Mylonites in ophiolite of Mirdita (Albania): Oceanic detachment shear zone

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ABSTRACT

The northern Mirdita ophiolite massifs in Albanian Dinarides formed at a slow-spreading ridge, active during the Jurassic (160–165 Ma). They share a common horizontal Jurassic–Lower Cretaceous sedimentary cover showing that they were not deeply and intrinsically affected by later Alpine thrusting. The western massifs of Mirdita, first oceanic core complex (OCC) and detachment shear zone described in ophiolites, compare with OCCs in slow-spreading ridges and provide continuous exposure of the deep internal structure of this system, revealing its kinematics, thanks to detailed structural mapping in peridotites and gabbros. The Mirdita detachments root in the Moho transition zone (MTZ), a weak zone at the top of asthenospheric mantle, where basaltic melts impregnate dunites. The OCC domes are plagioclase-amphibole-bearing mylonitic peridotites, ~400 m thick, grading downward within 200 m to harzburgitic mantle. The mylonitic detachments crossed Moho beneath a NNE-SSW–trending ridge. On the western side of OCC domes, the hanging wall of the ridge, crustal gabbros, and basalts are still preserved, despite being deeply affected by hydrothermal alteration. From there, the partial molten MTZ was detached as a shear zone, mixing with lower gabbros. The OCC emerged, migrating upsection and eastward over 5 km. Finally, the OCC front is observed in hornblende-rich syntectonic mylonites derived from upper gabbros and from the overlying former lid. Serpentization is static within these mylonites. A low-temperature detachment fault is expressed in small outcrops of western massifs, except south of Puka massif where the paragneissic harzburgite–bearing mylonitic peridotites, ~400 m thick, grading downward within 200 m to harzburgitic mantle. The mylonitic detachments crossed Moho beneath a NNE-SSW–trending ridge. On the western side of OCC domes, the hanging wall of the ridge, crustal gabbros, and basalts are still preserved, despite being deeply affected by hydrothermal alteration. From there, the partial molten MTZ was detached as a shear zone, mixing with lower gabbros. The OCC emerged, migrating upsection and eastward over 5 km. Finally, the OCC front is observed in hornblende-rich syntectonic mylonites derived from upper gabbros and from the overlying former lid. Serpentization is static within these mylonites. A low-temperature detachment fault is expressed in a sheared antigoritic melange at the margin of the mylonitic shear zone. Asthenospheric flow in the harzburgitic mantle beneath the ridge of origin has been preserved below the OCC rooting. The dominant asthenospheric flow direction trends parallel to the ridge axis. This mantle flow rotates over 200 m into the low-temperature mylonitic detachments, where OCC motion turns transversal to the ridge. Crystal preferred orientation measurements on six samples point to brown hornblende crystal growth during mylonitic flow and illustrate the change of olivine intra-crystalline slip system in mylonites compared to porphyroclastic harzburgite.

INTRODUCTION

Mirdita ophiolite is a NE-SW–trending structural belt in Albania, located between the alpine Pelagonian in the east and external Dinarides units in the west (Fig. 1A). Based on several field campaigns in the northern part of Mirdita during the 1990s, it seems to be one of the few and, so far, the best ophiolite where an oceanic core complex (OCC) has been identified, located within the western Mirdita massifs, Puka, and Krabbi (Fig. 1A insert) (Nicolas et al., 1999; Meshi et al., 2009). Other OCC candidates include Chenaiet (Manatschal et al., 2011) and Thetford Mine in eastern Canada, which has been compared to Mirdita (Tremblay et al., 2009). We suspect that the Othrys ophiolite in Greece could be another excellent OCC candidate, as part of the Othrys band of the same Dinaric belt (Dijkstra et al., 2001). The evidence for OCC interpretation in these massifs is based on similarities with the OCCs properties discovered in the Atlantic Ocean (Karson and Dick, 1983; Karson et al., 1987; Mivel et al., 1991; Tucholke, 1998) and since, described in other slow spreading ridges.

Western Mirdita Ophiolite, Largely Preserving Its Oceanic Setting

An unexpected feature increasing our interest for the western Mirdita massifs is that the Upper Jurassic and Lower Cretaceous marine sediments were transgressive over the ophiolite seafloor (Figs. 1A and 1B). The Upper Jurassic sedimentary cover starts with shallow-water radiolarian flysch and ophiolitic conglomerates grading to the limestone cliffs of Lower Cretaceous (Gawlick et al., 2008). These formations remained nearly horizontal in the present situation with an average 170°E15’ strike and dip in map (Fig. 1B). This discordance is mainly observed in the central zone and the eastern massifs, and only locally in small outcrops of western massifs, except south of Puka massif where the Upper Jurassic cover extends several kilometers (Anonymous, 1983). For these reasons, the present-day relief in the northern Mirdita ophiolite remains close to the original marine topography (Nicolas et al., 1999; Tremblay et al., 2009), despite local Dinaric flat-lying thrusts (Gawlick et al., 2008) that do not affect the horizontal attitudes of the marine cover of the Mirdita ophiolite. Besides the intense tectonic activity in the surrounding alpine units, this suggests that the Mirdita ophiolite was the uppermost nappe (Schmied et al., 2008; Roure et al., 2010), ruling out any major rotation during alpine events, a situation suggesting that the preserved structures have the same orientations that developed at a spreading center.

This new paper on the Mirdita ophiolite focuses on the OCCs. It contributes only indirectly to the regional geology that is complex and has been prepared...
by the excellent mapping at the 1/200,000 scale by the Albanese geologists (Anonymous, 1983). As a secondary result only, we will contribute by precisely locating the ridge from which the OCC emerged in Mirdita, so far a subject of vivid discussion (Maffione et al., 2013; Tremblay et al., 2015).

