Title: Petrological and tectono-magmatic significance of ophiolitic basalts from the Elba Island within the Alpine Corsica-Northern Apennine system

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Abstract

Two distinct ophiolitic units, which represent remnants of the Jurassic Ligurian-Piedmont Ocean, crop out in the Elba Island. They are the Monte Strega unit in central-eastern Elba and the Punta Polveraia-Fetovaia unit in western Elba. Ophiolitic rocks from the Monte Strega unit are commonly affected by ocean floor metamorphism, whereas those from the Punta Polveraia-Fetovaia unit are affected to various extent by thermo-metamorphism associated with the Late Miocene Monte Capanne monzogranitic intrusion. Both ophiolitic units include pillow lavas and dykes with compositions ranging from basalt to basaltic andesite, Fe-basalt, and Fe-basaltic andesite. Basaltic rocks from these distinct ophiolitic units show no chemical differences, apart those due to fractional crystallization processes. They display a clear tholeiitic nature with low Nb/Y ratios and relatively high TiO_2, P_2O_5, Zr, and Y contents. They generally display flat N-MORB normalized high field strength element patterns, which are similar to those of N-MORB. Chondrite-normalized rare earth element patterns show light REE / middle REE (LREE/MREE) depletion and marked heavy (H-) REE fractionation with respect to MREE. This HREE/MREE depletion indicates a garnet signature of their mantle sources. Accordingly, they can be classified as garnet-influenced MORB (G-MORB), based on Th, Nb, Ce, Dy, and Yb systematics. We suggest that the Elba Island ophiolitic basalts were generated at magma starved, slow-spreading mid-ocean ridge. REE, Th, and Nb partial melting modelling show that the compositions of the relatively primitive Elba Island ophiolitic basalts are compatible with partial melting of a depleted MORB mantle (DMM) source bearing garnet-pyroxenite relics. Hygromagmatophile element ratios suggest that basalts from both ophiolitic units were originated from chemically very similar mantle sources. A comparison with basalts and metabasalts from Alpine Corsica and northern Apennine ophiolitic units shows that the composition of the inferred mantle source for the Elba Island basalts is similar to that of some Lower *Schistes Lustrés* metabasalts of Alpine Corsica ophiolites, and some basalts from the Internal Ligurian units of northern Apennine. In contrast, it slightly differs from those of other ophiolitic units of Alpine Corsica and northern Apennine. The chemical differences observed between basalts and metabasalts from different Ligurian-Piedmont ophiolitic units were likely associated with different partial melting degrees of either DMM source or garnet-pyroxenite relics and/or different mixing proportions of melts derived from them, as well as to different compositions of garnet-pyroxenite relics.

1. Introduction

The Ligurian-Piedmont Ocean was a small Jurassic oceanic basin that developed between the European plate to the NW and the Adria plate to the SE (see Principi et al., 2004 and Bortolotti and Principi, 2005 for exhaustive reviews). The records of this ocean are represented by the ophiolitic rocks now scattered in the southeastern and central Mediterranean Cretaceous (?)- Tertiary orogenic belts (i.e., Alps, northern Apennine, Corsica, Calabria, and Betic Cordillera). Ophiolites are particularly abundant in the northeastern Corsica (the so-called Alpine Corsica) - Elba Island - northern Apennine transect (Fig. 1), where they occupy the higher position in the orogenic wedges. In Alpine Corsica, the ophiolitic successions are mainly represented by the high pressure-low temperature (HP-LT) metamorphic *Schistes Lustrés* units (e.g., Durand-Delga, 1984). Nonetheless, some ophiolitic units, which do not show HP-LT metamorphism also crop out in the Alpine Corsica. They are (Fig. 1) the Balagne, Nebbio, Pineto, and Rio Magno units (Padoa et al., 2001, 2002; Saccani et al., 2000, 2008). The Balagne and Nebbio ophiolites have been interpreted by several authors as correlative of the northern Apennine ophiolitic units (Abbate et al., 1980, 1986; Durand-Delga, 1984; Principi and Treves, 1984, Durand-Delga et al., 1997; Bortolotti et al., 2001).

In the northern Apennine, ophiolites crop out in the Ligurian units, which were divided into two groups, the Internal (IL) and External (EL) Ligurian units (Elter, 1972, 1975; Abbate et al., 1980). The IL ophiolites (Vara unit, see Principi et al., 2004 and references therein) preserve true oceanic lithospheric successions, whereas the EL ophiolites are exclusively represented by oceanic slide blocks and breccias in the Cretaceous and Eocene clastic formations (Abbate et al., 1980; Marroni et al., 1998, 2002; Bortolotti et al., 2001; Nirta et al., 2005). According to Principi et al. (2004), the IL units represent the northwestern side (restored to the Mesozoic polarity) of the Ligurian-Piedmont domain and occupy the higher tectonic position in the nappe pile, whereas the EL units represent the southeastern side of this oceanic domain.

Summarizing the geochemical studies carried out by many researchers, three varieties of mid-ocean ridge basalts (MORB) occur in the Alpine Corsica, western Alps, and northern Apennine ophiolites (e.g., Ohnenstetter et al., 1976, 1981; Beccaluva et al., 1977; Venturelli et al., 1979, 1981; Cortesogno and Gaggero, 1992; Vannucci et al., 1993; Marroni et al., 1998; Rampone et al., 1998; Bill et al., 2000; Saccani et al., 2000, 2008; Padoa et al., 2001, 2002; Desmurs et al., 2002; Rossi et al., 2002; Montanini et al., 2008). They are: 1) normal-type (N-) MORB; 2) enriched-type (E-) MORB; 3) a variety of N-MORB characterized by depletion in heavy rare earth elements (HREE) with respect to middle rare earth elements (MREE), which indicates a garnet signature of their mantle sources. Saccani (2015) has identified the latter variety as garnet-influenced MORB (G-MORB).

E-MORB (also defined as transitional-type MORB by Venturelli et al., 1979; 1981) are found basically in the Balagne, Nebbio (e.g., Saccani et al., 2008) and some western Alps ophiolitic units (e.g., Bill et al., 2000) and have been interpreted as generated from slightly enriched mantle sources during the early onset of the oceanic spreading (e.g., Beccaluva et al., 1977; Venturelli et al., 1979, 1981; Bill et al., 2000). G-MORB and N-MORB are found in most of the Alpine Corsica ophiolitic units (e.g., Saccani et al., 2008), as well as in the IL ophiolitic units (e.g., Montanini et al., 2008), in clasts in the Cretaceous-Eocene turbidites of the EL units, and in some western Alps ophiolitic units (e.g., Bill et al., 2000). G-MORB, which are volumetrically predominant, have been interpreted as generated from partial melting of a depleted mantle source locally bearing garnet-pyroxenite relics (e.g., Montanini et al., 2008; Saccani et al., 2008, 2015). The volumetrically minor N-MORB associated with G-MORB are interpreted as the result of partial melting of a pure depleted mantle source (Rampone et al., 2005). Dilek and Furnes (2011), Saccani (2015) and

Saccani et al. (2015) suggested that G-MORB rocks were basically generated at the ocean-continent transition zone during the early stages of ocean basin evolution and eventually during the mature phase of oceanic spreading.

