anomalies in Th, Ta, and Nb (Fig. 9). Andesite and dacite dikes have HFSE values between 0.5 and 3 times N-MORB and slight to major negative anomalies in Th, and Ta and Nb, respectively (Fig. 9). All these basaltic andesite, andesite and dacite dike rocks display a tendency toward lower overall enrichment in the elements between Ce and La. The boninitic dikes, on the other hand, show strong depletion as they all plot below unity on the MORB-normalized diagram (Fig. 9). The rhyolite dike mimics the patterns of the dacitic dikes, although it is clearly less enriched and significantly more depleted in Ti. All dikes (except boninites) show slight Y positive anomalies. Andesite, dacite, and rhyolite dikes have Th contents significantly higher than that of MORB.

The petrogenetic modeling of the dikes and lavas has shown that the WMO and EMO developed through a progressive evolution of MORB to IAT to boninitic magmas in a suprasubduction zone setting (Dilek et al., 2008), similar to the Western Hellenide ophiolites farther south in Greece (Pe-Piper et al., 2004; Saccani and Photiades, 2004). Melt generation, mixing and differentiation occurred in the subarc–forearc mantle above this inferred intra-oceanic subduction zone. These processes were affected by slab rollback-driven mantle return flow and arc–wedge corner flow that collectively played a major role in the evolution of the melting column above the subducting slab (Dilek et al., 2008, and references therein). Mantle diapirism caused by slab rollback was instrumental in partial melting of the sub-arc mantle. The widespread magmatic and tectonic rifting that we have documented from the EMO sheeted dike complex was an artifact of upper plate extension keeping pace with the retrograde slab motion (slab retreat) as expected in this petrogenetic model. The late-stage boninitic dikes (D3) and associated lavas were the products of shallow partial melting of relatively hot, hydrous, and repeatedly depleted (ultra-depleted) peridotites in the rapidly evolving suprasubduction zone mantle wedge.

The latest-stage D4 dikes and equivalent lavas in the EMO that are composed of rhyodacites and rhyolites show large variations in high concentrations in Th with respect to more mafic dikes and lavas. Because Th is little mobilized in a fluid phase, the major Th enrichment in these dike magmas needs an explanation. A generally high-Th source (up to ~20 ppm) in comparison to the Th contents of MORB is interpreted to be subducted sediments (Plank and Langmuir, 1998). Therefore, high-Th and U/Th and Ba/Th ratios in dacitic, rhyodacitic and rhyolitic dikes indicate sediment and fluid incorporation from the subducting slab. We infer that the high Th values of these dike rocks resulted from magmas that were originated from a mantle source enriched in Th by melts derived from subducted sediments (Dilek et al., 2008). This very late-stage phenomenon was most likely related to melting of continentally-derived (Pelagonia) sediments on the subducting plate.

5. Extensional tectonics in a SSZ setting and geodynamics of the Mirdita basin

The internal structure of the EMO sheeted dike complex and the petrogenetic-geochemical features of the dikes and lavas in the Mirdita ophiolite in general suggest a complex sea floor spreading history in a suprasubduction zone tectonic setting. The inferred SSZ extensional tectonics of the Mirdita ophiolite is reminiscent of the protoarc–forearc crustal evolution in the Izu–Bonin–Marianas system in the Western Pacific Ocean (Stern et al., 1989; Taylor et al., 1991; Klaus et al., 1992; Taylor, 1992; Bloomer et al., 1995; Gribble et al., 1996; Cosca et al., 1998; Ishizuka et al., 2002, 2003; Hawkins, 2003; Straub, 2003; Nishizawa et al., 2006; Takahashi et al., 2007). The changing sea floor spreading directions within the Mirdita basin, as inferred from the variations in dike orientations within the EMO sheeted dike complex, were most likely the manifestation of changes in the regional stress regime. We present the geodynamic evolution of the West Philippine Basin as a modern analogue for the Jurassic Mirdita basin in terms of its rotational sea floor spreading tectonics.

5.1 Mirdita arc–protoarc evolution

Initial spreading of the Mirdita basin occurred as the Apulian and Pelagonian micro-continent rifted apart in the late Triassic, producing the Krasta–Çukul – Pelagonia conjugate passive margin pair (Dilek et al., 2005). With continued rift-drift and sea floor spreading, extension and subsidence within the Mirdita rift zone reached pelagic depths by 175 Ma (Dilek et al., 2005; Fig. 10A). Continued rifting caused the non-adiabatic uplift of upper mantle rocks with limited
partial melting and resulted in the formation of a Hess-type incomplete oceanic crust (Dilek et al., 2005). This early Jurassic oceanic crust underwent tectonic extension and oceanic core complex formation that led to the exhumation of the Gomsiqe, Puka and Krabbi peridotite massifs facing the Apulian passive margin (Fig. 2; Robertson and Shallo, 2000; Dilek et al., 2005, 2007).