Oceanic Core Complex Detachment Zone

Extensional core complexes in the present setting are only known through indirect geophysical tools (DeMartin et al., 2007), by seafloor drilling (Ildefonse et al., 2007a; Blackman et al., 2011), or by submersible means (Karson et al., 2006). Typically, in the literature on OCCs from the Mid-Atlantic Ridge (MAR), a mechanically weak formation initiating detachments has been located in serpentinites at shallow and accessible depth (MacLeod et al., 2002; Escartín et al., 2003). A deeper origin has been claimed in oceanic OCCs where major detachment shear zones include a high-temperature mylonitic component. A mechanically weak melt-rich zone thus appears as a potential decoupling site (Schroeder and John, 2004; Karson et al., 2006; Hansen et al., 2013).

Following our 1999 paper, the present contribution relies on (1) a detailed survey of contact relationship between ophiolitic formations relating to OCC dynamics; (2) an improved cover in foliation and lineation measurements within the mylonitic and porphyroclastic peridotites leading to detachment kinematics; and (3) detailed petrostructural studies linked to mylonites develop-
development after melt impregnated mantle rocks. The aim of this new contribution is to understand better the rooting and evolution of OCC detachment, integrating the many recent developments concerning modern OCCs.

THE WESTERN MASSIFS IN NORTHERN MIRDITA OPHIOLITE

General Description

The Mirdita ophiolites are divided in the western and eastern domains on each side of the central Mirdita synform trending N-S. It is a saddle, up to 10 km wide, and extends over some 40 km to the south (Fig. 1A). This central domain, lying between the eastern and western peridotite massifs, represents oceanic crust intruded by copious plagiogranites.

The eastern massifs (Kukes, Lura, and Tropoje, Fig. 1A) represent typical harzburgitic ophiolites, rich in chromite deposits, showing the internal crustal organization of a classical ophiolite sequence (Pamic, 1983; Hoxha and Boullier, 1995; Nicolas et al., 1999). This eastern domain is largely covered by cuestas of Early Cretaceous limestones (Fig. 1B). The western massifs in northern Mirdita (Gomsiqë, Puka, and Krabbi) are mantle domes (Fig. 2), variously capped by a horizon of mylonitic plagioclase-amphibole peridotites (Figs. 3A and 3B). The nature of the mantle is clearly harzburgitic and not lherzolitic. Gomsiqë massif is thrust westward on the Krasta Formation of external Albanides and is separated eastward from the Puka massif by the Krë deep volcano-sedimentary shear zone (Figs. 2 and 3A). This shear zone contains an ophiolitic mélangé consisting of a serpentinite matrix (Figs. 3C and 4A) and including blocks up to hundreds of meters of gabbros and basalts, nearly undeformed (Fig. 4B), such as in a typical root zone of diabase dikes complex. It is along the western foot-
hills of Krabbi and Puka massifs that an undeformed crustal unit is exposed extending along the Dedaj Valley (Fig. 2). These lowlands are occupied by highly altered gabbros (Figs. 5A and 5B), locally covered by undeformed pillow basalts (Fig. 4C). Kaolin responsible for the whitish alteration of these gabbros has been mined in a few places. North in this valley, these gabbros are poorly layered with a weak magmatic foliation. Locally they are olivine-rich, interlayered with anorthositic and wehrlite bands. North of Dedaj (Fig. 2), wehrlites, issued from the MTZ, and intruding the lower gabbros, develop spectacular magmatic folds with mutual recrystallizations (Figs. 4D and 4E).

The western slopes of Puka and Krabbi domes are mostly composed of mylonitic peridotites that stand over porphyroclastic harzburgites (Fig. 6A), grading to high-temperature harzburgites at the base of the domes (Fig. 6B).
Figure 3. Cross sections in the northwestern Mirdita ophiolite (see Fig. 2 for location). (A) West-east cross section oriented perpendicular to the paleospreading axis. It shows Gomsiqë mantle body thrust westward upon a Krasta Formation cushion, and eastward in faulted contact with the Krë shear band, serpentinites (C) with knockers of the ophiolite. Eastward, the Puka oceanic core complex (OCC) dome exposes mantle harzburgite overlain by the mylonitic shear zone beneath the lower gabbros of the oceanic ridge. Like the underlying high-temperature mantle harzburgite, mylonites are affected by static development of lizardite veining (F). Beyond, the eastern limit of Puka dome is in faulted contact with the Central Mirdita crustal section. (B) North-south section nearly parallel to sheeted dikes and to the presumed ridge axis. Crossing Krabbi and Puka summits, this section illustrates the thickness of the mylonitic cover: 700 m elevation between Krabbi summit and the Fushë-Arres crustal synform that trends perpendicular to the paleoridge axis. Lower mylonites are harzburgitic (D); mylonites at contact with basalt of the lid are amphibolites locally (E). MTZ—Moho transition zone.
Figure 4. Lithotypes that crop out in the northwest massifs. (A) Serpentinite (antigorite schist) including xenoliths of oceanic crust, at all scales (Krë Valley). (B) Variform gabbro, recrystallized with black hornblende and intruded by a diabase dike, as xenolith in sheared serpentinite (Krë Valley). (C) Undeformed pillow lavas, few meters above weathered gabbro (Dedaj Valley). (D) Magmatic mixing between olivine gabbro and wehrlitic intrusion (north of Dedaj Valley), indicative of mixing at solidus temperature of gabbro-wehrlite 1200–1100 °C. This Dedaj Valley exposure, representative of lower crust is devoid of any solid-state deformation. (F) Gneissic gabbro amphibolitized, collected nearby interlayered gabbro-dunite mylonite (eastern margin of Krabbi Dome). (G) Gneissic gabbro exposed in the southeastern border of Krabbi Dome, near Fushë-Arres. Notice the small, undeformed diabase dikes perpendicular to the gabbro foliation (scale bar = 10 cm).
The Puka and Krabbi domes are wrapped by mylonitic covers, both ~400 ± 100 m thick (Figs. 3A, 3B, and 5C). The mylonites largely extend at the southern and northern margins of Krabbi and Puka domes, respectively, along the W-E–trending crustal synform of Fushë-Arres (Fig. 2). Mylonites are well exposed again on top of Krabbi dome (Fig. 5C) and along its northeastern limit (Fig. 2). Mylonites have either a dominant harzburgitic composition (Fig. 3D), interlayered with mylonitic gabbroic layers at various scales, from tens of centimeters (Fig. 6C) to millimeters, intermixing olivine and plagioclase (Figs. 6D and 6E). Parts of the mylonitic cover, in particular at southern Krabbi and northern Puka margins, along volcanic exposures of the Fushë-Arres synform, are represented by peridotite-rich brown hornblendic amphibole (Fig. 3E). Ultra-mylonitic bands, dominantly represented by hornblende-bearing peridotite, are either interlayered with or locally crosscutting the mylonite foliation (Figs. 6F and 6G).