Ophiolites from the Elba Island are very interesting as they represent the south-westernmost ophiolitic outcrop of the northern Apennines and may represent the link between Alpine Corsica and northern Apennine ophiolites. Nonetheless, while petrogenetic aspects of Alpine Corsica and northern Apennine ophiolitic basalts have extensively been studied, the Elba Island ophiolites are still poorly known. New geochemical data on the Elba Island ophiolitic basalts are presented in this paper with the aim of better constraining their petrogenetic processes and their possible mantle source composition. Then, the nature of the mantle sources will be discussed in comparison with those of similar ophiolitic basalts form Alpine Corsica and Ligurian units ophiolites.

2. Geological setting

The geology of the Elba Island is characterized by a complex stack of nappes, as well as by Late Miocene magmatic bodies. Bortolotti et al. (2001) and Principi et al. (2015) have proposed a new tectono-stratigraphic subdivision of the Elba Island, which distinguishes units in the western Elba (west to the NNE-SSW recent high angle normal fault) from units in the central-eastern Elba (Fig.2). In the central-eastern Elba, these authors have recognized nine tectonic units, which are (from bottom to top): 1) the Porto Azzurro unit; 2) the Ortano unit; 3) the Acquadolce unit; 4) the Monticiano-Roccastrada Unit; 5) the Tuscan Nappe; 6) the Gràssera unit; 7) the Monte Strega unit; 8) the Lacona unit; 9) the Ripanera unit. Moreover, the Porto Azzurro unit is intruded by some bodies of the La

Serra-Porto Azzurro monzogranite. In the western Elba Island two units have been recognized by Spohn (1981) and Coli et al. (2001) and recently formalized by Principi et al. (2015): 1) the Punta Polveraia-Fetovaia unit, which overlies the Monte Capanne monzogranite; 2) the Paleocene-Eocene Punta le Tombe unit (Fig. 2). According to Bortolotti et al. (2001), the Porto Azzurro, Ortano, Monticiano-Roccastrada, and Tuscan nappe units pertain to the Tuscan domain. In contrast, the Acquadolce and Gràssera units are comparable to the *Schistes Lustrés* of Alpine Corsica (e.g. Inzecca unit, Durand Delga, 1984), as well as to the calcschists of the Gorgona Island (Orti et al., 2002). According to Principi et al. (2015), the Monte Strega, Punta Polveraia-Fetovaia, Ripanera, and Lacona (*p.p.*) units pertain to the Ligurian oceanic domain. A detailed description of the geological setting of the Elba Island is beyond the scope of this paper. Ophiolites are included in the Monte Strega and Punta Polveraia-Fetovaia units. Therefore, only the geological setting of these ophiolite-bearing units will be discussed hereafter.

The general ophiolitic succession in the Elba Island consists (from bottom to top) of a mantle and gabbroic basement covered by Middle-Late Jurassic volcanic and subvolcanic rocks and Middle-Late Jurassic-Early Cretaceous sedimentary successions (Bortolotti et al., 2001; Principi et al., 2015). Mantle rocks are represented by serpentinites (Bortolotti et al., 1994; Tartarotti and Vaggelli, 1994) and ophicalcites (e.g., Cortesogno et al., 1987; Bortolotti et al., 2001). Lherzolites largely prevail, whereas spinel harzburgites and dunitic lenses are very scarce. Locally, gabbros may include little mafic and ultramafic cumulitic bodies of wehrlites and spinel-bearing mela-troctolites (Tartarotti and Vaggelli, 1994; Bortolotti et al., 1994). A sheeted dyke complex locally crops out (near the Colle Reciso pass) and consists of diorites, microgabbros, Fe-basalts, and plagiogranites. Basalts mainly occur as pillow lavas and subordinate pillow breccias. The Middle-Late Jurassic-Early Cretaceous sedimentary cover consist of (from bottom to top) the Monte Alpe cherts, the

Nisportino Formation, the Calpionella limestone, and the Palombini shales. The Monte Alpe Cherts show ages ranging from Late Bathonian-Middle Callovian and from Kimmeridgian to Early Tithonian (Bortolotti et al., 1994; Principi et al., 2015).

According to the recent reconstruction of Principi et al. (2015), the Monte Strega unit can be subdivided into six sub-units (Figs. 2, 3), which are (from bottom to top): 1) the Acquaviva sub-unit, including serpentinites (and/or ophicalcites) and Palombini shales; 2) the Monte Serra sub-unit, in which the sequence is almost complete from serpentinite to the Palombini shales; 3) the Sassi Turchini sub-unit exclusively consisting of serpentinized lherzolites and harzburgites; 4) the Volterraio sub-unit showing an almost complete succession from gabbro to Calpionella Limestone and locally to Palombini Shales; 5) the Bagnaia sub-unit, also showing a succession from gabbro to Calpionella limestone; 6) the Casa Galletti sub-unit consisting of small tectonic slices of serpentinites, gabbros, basalts, ophiolitic breccias, Calpionella limestone, and Palombini shales, though the mutual relationships between these rocks are unclear.

Ophiolites in the Punta Polveraia-Fetovaia unit in western Elba are represented by metaophiolites forming the thermo-metamorphic aureole associated with the intrusion of the Monte Capanne monzogranitic dome. Protoliths of the metaophiolitic sequences include serpentinites, gabbros cut by basaltic dykes, basalts, and a sedimentary cover (Figs. 2, 3). Metaserpentinites are common. They are often brecciated and frequently cut by steatitic and magnesitic veins, whereas basaltic and gabbroic rodingitized dykes are locally observed. Metagabbros show fine to pegmatoid isotropic texture. Locally, they occur as flaser gabbros often cut by basaltic dykes. In addition, few metres of gabbro breccia are locally found at the top of the gabbro sequence in the Fetovaia area. Metabasalts mainly occur as pillow lavas, whereas massive lavas are subordinate. They frequently show primary contacts with either gabbros or serpentinites. The maximum thickness of metabasalts is about 200 m. The sedimentary cover includes metacherts, metalimestones, and metashales, which are generally considered as the metamorphic equivalents of the Monte Alpe Cherts, Calpionella limestone, and Palombini shales of central-eastern Elba, respectively.

The effect of the thermo-metamorphic imprint within the metaophiolitic aureole is very variable. Generally, it sharply decreases with distance from the contact with monzogranites. Moreover, in some pillow lavas, inter-pillow areas are significantly affected by thermo-metamorphism, whereas pillow cores show little or even no metamorphism. Likewise, fractured gabbros show marked thermo-metamorphic imprint, whereas associated cross-cutting dykes display little metamorphic effects. Again, basalts, previously enveloped by pelitic sedimentary rocks (e.g., Palombini shales) are locally preserved from significant metamorphic imprint. Some authors have correlated these metaophiolites with the Monte Strega unit (e.g., Bouillin, 1983; Principi et al., 2015; Bortolotti et al., 2015, and references therein). Other authors suggested that the Punta Polveraia-Fetovaia metaophiolites are equivalent to the HP-LT metamorphic rocks of the *Schistes Lustrés* in Alpine Corsica and that their original metamorphic features were overprinted by thermal-metamorphism and deformation related to the Monte Capanne intrusion (Perrin, 1975; Coli et al., 2001).