The Mirdita basin started collapsing via intra-oceanic subduction (Fig. 10B) because of a regional compressional stress regime caused by the continental collisions that occurred farther north in the European side of Laurasia (Stampfl, 2001; Stampfl et al., 2001; Stampfl and Borel, 2004; Dilek et al., 2005, 2007). This Tethyan-wide contraction might also have resulted in a northwesterly motion and clockwise rotation of the Pelagonian microcontinent (Rosenbaum et al., 2002; Stampfl, 2001). Subduction and initial closure of the Mirdita basin occurred during 170–162 Ma, as constrained from 40Ar/39Ar ages of the metamorphic sole rocks (Vergély et al., 1998; Dimo-Lahitte et al., 2001), which are interpreted to represent subduction initiation (Insergueix-Filippi et al., 2000; Dimo-Lahitte et al., 2001; Wakabayashi and Dilek, 2001, 2003, and references therein). As the WNW-dipping (in present coordinate system) subduction zone was established, magmatic plumbing associated with this subduction produced an oceanic crust with MORB to island arc tholeiite (IAT) affinities (Domain-I) in an eastward extending incipient arc–forearc setting (Fig. 10B; Dilek et al., 2007, 2008). Rapid slab retreat due to slab rollback exceeding the convergence rates resulted in the upper plate extension which in turn led to the formation of the sheeted dike complex with D1 and D2 basalt to basaltic andesite dike generations.

A modern analogue for this kind of extensional forearc crust formation is best seen in the Izu–Bonin–Mariana (IBM) and Tonga regions, where older oceanic crust has been stretched and thinned by upper plate extension and has been overbuilt by new arc crust (Klaus et al., 1992; Stern and Bloomer, 1992; Taylor et al., 1991; Bloomer et al., 1995; Cosca et al., 1998). Crustal extension here is accommodated by high-to low-angle normal faults bounding half- and full-grabens, and the total amount of early rift-stage extension has been estimated to be ∼3 km. Border faults against the proto-remnant arc have dips ∼55° near the surface but attain sub-horizontal geometries at ∼2.8 km depth, suggesting that rift-related structures are detached at shallow crustal levels (Klaus et al., 1992). This extensional crustal architecture described from the IBM forearc crust is reminiscent of the structure of the upper oceanic crustal sequence in the Mirdita ophiolite as we document in this study.
The igneous stratigraphy of the IBM forearc crust has been well studied through the cores from ODP 786B (Arculus et al., 1992; Pearce et al., 1992, 1999; Cosca et al., 1998). The lower lavas composed of mafic pillow lavas and hyaloclastites and cut by individual dikes stratigraphically overlie low-Ca boninitic sheeted dikes (from 690 to 835 mbsf). The overlying upper lavas consist of lava flows, ranging in composition from bronzite andesite, andesite to dacite and rhyolite, and intercalating with breccias and rare sediments (from 160 to 69 mbsf). These lava flows are cut by dikes of similar compositions making up part of the volcanic sequence as feeder intrusions. High-Ca boninitic dikes crosscut the entire extrusive sequence representing the latest stage of forearc magmatism (Arculus et al., 1992). The crustal architecture and the geochemical make-up of the IBM forearc oceanic crust are thus remarkably similar to what we see in the Jurassic Mirdita ophiolite.

The closure of the basin continued in a zipper fashion from south to north, as a result of the impingement of the western edge of the clockwise rotating Pelagonian microcontinent at this arc-trench rollback system. This convergence and the diachronous closure of the basin caused the rotation of the rift axis to a WNW orientation (Fig. 10C). At the same time, shallowing subduction angle resulted in compression of the isotherms in the mantle wedge leading to the development of a thermal burst and the subsequent formation of boninitic melts (Martinez and Taylor, 2003). The late-stage boninitic magmatism in the Southern Dinaride belt north of the Mirdita zone might have been caused by the intersection of a southward-propagating active spreading center with the oceanic fracture zone at the northern termination of the protoarc (Fig. 10C; Deschamps and Lallemand, 2003). This stage of magmatism produced the upper oceanic crust (Domains II and III in Fig. 10C) that was composed mainly of andesitic and boninitic dikes (D3) and lavas in and across the previously formed incipient arc crust (Domain I). Partial melting of relatively hot, hydrous, and repeatedly depleted peridotite in the suprasubduction mantle wedge produced more evolved and felsic magmas feeding late-stage rhyodacitic and rhyolitic dikes (D4) and lavas. Higher U/Th and Ba/Th ratios and large Th-enrichment in these latest dikes and lavas (Dilek et al., 2008) were a result of melting of sediments on the subducting slab, which were derived from the adjacent Pelagonian subcontinent (Fig. 10C).