The base of the crustal section at the eastern contact of Krabbi and Puka massifs is represented by gabbros stretched in low-grade amphibolite facies (Figs. 4F and 4G). These gabbros belong to the north Mirdita central crustal domain.
Figure 6. Field structures in peridotites. (A) Mid-temperature porphyroclastic texture in harzburgite, with a strong foliation and lineation (see Fig. 7B). (B) High-temperature protogranular clinopyroxene-rich harzburgite. This peridotite is coarse grained (Fig. 7A) with some evidence of plastic strain (core of Puka massif). Protoplanular texture is defined by Mercier and Nicolas (1975) in mantle xenoliths as being in equilibrium with asthenospheric mantle at ~1200 °C. (C) Peridotite mylonite with gabbro layering (marker 3 cm) (near Ilballe, Krabbi massif). (D) Transition to mylonitic texture in plagioclase-rich peridotites, ascribed to Moho transition zone (MTZ) (marker 10 cm), west Krabbi dome. (E) Tight isoclinal folding in plagioclase-rich peridotite mylonite (marker 10 cm) (NW margin of Puka dome). Compare with thin sections of Figures 7C and 7D. (F) Isoclinal fold marked by gabbro layers in mylonitic peridotite. The folds are truncated by an ultramylonite band (top of northern Krabbi). (G) Peridotite mylonite, irregularly cut by an ultramylonite contorted "dikelet," exposed on Krabbi summit where mylonites are steeply dipping (marker 10 cm). Abbreviations: cpx—clinopyroxene; du—dunite; gb—gabbro; ol—olivine; opx—orthopyroxene; pl—peridotite—plagioclase-bearing peridotite.
Deformation in Mantle Rocks: Temperature and Strain Estimates

Photographs of representative thin sections in the mantle rocks from the studied massifs illustrate an evolution of harzburgite from coarse-grained to porphyroclastic texture (Figs. 7A–7C) observed in the mantle section of the studied massifs (see also Figs. 3A and 3B). This progressive evolution operates at decreasing temperature and increasing strain (Nicolas, 1989). (1) The protogranular or coarse-grained textures of Mercier and Nicolas (1975) mildly deformed at high-temperature ([high-T] ~1200 °C) in asthenospheric conditions (Fig. 7A); (2) medium-temperature ([mid-T] ~1000–1100 °C) porphyroclastic conditions, marked by grain-size reduction and irregular grain boundaries (Fig. 7B), and finally, (3) low-temperature ([low-T] <900 °C) porphyroclastic conditions, characterized by a flowing olivine matrix including orthopyroxene porphyroclasts (Fig. 7C). In these deformations, the flow proceeds dominantly by dislocation creep (Nicolas and Poirier, 1976). Shear senses are deduced from the obliquity of olivine (or orthopyroxene) crystallographic fabric (lattice slip plane and slip line), relative to the strain ellipsoid marked by foliation and lineation, respectively (Nicolas, 1989). In most cases, these relationships are observed directly through the optical microscope, in oriented thin sections, cut properly perpendicular to foliation and parallel to lineation.

Mylonites and then ultramylonites are represented here by their typical various lithologies, plagioclase-bearing peridotite, hornblende-bearing peridotite or amphibolite (Figs. 7D and 7E), all marking a sharp transition to the porphyroclastic harzburgite, due to their mineral phases layering. Shear-sense determination loses performance in mylonites when grain size decreases below 200 µm, and grain boundary sliding gets prominent (see section below on EBSD). Finally, kinematic analysis gets limited to flow plane and fold axes in ultramylonites, when the fine-grained matrix <50 µm behaves as a high-viscosity medium (Fig. 7F).

The last episode recorded in mantle rocks is a static lizardite network developed in olivine at low temperatures (below 400 °C) within high-T and low-T porphyroclastic peridotites, and even in the olivine-rich bands from mylonites (Figs. 3F and 7D). In this respect, ultramylonites are commonly absolutely fresh being largely impermeable to fluid circulation below 400 °C. Alternatively, sheared antigorite forms the matrix of the extended shear zone of Krë, between Gomsiqë and Puka massifs (Figs. 3A, 3C, 4A, and 7G).

Structural and Kinematic Analysis in Mirdita Western Massifs

With respect to our earlier structural and kinematic map covering the entire North Mirdita ophiolite (Nicolas et al., 1999), we have focused here on the two OCCs of Krabbi and Puka domes, integrating recent study (Meshi et al., 2010). We have complemented the coverage of Krabbi and Puka domes, with addition of a few measurements in the western ultramafic Gomsiqë massif (Figs. 8A and 8B). These data tend to confirm a dominant exposure of high-T harzburgite in this latter massif, with respect to mylonites. In the Puka and Krabbi mantle domes, high-T harzburgites are present in the lower zones northeast of Krabbi and in the east-central part of Puka. In harzburgites from Krabbi, as well as in Puka and Gomsiqë, the high-T foliation planes (Fig. 8A) are steeply dipping and parallel to the NE-SW–trending paleoridge, marked by sheeted dike orientation (see also Fig. 1A). High-T lineations consistently trend NE-SW with dominant shear sense top to SW (Fig. 8B). Transition to the low-T porphyroclastic conditions is marked by rotation of foliation into a NW-SE trend, with lineation gently plunging northwest, in both Krabbi and Puka massifs.