The current tectonic structure of the Elba Island units is the result of a complex geodynamic evolution, which includes three main stages. During the first stage (accretionary stage), the oceanic (ophiolitic) units were piled up onto the continental margin-type Tuscan units from the Late Cretaceous(?)-Eocene to the Early-Middle(?) Miocene (e.g., Principi and Treves, 1984; Bortolotti et al., 2001). The second stage consisted in an extensional tectonics associated with the uplift of the Apennine orogen. (Boccaletti et al., 1985; Malinverno e Ryan, 1986; Channel e Mareshal, 1989; Jolivet et al., 1991; Bortolotti et al., 2001). The third stage consisted in the emplacement and uplift of the Messinian main intrusive bodies (i.e. the Monte Capanne and La Serra-Porto Azzurro monzogranites), which caused the thermo-metamorphism and the last horizontal movements of the Elba units by means of low-angle faults (Keller and Pialli, 1990; Pertusati et al., 1993; Bouillin et al., 1994; Daniel and Jolivet, 1995; Bortolotti et al., 2001; Westerman et al., 2004; Collettini et al., 2006).

3. Sampling and Petrography

Sampling was performed on both the Monte Strega unit and Punta Polveraia-Fetovaia unit (Figs. 2, 3). Ophiolitic rocks from the Monte Strega unit are commonly affected by variable hydrothermal alteration and/or ocean floor metamorphism, whereas those from the Punta Polveraia-Fetovaia unit are also affected to various extent by thermo-metamorphism associated with the Monte Capanne intrusion. Sampling was therefore focused on volcanic rocks and dykes, which apparently showed moderate alteration or thermo-metamorphic imprint. Nonetheless, an extremely high degree of alteration has been recognized in some of the collected samples after preliminary petrographic and chemical analyses. In consequence, these samples have been excluded from this study. Nonetheless, the samples studied in this paper can be considered as fully representative of the various volcanic and subvolcanic lithologies of the Elba Island ophiolites.

In the Punta Polveraia-Fetovaia unit, two samples were taken from the pillow lava series (samples OG1 and MA1) and two samples were taken from dykes cutting the flaser gabbros (FE2 and PO1) (Fig. 3). In the Monte Strega unit, two samples were taken from the pillow lava series of the Volterraio sub-unit in different localities (V1 and MO1), whereas one sample was collected from the sheeted dykes of the same sub-unit (CR1). Another pillow lava was sampled in the Monte Serra sub-unit (MS1) (Fig. 3).

Although only less altered samples were studied in this paper, they were affected to some extent by low-grade ocean floor metamorphism, which has resulted in re-crystallization of the primary igneous phases. In contrast, the primary igneous textures are well preserved. The main mineralogical substitutions include albite replacing plagioclase and chlorite replacing clinopyroxene and glass. Variable amounts of amygdales and/or veins, usually filled with calcite or quartz, are observed in some samples. The studied rocks display a wide range of textural varieties. However, no significant textural differences can be observed between sample from the Monte Strega and Punta Polveraia-Fetovaia units. Therefore, their petrographic features will be described together. Samples MA1 and PO1 show holohyaline texture. Samples OG1, V1, and MS1 display hypocrystalline, aphyric texture characterized by small laths of plagioclase and interstitial clinopyroxene and glass. Sample V1 also show abundant opaque minerals occurring as both rare microphenocrysts and interstitial microliths. Sample FE2 has a slightly porphyritic texture (PI = 10) with large plagioclase phenocrysts (up to 1 cm) set in a micrognanular groundmass. Dyke CR1 shows a doleritic texture with fluidal plagioclase and granular, interstitial clinopyroxene. Sample MO1 shows sub-ophitic texture with euhedral plagioclase and subhedral clinopyroxene. Moreover, this rock contains abundant opaque minerals showing euhedral, subhedral and skeletal texture.

4. Analytical methods

Whole-rock major and some trace elements (Zn, Cu, Sc, Ga, Ni, Co, Cr, V, Ba, Pb) were determined by X-ray fluorescence (XRF) on pressed powder pellets, using an ARL Advant-XP automated X-ray spectrometer. Calibration was done with international reference samples and the matrix correction method proposed by Lachance and Trail (1966) was applied. Accuracy and detection limits were determined using both internal and international reference standards run as unknowns. Mean accuracies are generally less than 2% for major oxides (except MnO and P_2O_5 = ~10%) and 5% for trace element determinations. The detection limits for trace elements are: Ga = 4 ppm; Cu, Sc, Ba = 3 ppm; Zn, Ni, Co, Cr, V = 2 ppm. Volatile contents were determined as loss on ignition at 1000°C.

In addition, Rb, Sr, Y, Zr, Nb, Hf, Ta, Th, and U, as well as the rare earth elements (REE) were determined by inductively coupled plasma-mass spectrometry (ICP-MS) using a Thermo Series X-I spectrometer. The accuracy of the data and detection limits were evaluated using results for international standard rocks and the blind standards included in the sample set. Accuracy ranged from 1 to 6 relative percent. Detection limits (in ppm) are: Rb, Sr, Zr, Ta, U, Nd = 0.02; Y, Nb = 0.01; Hf, Th = 0.007; La, Ce, Eu, Tb, Ho = 0.05; Pr = 0.009; Sm, Er, Gd, Dy, Er, Tm, Yb, Lu = 0.002. All whole-rock analyses were performed at the Dipartimento di Fisica e Science della Terra, Università di Ferrara. Representative analyses are reported in Table 1 together with the comparison between determined and bibliographic element concentrations in a basaltic reference sample.

5. Geochemistry

The geochemical features of the Elba Island ophiolitic basalts are described using those elements, which are virtually immobile during low-temperature alteration and metamorphism (Pearce and Norry, 1979). They include some incompatible elements (e.g., Ti, P, Zr, Y, Sc, Nb, Ta, Hf, Th), middle (M-) REE and heavy (H-) REE, as well as some transition metals (e.g., Ni, Co, Cr, V). Large ion lithophile elements (LILE) are commonly mobilized during alteration. Nonetheless, Rb shows good correlations with respect to some immobile elements (e.g., r^2 for Rb vs. Zr = 0.95). Light REE (LREE) may also be mobilized during extensive alteration of metabasites. However, the good correlations between these elements and many immobile elements (e.g., r^2 for La vs. Zr = 0.90; r^2 for Ce vs. Zr = 0.90) indicate that LREE mobilization during alteration or metamorphism was negligible. Therefore, these elements have also been used. When compared to immobile elements, FeO, and MgO contents show fairly good correlations (e.g., r^2 for FeO vs. Zr = 0.80; r^2 for MgO vs. Zr = 0.81), suggesting that they have been moderately mobilized.