5.2. Comparison with the West Philippine Basin

This inferred sea floor spreading tectonics of the Jurassic Mirdita basin in a SSZ setting is reminiscent of the late Eocene–early Oligocene evolution of the West Philippine Basin (WPB) in the Western Pacific Ocean. The WPB represents an inactive marginal basin as part of the larger Philippine Sea Plate (Hamburger et al., 1983; Deschamps et al., 2002) and has a complex sea floor spreading evolution as a result of the intricate subduction history within the region. Geophysical investigations of the WPB have shown a complex sea floor spreading fabric with rotated abyssal hill features (Deschamps et al., 2002). In addition, the most recent 100 km of spreading that has occurred in the WPB displays variations in the sea floor spreading fabric, pointing to a change in ridge orientation with time. Collectively, these observations suggest that spreading direction in the WPB shifted while sea floor spreading was still in operation. Deschamps et al. (2002) showed that the initial spreading in the WPB prior to 35 Ma was oriented N10°E as determined from the sea floor fabric and abyssal hill orientations (Fig. 11A). This spreading direction was shifted to a N10°W orientation (Fig. 11B) ∼33 Ma due to the rotation of the sea floor spreading system to NE–SW possibly as a result of far-field stresses originated from regional tectonic events both to the west and east of the WPB (Deschamps et al., 2002). The most recent phase of sea floor spreading in the WPB occurred obliquely along a NW–SE rift valley creating a sea floor fabric that deformed the pre-existing sea floor structures in a broadly trans-tensional system (Fig. 11C). This last shift in the sea floor spreading direction was a result of the incipient collision between the northern part of the Philippine arc with rifted fragments of Eurasia, forcing a rapid reorientation of the spreading axis in the WPB. NE–SW extension continued until the E–W directed extension and sea floor spreading in the Parece–Vela arc began ∼26 Ma (Deschamps et al., 2002). The structural architecture of the sheeted dike complex (cross-cutting dikes generations and associated fault systems) in the Mirdita ophiolite suggests significant shifts in the direction of crustal extension as the protoarc–forearc crust developed in the rolling arc–trench system. Following the inception of intraoceanic subduction in the Mirdita basin, the extension was oriented ESE–WWN producing a predominantly NNE-trending tectonic fabric of Domain I (D1 dikes and F1 faults; Fig. 11I). Basaltic andesitic, andesitic to boninitic dikes of the D2 and D3 generations and associated fault systems crosscut this earlier fabric (Fig. 11III) and point to an ENE–WSW-directed extension in the forearc environment that produced Domain II. U/Pb Zircon dates from plagiogranite and quartz diorite intrusions (Fig. 2) associated with this stage of magmatism yield consistently similar ages ∼165 Ma (Dilek et al., 2008), providing a reliable time constraint for this phase of forearc accretion. The latest intrusions of rhyodacite, rhyolite and quartz microdiorite dikes have nearly WNW–ESE orientations, suggesting further rotation of the spreading direction to a more northerly orientation (Fig. 11III). Some
of the pre-existing fault systems in the highly extended forearc crust might have been reactivated during this phase, developing dike-perpendicular oblique-slip faults.

6. Conclusions

The Middle Jurassic Mirdita ophiolite in the northern Albanian ophiolite belt contains a nearly 10-km-wide sheeted dike complex that record the extensional tectonic evolution and rifting history of an ancient incipient arc–forearc crust. The WMO consists of lherzolitic peridotites intruded by gabbros and overlain by MORB-type extrusive rocks. The EMO includes a complete Penrose-type ophiolite pseudostratigraphy with a 1.1-km-thick extrusive sequence containing MORB-type pillow lavas at the bottom that are progressively transitional upward and laterally eastward into an IAT assemblage composed of basaltic andesite, andesite, rhyodacite, boninite and rhyolite.

Crosscutting relations of dike intrusions within the SDC define four dike generations with different orientations that mimic the compositional ranges in the extrusive sequence. D1 and D2 dikes composed of basalts and basaltic andesites (respectively) constitute the oldest dike generations with NNE and NNW orientations and are crosscut by dike-parallel normal faults (F1) forming local grabens. These dikes, normal faults, and graben structures represent the early stages of rifting of an incipient arc–forearc crust that formed in the upper plate of an ESE-retreating, intraoceanic subduction slab within the Mirdita basin. Andesitic and boninitic D3 dikes intruding the earlier dike generations in the eastern part of the SDC have WNW orientations and are cut by and rotated along dike-parallel F2 faults that display extensive epidote and chalcopyrite mineralization. These dikes were derived
from magmas that were produced from partial melting of hot, hydrous, and ultra-depleted harzburgites in the SSZ mantle wedge. Boninitic melt formation was most likely related to the compression of isotherms in the mantle wedge caused by the shallowing subduction angle as a result of the convergence of Pelagonia. The impingement of the clockwise rotating Pelagonia on the trench may also have caused the spreading axis to shift to a WNW–ESE orientation. The latest stage and highly evolved rhydactitic and rhyolitic D4 dikes and their extrusive counterparts were developed along this WNW-oriented spreading axis and were constructed on and across the extended incipient arc–forearc crust. The rifted protoarc–forearc evolution of the Jurassic Mirdita ophiolite and the rotational history of its paleo-spread direction to a more easterly orientation and andesitic–boninitic magmatism accompanied and followed by the eruption of highly differentiated lavas. This late-stage magmatism and the resultant oceanic crust (Domain III) were constructed on and across the pre-existing protoarc–forearc crust. See text for further discussion.

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