The mylonitic zone in the northeast part of Krabbi massif is in continuity with low-T mantle flow, marking a shear zone trending NW-SE with a dominant dextral shear sense. In the upper Krabbi dome, mylonitic foliations are flat or gently dipping west with lineation downdip.

Mylonites crop out in the northern end of the Puka dome. Mylonitic foliations are flat at the northern contact with the basaltic lid of Fushë-Arres formation; they steepen when relayed in porphyroclastic low-T conditions at the western contact with gabbros of the Dedaj-Krë zone. Mylonitic lineations trend E-W, with a dominant westward shear sense marked at the western margin. It should be recalled that mylonites in the domes vary on a local scale, and shear-sense determinations lose confidence.

Altogether in both Krabbi and Puka domes, high-T foliations beneath the OCC envelope are trending NE-SW, parallel to the sheeted dikes marking the Mirdita paleoridge NE-SW orientation (see also Fig. 1). High-T lineations gently plunging SW indicate that asthenospheric mantle flow is ridge parallel, and flow direction is moderately south plunging. The structural maps of the mantle section confirm the structural organization shown in cross sections (Fig. 3). Puka and Krabbi domes are mostly composed of a mylonitic wrapper ~400 ± 100 m thick, overlying porphyroclastic peridotites grading to high-T harzburgites at the base of the domes. The mylonites grade upsection from harzburgitic composition to plagioclase-hornblende-bearing peridotites, with increasing hornblende content at the contact with the basaltic lid.

Electron Backscatter Diffraction Measurements and Mylonites

Electron backscatter diffraction (EBSD) is a powerful tool to study the fabrics and the mineralogy in fine-grained mylonites. The EBSD measurements were carried out using the CamScan X500FE Crystal Probe equipped with a HKL Nordlys camera and HKL Channel 5 suite of programs installed at Geosciences Montpellier. Texture analysis was carried out using the MTEX, the open-source MATLAB toolbox for texture analysis (Hielscher and Schaeben, 2008). Due to the reduced grain size (500 µm down to <50 µm), measurements covered only a partial surface of the thin section, 7–25 mm², at a step size of 5 µm. The indexation rate is between 70% and 75%.

Six samples were collected for EBSD investigations (Table 1). The results of the three selected samples, representative of low-T porphyroclastic (sample 12A33), mylonitic (sample 12A16), and ultramylonitic (sample 12A13) textures, will be described and discussed (see location in Fig. 2 and texture in Fig. 7).
Figure 7. Textural evolution in thin section. Plain-light and same magnification to compare the contrasts in grain size (see sample locations in Fig. 2). The thin sections are cut in the XZ plane of finite strain (perpendicular to foliation and parallel to mineral lineation). (A) High-temperature porphyroclastic harzburgite (98P21), protogranular texture, polygonal olivine grains 2–5 mm, with sub-boundaries; note the undeformed network of lizardite veining. (B) Mid-temperature porphyroclastic harzburgite (98P6), foliated, grain size 2–3 mm. (C) Low-temperature porphyroclastic harzburgite (12A33), olivine matrix, grain-size 200–500 µm, orthopyroxene (opx) porphyroclasts gliding on (100) slip plane, or ribbon shaped. (D) Plagioclase-bearing peridotite (12A16), olivine layers and/or plagioclase-rich layers, grain-size ~100 µm, lizardite (liz) ribbons. (E) Mylonitic amphibolite (96AA47), brown hornblende (hb), grain size ~1 mm, recrystallized plagioclase (pl) ~100 µm. (F) Ultramylonitic harzburgite (12A13), viscous matrix of olivine, grain size <50 µm, body rotation of orthopyroxene porphyroclasts. (G) Sheared serpentinite (96AA58), lamellar antigorite including lenticular clinopyroxene (cpx) xenocrysts 1–5 mm. (H) Olivine gabbro (96AA54), magmatic texture, concave olivine grains (ol) 2–3 mm. See sample locations on map (Fig. 2). Electron backscatter diffraction (EBSD) samples are labeled on photographs.
Figure 9 illustrates the phase distribution map and pole figures of crystal preferred orientation (CPO). The phase map provides the grain size and the modal composition based on the total indexed phases (Table 1). Based on the observation on the large set of thin sections, the non-indexed phase in the six studied samples is dominantly serpentine and iron hydroxide. Thus this parameter in Table 1 is a measure of the rate of greenschist alteration, ~50% in coarse-grained mantle harzburgite, decreasing to 30% in mylonites.

Sample 12A33, a clinopyroxene-plagioclase–bearing harzburgite from north Krabbi is representative of low-T porphyroclastic texture (Fig. 7C) composed of a recrystallized matrix (grain-size 200–500 µm), including all phases (Table 1), 49% olivine, 6% clinopyroxene, 5% plagioclase, 2% hornblende, 13% orthopyroxene partly included in the matrix, and also present as residual porphyroclasts. The 27% non-indexed phase is serpentine (lizardite). The olivine (forsterite) CPO is consistent with the [100][010] high-T olivine slip system.
consistent with its porphyroclastic texture. The mild CPO of enstatite restricts the importance of intracrystalline glide on the expected slip plane (100), anticipated from the orientation and habitus of some porphyroclasts (Fig. 7C).