After a preliminary study, it resulted that no significant chemical differences can be recognized between samples from the Monte Strega and Punta Polveraia-Fetovaia units. Therefore, the chemical features of samples from both these units will hereafter be described together. The Elba Island volcanic and subvolcanic rocks range in composition from basalt to basaltic andesite, Fe-basalt, and Fe-basaltic andesite (Table 1). Basalts and basaltic andesites have SiO_2 ranging from 46.21 to 54.67 wt%. MgO abundance in these rocks ranges from 3.70 to 11.36 wt%, whereas FeO_t is in the range 6.97-10.01 wt%. Compared to basalts and basaltic andesites, Fe-basaltic rocks have similar silica and magnesium contents (SiO_2 = 47.69-53.99 wt%, MgO = 2.10-8.72 wt%), but show higher FeO_t (11.93 – 13.37 wt%) content. Viewed overall, the basaltic rocks from the Elba Island ophiolitic units display a clear sub-alkaline, tholeiitic nature, as testified by low Nb/Y ratios (0.06 - 0.16), as well as by the Zr/Y ratios (2.5-4.6), which are both in the range for high-Ti tholeiitic basalts from mid-ocean ridge settings (Pearce, 1982). The relatively high TiO_2, P_2O_5, Zr, and Y contents coupled with relatively low Th and Ta contents (Table 1) also highlight the tholeiitic nature of these rocks.

Variations of some selected major and trace elements vs. Zr (used here as fractionation index) are presented in Figure 4. The abundance of P_2O_5, Y and many other incompatible elements (e.g., Nb, Th, Ta, REE, Table 1) increases with increasing Zr. By contrast, Cr (Fig. 4), as well as Co and Ni (not shown) displays a marked decrease with increasing Zr. FeO_t, TiO_2, and V display the typical tholeiitic trend; that is, increase from the less to the moderately evolved basalts followed by a further sharp increase toward Fe-basalts, then decrease toward the more evolved Fe-basaltic andesites (Fig. 4).

All rock-types, except the most fractionated Fe-basaltic andesite CR1, display rather flat HFSE patterns in N-MORB normalized diagrams, close to the value of 1 (Figs. 5a, c). Only the relatively primitive basalt FE2 show limited Th, U, Nb, and Zr depletion (Fig. 5a). Chondrite-normalized REE patterns (Figs. 5b, d) show variable LREE/MREE depletion (e.g., La_N/Sm_N = 0.32-0.79) and marked HREE depletion with respect to MREE (e.g., Sm_N/Yb_N = 1.49-2.10). Such a marked HREE/MREE fractionation is a distinguishing feature of many MORB-type ophiolitic basalts cropping out in several Alpine-type Tethyan ophiolites (e.g., Western Alps, northern Apennine, and Alpine Corsica; Desmurs et al., 2002; Montanini et al., 2008; Saccani et al., 2008; Saccani, 2015). This significant HREE/MREE depletion is interpreted as a clear garnet signature of their mantle sources (Montanini et al., 2006, 2008; Saccani et al., 2008; Saccani, 2015). Saccani (2015) used the term G-MORB (garnet-influenced MORB) for identifying MORB-type basalts characterized by a clear garnet signature. This author also proposed a diagram for discriminating G-MORBs form typical normal-type (N-) MORBs (Fig. 6). In fact, in

Figure 6a the Elba Island ophiolitic basalts plot in the field for depleted MORB-type rocks, whereas in Figure 6b they plot in the field for G-MORBs.

Low-pressure fractional crystallization has played a major role in controlling the compositional variations observed within the ophiolitic basaltic rocks from the Elba Island. The general increase in incompatible elements, as well as FeO_t and V coupled with the rapid decrease in compatible Cr relative to Zr, is characteristic of tholeiitic-type magmatic fractionation trends (Fig. 4). The elemental variations are consistent with a magmatic evolution controlled by fractional crystallization of (olivine) + plagioclase + clinopyroxene + Fe-Ti oxides. Accordingly, with the exception of sample PO1, the negative Eu anomalies (Eu/Eu*) = 0.76-0.93) is indicative for plagioclase fractional crystallization (Figs. 5b, d). These conclusions are in agreement with petrographic evidence. Although co-magmatic relationships cannot straightforwardly be established, the variation trends in Figure 4, seem to indicate that, irrespective of the ophiolitic sub-unit of provenance, the more fractionated rocks evolved from compositionally similar primary melts.

6. Discussion

6.1. Mantle melting processes and magma generation

The main distinctive feature of Elba Island G-MORB consists in a marked HREE depletion with respect to MREE, which can be explained by variable influence of a garnet signature in their mantle sources (e.g., Montanini et al., 2008). Saccani et al. (2008) suggested that the garnet signature characterizing similar G-MORB from Alpine Corsica ophiolites is mainly related to the melting of a depleted MORB mantle source heterogeneously characterized by garnet-bearing mafic/ultramafic layers. Nonetheless, minor volumes of these rocks may have resulted from polybaric melting staring in the garnet peridotite stability field and continuing in the spinel-facies peridotite.

In order to constrain the possible mantle source composition and melting processes responsible for the formation of Elba Island ophiolitic volcanic and subvolcanic rocks, partial melting modellings were carried out. A rigorous quantification of the melting processes is not possible as the composition of the mantle sources is difficult to constrain. However, a semi-quantitative modelling of appropriate incompatible elements and REE can place some effective constraints. In particular, the composition of garnet-bearing mafic/ultramafic layers eventually involved in melting processes can only be postulated, as they commonly show quite different compositions (e.g., Liu et al., 2005). Therefore, in the modellings carried out hereafter, we will use a garnet-pyroxenite composition inferred from Liu et al. (2005) selected in order to best fit the composition of Elba Island basalts.

LREE/HREE and MREE/HREE ratios are particularly useful to model the garnet signature in melting processes. Therefore, non-modal, batch partial melting modelling using Ce/Yb and Dy/Yb ratios is presented in Figure 7. This Figure shows that the compositions of the less fractionated basalts from Elba Island ophiolites are compatible with low degree of melting (2.5-5%) of a garnet-pyroxenite and mixing of these melts with melts generated from 12.5-15% partial melting of a depleted MORB-type mantle (DMM) source (Workman and Hart, 2005) in the spinel-facies.

Modelling using the whole REE spectrum is presented in Figure 8. This modelling confirms that the composition of the most primitive Elba Island basalts is compatible with melts originated by mixing of melts derived from ~12.5% non-modal batch partial melting of a DMM source in the spinel-facies and melts derived from 2.5-5% partial melting of a theoretical garnet-pyroxenite inferred from Liu et al. (2005). REE modelling in Figure 8b show that melting of DMM source that starts in the garnet-facies and continues to larger degrees in the spinel-facies (with various combinations of melting fractions in the garnet- and spinel-facies) would generate primary melts characterized by LREE/MREE ratios (e.g., La_N/Sm_N = 0.26-0.52) lower than those observed in relatively primitive Elba Island basalts (e.g., La_N/Sm_N = 0.65-0.79). Likewise, partial melts generated from this melting process would have MREE/HREE ratios (e.g., Sm_N/Yb_N = 1.96-3.40) higher than those observed in Elba Island basalts (e.g., Sm_N/Yb_N = 1.49). Therefore, the hypothesis of generation of the Elba Island basalts from polybaric melting of a DMM source can reasonably be disregarded.