The mylonite sample 12A16 is a plagioclase-amphibole–bearing peridotite from north Puka, composed of a recrystallized matrix (grain-size ~100 µm) strongly banded at the millimeter scale (Fig. 7D). Its composition (Table 1), 29% olivine, 10% orthopyroxene, 1% clinopyroxene, 8% plagioclase, and 20% hornblende, departs from composition of plagioclase-amphibole–bearing peridotite, falling in the troctolitic field (with pargasite developed from diopside). The 31% non-indexed phases correspond partly to iron hydroxide and largely to the static development of serpentine lizardite in the olivine-rich bands (Figs. 3F and 7D). Only pargasitic amphibole exhibits a strong CPO of its three indexes consistent with oriented growth. Enstatite has a weak CPO similar to that observed in porphyroclastic harzburgite 12A33, (001) close to foliation.
The ultramydonite 12A13 is a peridotite from north Puka, composed of a fluidal matrix (grain size <50 µm) (Fig. 7F), including rounded orthopyroxene clasts enclosed by an asymmetrical pressure shadow that points to rotation in the flowing matrix. Its composition (Table 1), 54% olivine, 10% orthopyroxene, 1% clinopyroxene, 2% plagioclase, and 9% hornblende, is closer to lherzolite, assuming that pargasitic amphibole develops at the expense of clinopyroxene. The relatively low 23% non-indexed phases suggest a limited fraction of seawater penetrating the ultramydonite. Strong olivine CPO evolves when compared to sample 12A33. Obliquity of crystallographic axes on strain ellipsoid disappears, and olivine slip system [001](010) is now prominent. Pargasitic amphibole presents an expected CPO [001] axis parallel to lineation, indicative of crystal growth in mantle flow. Enstatite CPO is random.

### DISCUSSION

#### Critical Interfaces Related to Detachment

A dunitic Moho transition zone (MTZ) on top of the uppermost harzburgitic mantle of ophiolites is observed beneath Moho and the crustal lower gabbros, either in a slow-spreading (Karson et al., 1984; Nicolas, 1989) or in a fast-spreading system like Oman, where the MTZ is marked by an interlayering of dunite with gabbro sills (Boudier and Nicolas, 1995).

The detailed mapping of mylonites distribution in the studied domain of Mirdita ophiolite (Figs. 2, 3, and 8) has shown their dominant location at the interface of the mantle domes and the continuous crustal exposure. Mylonites mark the transition from high-T harzburgite to lower-crust components located at the western margin of Krabbi massif, along the Dedaj valley. This valley offers the best exposures of lower gabbros including wehrlites, highly deformed in magmatic conditions (Figs. 4D and 4E), cropping near mylonitic peridotites of the western slope of Krabbi massif. Eastward (Figs. 2 and 8), a second type of contact between the OCC detachment and the overlying basaltic lid (basalts and diabase dikes) is located along the Fushë-Arres synform between Krabbi and Puka domes. Here, mylonitic amphibole-rich peridotites and amphibolites issued from this lid crop out at both contacts with Krabbi and Puka domes. Continuing ridge magmatic activity during slip on the shear zone is attested to by a number of new diabase dikes cutting the mylonitic detachment domes. Finally, mylonites developed from plagioclase-rich peridotites are exposed on the eastern margin of Krabbi dome, in contact with sheared crustal gabbros from the Mirdita central crustal section.

The thickness of the transition from high-T harzburgite to mylonitic detachments is ~400 m, measured in both OCCs (Figs. 3 and 5C). The intensely deformed peridotites at the base of the detachment are typically rich in olivine, with a few orthopyroxene large clasts, derived from harzburgitic mantle (Fig. 7C). The overlying mylonitic peridotites are finely layered with gabbroic bands richer in minute grains of plagioclase and clinopyroxene (Figs. 6C–6E). These composite mylonites located between high-T porphyroclastic mantle harzburgite and crustal gabbro are inferred to be issued from a Moho transition zone composed of mantle peridotite irregularly impregnated by gabroic melt (Fig. 10A). Thus in Mirdita, a former MTZ is identified as being the main component of the mylonitic domes, mapped so far as plagioclase lherzolites (Anonymous, 1983). These facies represented the main signature of Mirdita western massifs contrasting with the harzburgitic mantle of the eastern massifs (Anonymous, 1983; Pamic, 1983).

### TABLE 1. MODAL COMPOSITION OF PERIDOTITES (FROM EBSD DATA)

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<th>Sample</th>
<th>Type</th>
<th>Olivine</th>
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<th>Clinopyroxene</th>
<th>Plagioclase</th>
<th>Amphibole</th>
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<td>1.07</td>
<td>0.14</td>
<td>14.6</td>
<td>33.4</td>
</tr>
<tr>
<td>12A16 N-Puka</td>
<td>Mylonite</td>
<td>29.3</td>
<td>9.5</td>
<td>1.2</td>
<td>8.4</td>
<td>20.9</td>
<td>30.7</td>
</tr>
</tbody>
</table>

*Non-indexed phases = oxides and serpentine.

Note: Modal composition obtained from electron backscatter diffraction (EBSD) measurements on six samples studied. The modal composition is computed excluding non-indexed phases (dominantly serpentine, oxides, and low-grade alteration microphases). Samples are classified on the basis of increasing pargasite content.
Figure 9. Electron backscatter diffraction (EBSD) results from Mirdita selected samples (see location on Fig. 2) (Table 1). The thin sections are cut in the XZ plane of finite strain (perpendicular to foliation and parallel to mineral lineation). Maps in the left column show distribution phases. Red—forsterite (Fo); blue—enstatite (En); green—diopside (Di); yellow—bytownite (By); gray—pargasite (Pg); black—non-indexed phases (see also Table 1). In the right column, corresponding pole figures show crystal preferred orientation (CPO) of forsterite (Fo), enstatite (En), and pargasitic amphibole (Pa) (modes bracketed; see Table 1). White line is the trace of foliation (same orientation as in the phase map). Lower hemisphere stereoplots; contours at 0.5 multiple of a uniform distribution (m.u.d.). (A) Sample 12A33 from north Krabbi, porphyroclastic plagioclase-bearing lherzolite; grain size 200–500 µm. (B) Sample 12A16, amphibole-rich mylonite from northwest Puka, grain size ~100 µm. (C) Sample 12A13 from north Puka, ultramylonite peridotite, grain size <50 µm.
The Moho Transition Zone as a Detachment Surface

The Moho transition zone (MTZ) plays a major role in oceanic accretion. Its composition, shape, and orientation are highly dependent on the spreading rate (see below). Due to its partially molten nature, MTZ rheology is weaker than its mantle environment, and the OCC detachment tends to remain channeled within it.

The MTZ concept has been developed in the fast-spreading Oman ophiolites (Boudier and Nicolas, 1995), and it is now described in the East Pacific Rise (EPR) (Crawford and Webb, 2002; Carbotte et al., 2013). The MTZ is locally much thicker in slow-spreading ophiolites than in fast-spreading ophiolites, despite a much larger heat supply within it. In ophiolites representative of a slow to moderate spreading rate, the MTZ thickness ranges from 1 to 3 km (see compilation in Nicolas and Boudier, 2003). In Kukes massif from eastern Mirdita (Fig. 1), MTZ documented as a dunitic domain, varies from 1.5 to 2.5 km (Hohxa and Boullier, 1995); in Bulqiza massif (Fig. 1), MTZ thickness marked by dunite is over 2 km (Meshi et al., 2009). In both cases, foliations in peridotite are steeply dipping and abut on flat, layered gabbros through a pyroxene-rich banded unit a few hundred meters thick.

Due to (1) the systematic location of the mylonite at contact between mantle harzburgite and crustal formations and (2) the textural transition from porphyroclastic to mylonitic harzburgite and to plagioclase and/or hornblende mylonitic peridotite, we concluded that the shear detachment is initiated at a Moho transition zone. Merging from asthenospheric harzburgites, sheared deformation localized in the melt-rich MTZ, accounts for plagioclase-bearing peridotite mylonites and gabbroic layers. Upward migration of the detachment along crustal gabbros and basaltic dikes accounts for amphibole-rich mylonitic peridotite (Fig. 10A).

This conclusion concerning rooting of the detachment at depth, down to asthenospheric mantle, was also reached at Trans-Atlantic Geotraverse (TAG) (Mid-Atlantic Ridge 26°N) by deMartin et al. (2007), who reported results of a seismic study of a steep and active fault zone. Temperatures in detachment have been evaluated between 700 and 900 °C for an estimated depth ~7 km (Schroeder and John, 2004; Hansen et al., 2013) in mylonites from the Mid-Atlantic Ridge, Atlantis, and in Kane OCCs, respectively.

Figure 10. Time sequences represent the time evolution of the oceanic core complex (OCC) detachment as recorded in the fossilized OCC of Mirdita. (A) Step 1 is initiation of the detachment at the Mohorovičić discontinuity (the Moho), in a zone located at the ridge margin of a slow-spreading system, still composed of mantle impregnated by melt. This Moho transition zone (MTZ) would evolve, during cooling, and melt extraction toward the gabbro crustal section, in a thick dunitic MTZ, as observed in ophiolites representative of low- to mid-spreading rate. The OCC detachment is an alternative evolution. (B) Step 2 accounts for the hydrothermal path as recorded in studied mylonites, enriched in hornblende amphibole upsection. Quantification of progressive hydration during upward progression along the detachment is based on electron backscatter diffraction (EBSD) measurements (Table 1) of amphibole content (average 2% water in hornblende). (C) Step 3 is the final situation as represented in the fossil OCC from Mirdita ophiolite. HT—high-temperature; LT—low temperature.
Seawater Penetration at the Ridge

Phase distribution maps in our EBSD study provide accurate modal compositions. The seawater fraction in the detachments up to Moho is tentatively evaluated based on amphibole fractions in the mylonites, assuming an ~0.2% water content in amphiboles. The six representative mylonite samples analyzed (Table 1) are classified according to their amphibole content. Our field observations show that the harzburgitic mylonites are in contact with the low-T porphyroclastic harzburgites, at the base of the detachment, although hornblende-rich mylonites are located at the upper contact with the basaltic lid (Figs. 3 and 8). This distribution suggests that a decreasing fraction of seawater has penetrated along the ridge plane attaining on the order of 0.2% at Moho and rapidly decreasing below within the MTZ, to virtually disappear within the underlying mantle harzburgites (Fig. 10B). This compares with the deep-seawater crustal penetration, 6–7 km below seafloor as estimated at the Mid-Atlantic Ridge OCCs (Schroeder and John, 2004; deMartin et al., 2007; Hansen et al., 2013).

The lower-grade hydrous alteration, low-amphibolite, greenschist metamorphism in the detachment mylonites is not significant. This is inferred from the EBSD maps and modal composition (Table 1) stating that the non-indexed phases point to similar value in porphyroclastic harzburgite and in mylonites. The porphyroclastic harzburgite is devoid of greenschist phases except serpentine lizardite observed under the optical microscope. Similar observation is valid concerning the mylonites studied. The hydrous phase observed is lizardite largely developed at the expense of olivine-rich bands (Fig. 3F) and consistently contributes to the 30% non-indexed phases, in addition to iron hydroxides. This leaves little space for the development of hydrous phases, actinolite, talc, and chlorite, during the low-T stage of the exhumation process. The development of static lizardite suggests that the tectonic activity along the shear detachment had ceased below 400 °C, the upper limit for alteration in lizardite. The detachment was possibly relayed along antigorite-schist–sheared mélange exposed in particular in the Krë shear zone (Figs. 3C and 4A) that could represent the latest and separate stage of the exhumation process.