Because of their higher LREE/HREE ratios, as well as Th, Ta, and Nb concentrations compared to N-MORB, some authors have interpreted similar rocks from Alpine Corsica and northern Apennine ophiolites as E-MORB generated from slightly enriched mantle sources during the onset of the oceanic spreading (e.g., Beccaluva et al., 1977; Venturelli et al., 1979, 1981). With the exception of Fe-basalt V1, Elba Island basaltic rocks show higher $(La/Yb)_N$ ratios (Table 1) compared to N-MORB (La_N/Yb_N = 0.59, Sun and McDonough, 1989). Therefore, the hypothesis that Elba Island ophiolitic basalts may were derived from partial melting of a slightly enriched source has been tested using non-modal, batch partial melting modellings based on Th concentration and Nb/Yb ratio (Fig. 9). The diagram in Figure 9 has the advantage to combine two types of information in a single plot. The abundance of Th and Nb is used to evaluate the enrichment of the source, whereas the Nb/Yb ratio is sensitive of the presence of residual garnet in the source. This Figure shows the melting curves for two compositionally different mantle sources melting in both garnet- and spinel-facies, which are: 1) a DMM source (Workman and Hart, 2005); 2) a theoretical slightly enriched DMM source with Nb = 0.63 ppm, Th = 0.08 ppm, Yb = 0.35 ppm. The compositions of source 2) was assumed based on modellings recently presented by Saccani et al. (2013) for explaining the genesis of E-MORB. Moreover, the melting curve for the garnet-pyroxenite source used in Figures 7 and 8 is also shown in Figure 9. Th-Nb-Yb modelling shows that the less fractionated Elba Island basalts cannot be derived from partial melts originating from a slightly enriched mantle source. Rather, results from the Th-Nb-Yb modelling shown in Figure 9 are in agreement with results obtained from REE modelling (Figs. 7 and 8). The Th and Nb composition of Elba Island basalts is indeed compatible with melts originated by mixing of melts derived from ~15% non-modal batch partial melting of a DMM source in the spinel-facies and melts derived from 5-10% partial melting of a theoretical garnet-pyroxenite.

All Elba Island basalts and Fe-basalts fall within the MORB-OIB array (Fig. 5a) suggesting that a chemical influence of a crustal component was very limited or absent. Moreover, crustal contamination would raise the Zr/Nb and Zr/Y ratios with respect to a pure mantle source. Zr/Nb (34.3) and Zr/Y (2.48) ratios of the less fractionated Elba Island basalt are very similar to those observed in basalts generated from a pure depleted mantle source (Zr/Nb = 31.8) and Zr/Y = 2.64; Sun and McDonough, 1989).

6.2. Comparison with basalts from other Alpine Corsica and Apennine ophiolitic units

In order to constrain the tectono-magmatic significance of the Elba Island ophiolitic basalts within the Alpine Corsica-Elba-Apennine sector of the Ligurian-Piedmont oceanic basin, we have compiled data from several ophiolitic units from both Alpine Corsica and northern Apennine. They are: 1) the Balagne and Nebbio unit; 2) the Upper *Schistes Lustrés*; 3) the Lower *Schistes Lustrés*; 4) the Rio Magno and Pineto units, in Alpine Corsica; as well as 5) the ophiolitic debris in the EL units; 6) the IL ophiolitic units, in northern Apennine (Beccaluva et al., 1977; Venturelli et al., 1979, 1981; Cortesogno and

Gaggero, 1992; Vannucci et al., 1993; Rampone et al., 1995, 1998; Marroni et al., 1998; Rossi et al., 2002; Padoa et al., 2002; Saccani et al., 2000, 2008; Montanini et al., 2008). The main geochemical characteristics of basalts from these units are summarized in the N-MORB normalized incompatible element and Chondrite-normalized REE diagrams in Figure 10.

The Balagne and Nebbio units are located in the most external tectonic position with respect to the other ophiolitic nappes. They largely consist of basalts showing slightly enriched incompatible element and LREE patterns (Figs. 10a, b), suggesting an E-MORB-type chemistry. Nonetheless, a few basalts, generally found towards the top of these ophiolitic sequences (Saccani et al., 2008), show incompatible element depleted patterns and REE patterns featuring LREE/MREE and HREE/MREE depletion, which are compatible with a G-MORB chemistry. Accordingly, these basalts plot in the field for G-MORB in Figure 6b. The Rio Magno and Pineto units, which are located in the highest tectonic position in the ophiolitic nappe, are mainly characterized by the occurrence of basalts showing LREE depleted patterns, as well as Th, Ta, and Nb depletion (Figs. 10c, d). The chemistry of these basalts strongly resembles that of N-MORB (Fig. 6b). However, a few basalts from the Pineto unit show depleted incompatible element patterns, as well as LREE/MREE and HREE/MREE depleted patterns (Figs. 10c, d) suggesting G-MORB type chemistry, as also evidenced in Figure 6b. The Upper and Lower *Schistes Lustrés* units largely consists of metabasalts with G-MORB chemistry, as suggested by a general depletion in incompatible elements coupled with HREE/MREE depleted patterns (Figs. 10e-h). Nonetheless, both these units also include a few basalts showing N-MORB features, such as LREE/HREE depletion (Figs. 10f, h). These conclusions are also supported by the discrimination diagram in Figure 6b. Moreover, the Upper *Schistes Lustrés* unit also includes a couple of basalts having comparatively higher incompatible element patterns, as well as high LREE/MREE and MREE/HREE ratios, which point out for a clear E-MORB chemistry. Basalts from the EL and IL units in northern Apennine both show G-MORB chemistry (Fig. 6b). However, when compared to IL basalts, the EL basalts show generally higher incompatible elements values coupled with higher LREE concentrations (Figs. 10i, j).

The Elba Island ophiolitic basalts show general chemical similarities with G-MORB from the Alpine Corsica Upper and Lower *Schistes Lustrés* units, as well as from the IL units of northern Apennine (Figs. 5, 6, 10). This implies that basalts from these units shared generally similar mantle sources and petrogenetic processes. Nonetheless, some chemical differences, particularly in Th, Ta, Nb, and REE ratios, between basalts from all these ophiolitic units likely reflect small chemical differences in their mantle source. An estimation of the composition of primary magmas and relative mantle sources can also be obtained using hygromagmatophile element ratios, such as Th/Ta and Th/Tb ratios. These elements are weakly fractionated during partial melting and moderate extent of fractional crystallization. Therefore, the population of samples originating from chemically similar mantle sources will show similar values of ratio/ratio of hygromagmatophile elements, representing, in turn, the elemental ratios in the source (Allègre and Minster, 1978). The (Th/Ta)/(Th/Tb) ratios for the less evolved basalts from both the Monte Strega and Punta Polveraia-Fetovaia units are very similar and range from 0.11 to 0.19. This suggests that all the ophiolitic basalts from the Elba Island were originated from compositionally similar mantle sources. Compared to the Elba Island ophiolitic basalts, similar rocks from both Upper and Lower *Schistes Lustrés* and Pineto units in Alpine Corsica show a much wider variation of (Th/Ta)/(Th/Tb) ratios (0.11-0.31, Saccani et al., 2008) suggesting that different basalts from these units were most likely originated from chemically slightly different mantle sources and/or petrogenetic processes. In contrast, N-MORB from the Rio

Magno, Pineto, and *Schistes Lustrés* units have (Th/Ta)/(Th/Tb) ratios ranging from 0.22 to 0.25 and from 0.20 to 0.31, respectively (Saccani et al., 2008) suggesting mantle source compositions different from those of the Elba Island basalts. E-MORB from the Balagne, Nebbio, and Upper *Schistes Lustrés* units have very high (Th/Ta)/(Th/Tb) ratios (0.43 to 0.51, Saccani et al., 2008) suggesting mantle source compositions very different from those of the Elba Island basalts, as well as from those of other Alpine Corsica ophiolites.

In fact, relatively primitive N-MORB from the Rio Magno, Pineto, and *Schistes Lustrés* units are compatible with 10-20% partial melting of a DMM source in the spinel stability field (Figs. 7, 9). In contrast, relatively primitive E-MORB from the Balagne, Nebbio, and Upper *Schistes Lustrés* units are compatible with low degree (7-12%) partial melting of a slightly enriched mantle source in the spinel stability field (Fig. 9).

Based on REE ratios (Fig. 7) and Th-Nb-Yb composition (Fig. 9) the G-MORB from Elba Island ophiolites and some equivalent basalts from the Lower *Schistes Lustrés* and IL units were likely derived from very similar mantle sources, as well as similar petrogenetic processes. In contrast, other G-MORB from the Lower *Schistes Lustrés* and IL units, as well as from the Upper *Schistes Lustrés*, EL, Balagne, and Pineto units display quite different REE ratios (Fig. 7) and Th-Nb-Yb composition (Fig. 9). In fact, these G-MORB from the Lower *Schistes Lustrés* display $(Ce/Yb)_N$ ratios similar to those of Elba Island basalts, but relatively higher $(Dy/Yb)_N$ ratios (Fig. 7) and Th (Fig. 9). Likewise, G-MORB from the Upper *Schistes Lustrés* display comparatively higher $(Ce/Yb)_N$ and $(Dy/Yb)_N$ ratios (Fig. 7). These features likely account for a different composition of the garnet-pyroxenite involved in the melting process or higher degree of melting of the garnet-pyroxenite. Indeed, garnet-pyroxenites found in the mantle rocks commonly show quite different compositions (e.g., Liu et al., 2005). In contrast, G-MORB from the Balagne and Pineto units show higher LREE enrichment with respect to MREE (Figs. 10b, d), higher MREE/HREE ratios (Fig. 7) and higher Nb and Th concentrations (Fig. 9) when compared to other G-MORB. These features suggest a source slightly enriched in LREE and Th and Nb. This conclusion is agreement with the widespread occurrence of E-MORB in the Balagne unit, which clearly point out for a slightly enriched mantle source in the Balagne sector of the Ligurian-Piedmont Ocean. In summary, the chemical differences observed within G-MORB from the various ophiolitic units is likely due to a combination of some factors: 1) different compositions of the garnet-pyroxenites involved in the melting processes (i.e., mantle source heterogeneity); 2) different melting degrees of both DMM and garnet-pyroxenite; 3) different proportions of melts generated from the DMM and garnet-pyroxenite sources.

6.3. Tectono-magmatic significance and geodynamic implications

In the previous sections it has been shown that the studied basaltic rocks from the Elba Island consist of G-MORB type rocks that were originated from partial melting of a DMM source bearing garnet-pyroxenite relics. G-MORB type basaltic rocks showing either similar or slightly different chemical compositions with respect to those of the Elba Island, are very common in Alpine Corsica and northern Apennine ophiolitic units. In addition, E-MORB rocks are particularly abundant in the Balagne and Nebbio units in Alpine Corsica, whereas N-MORB rocks are mainly found in the Pineto and Rio Magno units and subordinately in the Upper and Lower *Schistes Lustrés* units. According to the Saccani (2015), basalts showing clear garnet signature are found in the Continental Margin (CM) ophiolites of Dilek and Furnes (2011), which commonly represent fragments of the ocean-continent transition zone (OCTZ) forming during the continental breakup and the following early stages of oceanic basin evolution.

A possible tectono-magmatic model that can explain the genesis of G-MORB rocks from the Elba Island, Alpine Corsica, and northern Apennine ophiolites, as well as the genesis of E-MORB and N-MORB rocks from some Alpine Corsica ophiolitic units is shown in Figure 11. This model takes account of the rifting model proposed for the Ligurian-Piedmont oceanic basin, which is manly based on the reconstruction of the architecture of the paired continental margin in northern Apennine and Alpine Corsica (see Marroni and Pandolfi, 2007 and Saccani et al., 2015 for references).

The Middle Triassic rifting phase (Fig. 11a) was preceded by a long-lived Permo-Triassic evolution, which record the transition from the extensional processes to the inception of the true rifting phases (Durand-Delga, 1984; Froitzheim and Manatschal, 1996). The geometry of normal faults, which are east-verging in Southalpine and Austroalpine domains (Bertotti et al., 1993; Bernoulli et al., 2003) and west-verging in the Briançonnais and Dauphinois domains (Lemoine and Trumpy, 1987), suggest that the first rifting phase was dominated by lithosphere stretching by pure shear extension (Fig. 11a).

A second stage of rifting, which developed during Early-Middle Jurassic, was characterized by an asymmetric configuration. The geological features of the EL units indicate that the OCTZ at the Adria plate was characterized by a wide, ocean-continent transition showing exhumation of subcontinental mantle and lower continental crust to the sea floor, as well as extensional allochthonous (see Marroni and Pandolfi, 2007 and references therein). Conversely, the OCTZ at the European continental margin indicates a sharp transition characterized by exposure of rocks belonging to upper continental crust affected by escarpments induced by high-angle normal faulting (e.g., Durand-Delga, 1984; Froitzheim and Manatschal, 1996).