Finally, the deep, whitish alteration affecting gabbros and basalts west of Puka and Krabbi domes (Fig. 5B) has been ascribed to a Pliocene–Quaternary episode in the Albania 1/200,000° geologic map (Anonymous, 1983). However, weathering of their paleosoils could be older. This extensive alteration product is kaolinite, mined in a few places, and this necessitates temperatures above 80 °C (Ross and Kerr, 1931). It points to equilibrium temperature too high for groundwater. We assume that the detachment fault could have introduced seawater resulting from hot hydrothermal fluids percolating from the uprisal OCCs (Fig. 10).

Ridge Location in Western Mirdita

In Mirdita, the sheeted dikes are steep and oriented N-S to NNE-SSW (Nicolas et al., 1999), suggesting that the ridge was oriented accordingly. Here, we discuss the location of the ridge axis from which the Puka-Krabbi detachments have merged. Was it located to the west between Gomsiqë and these OCCs or to the east in the central Mirdita synform, between these western massifs and the Kukes ophiolite (Fig. 1)? In our previous paper, we had no argument supporting either side for the ridge of origin. Here, we have located the hanging wall on the eastern side of the Krë shear zone, between Gomsiqë and Puka massifs (Figs. 2 and 3). This is supported by observations of the absence of plastic strain and a common magmatic fabric in these lower gabbros associated with wehrlitic intrusions from Dedaj Valley (Fig. 4D and 4E). This domain of crustal exposure devoid of solid-state deformation, a remnant of ridge accretion, would represent the hanging wall of detachment, west of Krabbi dome. The next exposure of the hanging wall is represented by the lid formations, lava flows, and dikes of the Fushë-Arres synform. Here, the flat setting of the diabase dikes (Fig. 8A) may account for the hanging-wall tilting.

The detachments, progressing upsection within the crust and cooling, reached upper gabbros that were plastically deformed, together with the MTZ, thinned and transformed into plagioclase-bearing peridotite mylonites (Fig. 10A). At the level of the lid, part of the sheeted dikes was transformed to mylonitic amphibolites (Figs. 2 and 7E). Fresh diabase dikes that cut the mylonitic detachment point to continuous magmatic activity during the exhumation (Fig. 4G). The major shear zone of Krë containing large undeformed crustal knockers in a matrix of antigorite schists (Figs. 3A, 3C, 4A, and 4B) may derive from the last stage of detachments. The deep and extensive kaolinization of plagioclase in gabbros from the lowlands of Dedaj Valley is specific to this zone. It requires massive hot-water circulation within the hanging wall.

This query about the site of the paleo-ridge is important for the regional geology and for the modeling of west Mirdita OCCs. Oceanic core complex detachments in the Atlantic ridges could have emerged on either side of the ridge as documented at Kane OCC from the Mid-Atlantic Ridge (MAR) (Dick et al., 2008). The question has been addressed in Mirdita by Maffione et al. (2013), based on comparison of magnetization measured in the OCC footwall and hanging wall, a method experimented in Mid-Atlantic Ridge OCCs (Morris et al., 2009). Comparison of magnetization in gabbro and peridotite on the Puka eastern slope in Mirdita, lead Maffione et al. (2013) to assume a 46° counterclockwise rotation of the footwall around a subhorizontal axis trending N-S, thus localizing the ridge axis east of Puka massif. Alternative contribution to this question is provided by fission-track thermochronology (Muceku et al., 2008). In the western massifs concerned here, these authors identify the Krë shear zone between Gomsiqë and Puka massifs as part of a series of pre-Cretaceous thrust. This early group of thrust affects the ophiolite and relates to a major discontinuity during obduction or accretion, which is thus consistent with possible rooting of OCCs detachment along this line, as inferred from our detailed structural mapping.

Model for the Detachment

Recent papers (Nicolas et al., 1999; Tremblay et al., 2009) fully confirm the Upper Jurassic nearly intact seafloor topography above the internal structure of the northern Mirdita ophiolite, beneath nearly horizontal, transgressive
marine sediments. This fortunate situation of Mirdita OCCs in terms of tectonics simplifies the interpretation because it excludes late large rotations. Thanks to exposure of rocks with preserved asthenospheric fabric, and their relationship to shallower units, these entries improve the knowledge of deep kinematics of OCC. The frame of the model for Mirdita ophiolite of Figure 11 is inspired from geophysical models providing information on the deep structures of OCC detachments along the MAR ridge axis. These models are based on seismic data across the TAG at 26°N (de Martin et al., 2007), on gravimetric data at the 30°N Atlantis detachment (Nooner et al., 2003; Henig et al., 2012), and on detachment geology (Schröeder and John, 2004; Karson et al., 2006; Ildefonse et al., 2007b; Dick et al., 2008, Hansen et al., 2013).

The first evidence from the detailed mapping in western Mirdita (Figs. 8A and 8B) is the poor structural organization compared to other ophiolite bodies (Nicolas, 1989). In the field, the spectacular mylonites result in fairly scattered local orientations. At the scale of the map, the disorder also has another source that is the complexity of the kinematic information carried: from high-T, ridge-related longitudinal mantle flow to low-T transversal, detachment-related flow. Nevertheless, Figure 11 illustrates the complexity introduced by the detachment of the Mirdita domes, from their origin in the melt-rich, ~2-km-thick MTZ and their intrusion along the slope of the lithosphere-asthenosphere limit below the ridge axis. The shear detachment has been initiated into mantle peridotites, with prints of the high-T asthenospheric mantle flow, attached to the ridge of origin (Fig. 10A) and reflecting its kinematics (Fig. 8B). Progressing upward, the detachment tends to orient into a transverse northwest trend, as recorded in the overlying low-T porphyroclastic harzburgites and in mylonites near the hanging wall of detachments (Fig. 8B). On top of the mantle dome, mylonites trend into a flat settling and reflect some disorder of the flow directions (Figs. 8A and 8B). The shear detachment stretched to 400-m-thick mylonites points to an estimate close to the 450 m inferred in Kane OCC (Hansen et al., 2013). The clockwise rotation of the OCC footwall is consistent with the dominant shear sense deduced from the kinematic mapping (Fig. 8B). Kinematic indicators gathered in the high-T asthenospheric harzburgites, having preserved the print of mantle flow parallel to the ridge of origin, suggest that the ridge was active at the same time as the detachments were being initiated.