The Early-Middle Jurassic rifting stage was characterized by amagmatic extension throughout low-angle detachment fault. The subsequent Middle-Late Jurassic oceanic formation was characterized by magma starved slow-spreading mid-ocean ridge (e.g., Menna et al., 2007 and references therein). At these stages, the upwelling of the asthenosphere, in response to lithospheric extension and continental rifting, was associated with limited partial melting of heterogeneous mantle sources (see also Rampone and Hofmann, 2012), locally bearing garnet-pyroxenite relics (Fig. 11b). Piccardo (2008) suggested that garnet-pyroxenite relics were left in the DMM melting source after the delamination and sinking of portions of the deep garnet-pyroxenite-bearing lithospheric mantle. This partial melting process resulted in the formation of G-MORB type rocks from the Elba Island ophiolites, as well as from Alpine Corsica, IL and EL ophiolites. However, little chemical variations can be observed within the G-MORB rock-group. In particular, different MREE/HREE and hygromagmatophile element ratios observed in G-MORB rocks were likely associated with different partial melting degrees of either DMM source or garnet-pyroxenite relics and/or different mixing proportions of melts derived from them. Such a complex combination of melting degrees and melt mixing proportions likely depend on local heterogeneities of the DMM source and local composition of the garnet-pyroxenite relics, as well as depth of melting (i.e., temperature). The model presented in Figure 11b can account for the complex combination of these factors, as it implies that garnet-pyroxenite relics may have different compositions and may be randomly distributed at different depths. The model in Figure 11b can also explain the formation of volumetrically minor basalts showing typical N-MORB composition cropping out in the Rio Magno, Pineto, and *Schistes Lustrés* in Alpine Corsica (Saccani et al., 2008; Saccani, 2015), as well as in the Ligurian ophiolites (Rampone et al., 2005). N-MORB primary melts having low MREE/HREE ratios can indeed be produced by partial melting of a pure DMM source, which was not locally affected by garnet-bearing rocks. In contrast, the LREE enriched basalts (E-MORB) from the Balagne, Nebbio, and subordinately from the

Upper *Schistes Lustrés* units are consistent with partial melting of a slightly enriched mantle source, which can be associated, in turn, to the embryonic stage of oceanic formation.

In summary, the paleogeographic and paleotectonic position within the Ligurian-Piedmont Ocean of the different ophiolitic units in the Alpine Corsica-Elba Island-northern Apennine transect is difficult to be constrained based only on basalt geochemistry. Only the E-MORB rocks of the Balagne and Nebbio units can be refereed to the embryonic stage of oceanic formation close to the European continental margin (see Bill et al., 2000 for an exhaustive review and references). In contrast, chemically different G-MORB, as well as N-MORB rocks are almost randomly distributed in the Alpine Corsica-Elba Island- northern Apennine ophiolitic units. This suggest that the different composition of basalts is basically associated with mantle heterogeneities rather than their paleogeographic and paleotectonic position (see also Saccani et al., 2015). It can also be postulated that the influence of mantle heterogeneities on basalt compositions likely was not limited to the OCTZ, but also somewhat extended to later phases of oceanic spreading. In fact, the Pineto and Rio Magno units, which are interpreted as generated in more internal oceanic positions (Saccani et al., 2000; Padoa et al., 2001, 2002), though predominantly characterized by N-MORB, also include garnet-influenced basalts.

7. Conclusions

Ophiolites in the Elba Island represent remnants of the Jurassic Ligurian-Piedmont Ocean and crop out in two distinct units: the non-metamorphic Monte Strega unit (central-eastern Elba) and the Punta Polveraia-Fetovaia unit (western Elba), which underwent thermo-metamorphism associated with the Monte Capanne monzogranitic intrusion. Both ophiolitic units include pillow lavas and dykes with compositions ranging from basalt to basaltic andesite, Fe-basalt, and Fe-basaltic andesite. The main conclusions based on geochemical and petrologic investigation on ophiolitic basaltic rocks carried out in this study are summarized below:

1) Basaltic rocks from distinct ophiolitic units show no chemical differences, apart those due to fractional crystallization processes. They display a clear tholeiitic nature broadly resembling that of N-MORB. However, REE patterns show marked HREE depletion with respect to MREE, which indicates a clear garnet signature of their mantle sources. In fact, they can be classified as garnet-influenced MORB (G-MORB), based on Th, Nb, Ce, Dy, and Yb constraints.

2) REE, Th, and Nb partial melting modelling show that the compositions of the most primitive Elba Island ophiolitic basalts are compatible with partial melting of a depleted MORB mantle (DMM) source bearing garnet-pyroxenite relics. Hygromagmatophile element ratios suggest that basalts from both ophiolitic units were originated from a chemically common mantle source.

3) The composition of the inferred mantle source for the Elba Island basalts is similar to that of some Lower *Schistes Lustrés* metabasalts, as well as to that of some IL unit basalts. In contrast, it slightly differs from those of other ophiolitic units of Alpine Corsica (Pineto, Balagne, and Lower *Schistes Lustrés* units).

4) We suggest that the Elba Island ophiolitic basalts were generated at magma starved, slow- spreading mid-ocean ridge. The chemical differences observed between basalts and metabasalts from different Ligurian-Piedmont ophiolitic units were likely associated with different partial melting degrees of either DMM source or garnet-pyroxenite relics and/or

different mixing proportions of melts derived from them, as well as to different compositions of garnet-pyroxenite relics.

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Table Caption

Table 1. Representative major and trace element analyses of volcanic and subvolcanic rocks from the Elba Island ophiolites. Abbreviations, bas: basalt; bas and: basaltic andesite; Fe-bas: ferrobasalt; Fe-bas and: ferrobasaltic andesite. Mg# = 100xMg/(Mg+Fe). Fe_2O_3 = 0.15xFeO. Normalizing values for REE ratios are from Sun and McDonough (1989). The comparison between reference and analyzed compositions of the international reference sample BHVO-1 (Govindaraju, 1994) is also shown.

Figure Captions

Figure 1. Simplified tectonic scheme of the Alpine Corsica - Elba Island - northern Apennine transect. Modified after Saccani et al. (2000) and Marroni and Pandolfi (2007).

Figure 2. Schematic tectonic map of the Elba Island and location of samples (stars). Modified from Principi et al. (2015).

Figure 3. Simplified stratigraphic columns of the Monte Strega (central-eastern Elba) and Punta Polveraia-Fetovaia (western Elba) ophiolitic units. The location of samples, as well as the mutual tectonic relationships of the different sub-units of the Monte Strega units are also shown. Modified from Bortolotti et al. (2015).

Figure 4. Variation of selected major and trace elements vs. Zr for volcanic and subvolcanic rocks from the Elba Island ophiolites. Major element oxides are recalculated on anhydrous bases. Arrows broadly indicate fractionation trends.

Figure 5. N-MORB normalized incompatible element patterns (a, c) and Chondrite-normalized REE patterns (b, d) for volcanic and subvolcanic rocks from the Elba Island ophiolites. Normalizing values are from Sun and McDonough (1989).