![Figure 11. Model of emplacement of core complex in Mirdita western masses. The model integrates the best documented structures in Krabbi massif: (1) The frozen spreading axis, represented by oceanic crust of Dedaj valley, devoid of sheared deformation, is the hanging wall. Crust and mantle section represented in this domain is based on structural mapping in Kukes and Bulqiza eastern masses (Hoxha and Boullier, 1995; Meshi et al., 2010). (2) The detachment roots in the soft zone at Moho level, progress upward, integrating first gabbros, then basaltic lid at contact. (3) Fission and shear sense along the detachment recorded in the lithospheric mantle flow and in mylonites refer to structural map of Figure 8. The flow line is consistently trending NW-SE; the shear sense in the model is optimized from poor resolution of shear-sense measurements (Fig. 8B). (4) Flow direction and shear sense in asthenospheric mantle rely on the most consistent kinematic results (Fig. 8), indicative of asthenospheric mantle flow parallel to the ridge. The dynamics of the system result in clockwise rotation and upward movement of the footwall. (5) The break-away is assigned to the eastern contact of mantle domes with gneissic gabbros of the central Mirdita crustal domain (Figs. 2, 4F, and 4G). Abbreviations: Du—dunite; Gb—gabbro; Hz—harzburgite; Wh—wehrlite.](1200°C_1.jpg)
Mid-Atlantic Ridge OCCs Detachment Surface

Initiating a detachment surface beneath the rift valley necessitates the presence of a mechanically weak horizon. Good candidates are either serpentinites forming at T<500 °C from shallow mantle or at greater depth of the domain of melt impregnation. The major shear zones in oceanic core complexes include both a high-T mylonitic component, typically capped by a lower-T semi-brittle shear zone (detachment fault).

In particular, outcrops at the MAR (19°45′N) and at the central part of the Atlantis massif where the sampling is superficial yield essentially low-temperature fault schists and sheared serpentinites. Based on such evidence, MacLeod et al. (2002) and Escartín et al. (2003) tend to extend their results to other core complexes on shallow detachments within serpentinites. In Mirdita, sheared serpentinites have only a local contribution along the frozen limit of the detachment (Krë shear zone). In serpentized peridotites and MTZ mylonites, all thin sections show that lizardite postdates any deformation.

Oceanic sampling has also produced a significant number of mylonites on the southern slope of Atlantis Massif, 30°N MAR (Schroeder and John, 2004; Karson et al., 2006), as well as on domes of Kane megamullion (Dick et al., 2008; Hansen et al., 2013). Studies of the high-T sheared samples offer many similarities with the detachment facies described in Mirdita, in particular the strain evolution recorded on the 400 m reconstructed petrostructural log at Kane (Hansen et al., 2013).

Based on this transition in Mirdita, and on mixed layers of gabbro-peridotite, we have ascribed the OCC detachment to the MTZ as described in ophiolites. This option departs from some OCC models that assign the weak zone initiating the detachment to gabbro intrusion in mantle rocks for the Atlantis Massif (e.g., Ildefonse et al., 2007b; Blackman et al., 2011) or for Kane OCC (Dick et al., 2008), according to Cannat’s (1993) model of a slow-spreading ridge. Altogether, we notice that some MTZ characteristics are identified as mantle components in the gabbro section of the Atlantis Massif (Suhr et al., 2008; Drouin et al., 2010), providing some credit to the existence of a MTZ at the root of the oceanic core complex. The MTZ option in Mirdita is also supported by the continuous exposure of the oceanic crust overlying the mantle domes in the mapped area. This discussion may relate to the complex structure of oceanic lithosphere and its strong dependence on spreading rate.

CONCLUSIONS

Oceanic core complexes (OCCs) exposed in the northern Mirdita ophiolite complement fragmentary information available for modern OCCs. The dome-shaped structure of both massifs in Mirdita comprising a mantle core wrapped by the detachment zone provides a 3D image of the OCC. Thermal evolution and kinematics of the detachment are deduced from detailed petrostructural mapping.

The detachment shear zone is composed of mylonitic amphibole-plagioclase peridotites, underlain by porphyroclastic harzburgite, and capping asthenospheric harzburgitic mantle rocks. The detachment is localized at Moho level and initiated in a melt-impregnated mantle. This option departs from some OCC models that invoke an intrusive magma chamber at the deep root of the detachment shear zone. Both models could relate to slightly different spreading rates. The shear-detachment mylonites are devoid of green-schist-facies hydrous phases, and serpentinization is static. A low-T antigorite schist mélangé at the western margin of the shear detachment may represent a separate last phase of the exhumation.

Root of the detachment is localized west of the domes along a N-S–trending paleoridge. Tracing progressive textural and kinematic evolution, a rapid transition from ridge-parallel asthenospheric accretion to ridge-transverse OCC shear detachment is inferred. Detachment progressed eastward, including lid formations in the shear domain (margins of the Fushê-Arres synform). Lattice-preferred orientation of mineral phases in mylonites reveals dominant activation of the low-T [001][010] slip system in olivine; strong orientation of [001] hornblende along the lineation is indicative of amphibole growing in the deformation path.

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REFERENCES CITED

Hansen, L.N., Cheadle, M.J., John, B.E., Swapp, S.M., Dick, H.J.B., Tucholke, B.E., and Tivey, 