Figure 6. N-MORB normalized Th vs. Nb (a) and Chondrite-normalized Dy/Yb vs. Ce/Yb (b) diagrams (Saccani, 2015) for volcanic and subvolcanic rocks from the Elba Island ophiolites. Normalizing values are from Sun and McDonough (1989). Abbreviations, N-MORB: normal-type mid-ocean ridge basalts; G-MORB: garnet-influenced mid-ocean ridge basalts. The compositional variation of ophiolitic basalts from Alpine Corsica Upper *Schistes Lustrés* (USL), Lower *Schistes Lustrés* (LSL), Balagne (Ba), Rio Magno (RM) and Pineto (Pi) units, as well as from N. Apennine External Ligurian (EL) and Internal Ligurian (IL) units are reported for comparison. Data source: Beccaluva et al. (1977), Venturelli et al. (1979, 1981), Cortesogno and Gaggero (1992), Vannucci et al. (1993),

Marroni et al. (1998), Rampone et al. (1998), Saccani et al. (2000, 2008), Padoa et al. (2001, 2002), Rossi et al. (2002), Montanini et al. (2008).

Figure 7. (a) Non-modal batch melting curves on $(Dy/Yb)_N$ vs. $(Ce/Yb)_N$ diagram for a garnet pyroxenite (gt-px.te) and a depleted MORB mantle (DMM) source in both garnet (gt) and spinel (sp) stability fields. Dashed lines represent the mixing lines of various melt fractions from different sources. DMM composition is from Workman and Hart (2005), garnet-pyroxenite composition is inferred from Liu et al. (2005). Source modes and melting proportions for the DMM source are from Thirlwall et al. (1994). Source modes and melting proportions for the garnet-pyroxenite are both clinopyroxene 0.7 – garnet 0.3. Partition coefficients are from McKenzie and O'Nions (1991) except for garnet, which are from Fujimaki et al. (1984). Box indicates the area expanded in panel (b). (b) Plot of the most primitive basalts from Elba Island ophiolites on the close up of the melting model in panel (a). Dashed lines represent the mixing lines of various melt fractions between sp-DMM + garnet-pyroxenite relics, as well as various melt fractions between sp-DMM + gt-DMM. The percentages of melt fractions from each source are indicated on the mixing line. Mixing proportions between different partial melts are not shown. However, samples plot in the range from 0.6 – 0.7 melt from sp-DMM + 0.4 – 0.3 melt from garnet-pyroxenite. The compositional variation of ophiolitic basalts from Alpine Corsica Upper *Schistes Lustrés* (USL), Lower *Schistes Lustrés* (LSL), Balagne (Ba), Rio Magno (RM) and Pineto (Pi) units, as well as from N. Apennine External Ligurian (EL) and Internal Ligurian (IL) units are reported for comparison. Data source: Beccaluva et al. (1977), Venturelli et al. (1979, 1981), Cortesogno and Gaggero (1992), Vannucci et al. (1993), Marroni et al. (1998), Rampone et al. (1998), Saccani et al. (2000, 2008), Padoa et al. (2001, 2002), Rossi et al. (2002), Montanini et al. (2008).

Figure 8. Melting model results for a depleted MORB mantle (DMM) source in the spinel stability field + garnet-pyroxenite (gt-px.te) relics (a) and for a DMM source in the garnet (gt) + spinel (sp) stability fields (b). DMM composition is from Workman and Hart (2005), garnet-pyroxenite composition is inferred from Liu et al. (2005). Source modes and melting proportions for the DMM source are from Thirlwall et al. (1994). Source modes and melting proportions for the garnet-pyroxenite are both clinopyroxene 0.7 – garnet 0.3. Partition coefficients are from McKenzie and O'Nions (1991), except for garnet, which are from Fujimaki et al. (1984). Numbers on the curves in (a) indicate various proportions of melt fractions % (F) from different sources. 1: F gt-px.te = 2.5, F DMM = 5; 2: F gt-px.te = 2.5, F DMM = 10; 3: F gt-px.te = 2.5, F DMM = 12.5; 4: F gt-px.te = 2.5, F DMM = 15; 5: F gt-px.te = 5, F DMM = 12.5. For all curves a mixing of 70% partial melt from DMM + 30% partial melt from gt-pyroxenite is assumed. Numbers on the curves in (b) indicate various proportions of melt fractions % (F) in the garnet and spinel stability fields. 1: F gt = 0.5 + F sp = 2.5; 2: F gt = 0.5 + F sp = 5; 3: F gt = 0.5 + F sp = 8; 4: F gt = 1 + F sp = 2.5; 5: F gt = 1 + F sp = 5; 6: F gt = 0.5 + F sp = 8; 7: F gt = 2 + F sp = 2.5; 8: F gt = 2 + F sp = 5.

Figure 9. Plot of the Th vs. Nb/Yb compositional variations of the most primitive basalts from Elba Island ophiolites compared to non-modal batch melting curves for depleted MORB mantle (DMM), and slightly enriched mantle source in both garnet (gt) and spinel (sp) stability fields, as well as garnet-pyroxenite. DMM composition is from Workman and Hart (2005), garnet-pyroxenite composition is inferred from Liu et al. (2005), enriched mantle composition is from Saccani et al. (2013). Source modes and melting proportions for DMM and enriched sources are from Thirlwall et al. (1994). Source modes and melting

proportions for the garnet-pyroxenite are both clinopyroxene 0.7 – garnet 0.3. Partition coefficients are from McKenzie and O’Nions (1991), except for Nb in garnet, which is from Green et al. (2000). Dashed lines represent the mixing lines of various melt fractions from different sources. The compositional variation of ophiolitic basalts from Alpine Corsica Upper *Schistes Lustrés* (USL), Lower *Schistes Lustrés* (LSL), Balagne (Ba), Rio Magno (RM) and Pineto (Pi) units, as well as from N. Apennine External Ligurian (EL) and Internal Ligurian (IL) units are reported for comparison. Data source: Beccaluva et al. (1977), Venturelli et al. (1979, 1981), Cortesogno and Gaggero (1992), Vannucci et al. (1993), Marroni et al. (1998), Rampone et al. (1998), Saccani et al. (2000, 2008), Padoa et al. (2001, 2002), Rossi et al. (2002), Montanini et al. (2008). Other abbreviations, G- G-MORB type, N-: N-MORB type, E-: E-MORB type.

Figure 10. N-MORB normalized incompatible element patterns (left column) and Chondrite-normalized REE patterns (right column) for basaltic rocks from the Alpine Corsica and northern Apennine ophiolitic units. Data source: Beccaluva et al. (1977), Venturelli et al. (1979, 1981), Cortesogno and Gaggero (1992), Vannucci et al. (1993), Marroni et al. (1998), Rampone et al. (1998), Saccani et al. (2000, 2008), Padoa et al. (2001, 2002), Rossi et al. (2002), Montanini et al. (2008). Other abbreviations, MORB: mid-ocean ridge basalt, G-MORB: garnet-influenced type MORB; N-MORB: normal type MORB, E-MORB: enriched type MORB. Normalizing values are from Sun and McDonough (1989).

Figure 11. Tectono-magmatic model for the formation of garnet-influenced mid-ocean ridge basalts (G-MORB) from the Elba Island ophiolites. Modified after Marroni and

Pandolfi (2007) and Saccani et al. (2015). a) Triassic rift phase; b) Late Jurassic oceanic spreading phase; c) close-up view of the ocean floor stratigraphy near the mid-ocean ridge.