Geologica Acta, Vol.14, N° 3, September 2016, 299-314
DOI: 10.1344/GeologicaActa2016.14.3.6

geologica acta

New constraints on the origin of the ophiolitic rocks within sin-orogenic turbiditic sequences at Cilento region (southern Italy)

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ABSTRACT

Mafic igneous rocks (pillow lavas and gabbros) embedded as olistoliths within Miocene turbiditic sequences crop out in the Cilento area at the Mount Centaurino (Campania region, Southern Italy). The concentration of major oxides, as well as trace element ratios (Nb/Yb, Nb/Ta, Th/Nb) and the chondrite-normalized Rare Earth Elements (REE) patterns suggest a tholeiitic character with Mid Oceanic Ridge Basalts (MORB) affinity. The chemical composition of pillow lavas is consistent with magmas generated by 10% degrees of non-modal fractional partial melting, of a spinel-bearing MORB-type asthenospheric mantle. Regarding gabbros, the calculated composition of parental melts in equilibrium with the clinopyroxenes show a wide compositional range, and there are very different from the pillow basalts of the Mount Centaurino, suggesting that the clinopyroxenes might have derived from more evolved melts compared to those that produced the basalts. The origin of these olistoliths is not yet understood. Here we suggest that these rocks represent fragment of a dismantled accretionary wedge embedded during the deposition of the Cilento group sedimentary successions in a thrust top basin.

KEYWORDS **Southern Apennine. Cilento region. Mount Centaurino. Ophiolitic olistoliths. MORB-type rocks.**

INTRODUCTION

Ophiolites are the remnants of ancient oceanic lithosphere tectonically emplaced onto continental margins (Dilek and Furnes, 2014). According to these authors, there are ophiolites that bear geochemical and petrographic evidences of interaction with subduction-related melts (suprasubduction zone setting), while in other cases there are lithologies in ophiolites resembling original compositions (continental margin and mid-ocean ridge settings). The Jurassic ophiolites of the Alps and Apennines represent fragments of a slow to ultra-slow spreading oceanic basin named Ligurian, Piemonte-Ligurian or Alpine Tethys, (*e.g.* Beccaluva *et al.*, 1984; Rampone and Piccardo, 2000; Piccardo *et al.*, 2004; Piccardo, 2008; Tortorici *et al.*, 2009; Vignaroli *et al.*, 2009; Vissers *et al.*, 2013), located between the southern paleo-European continental margin and the western margin of the Adria Plate (Stampfli and Hochard, 2009, and references therein), that were obducted, with different polarity on continental crust during its closure (Bortolotti and Principi, 2005; Dilek and Furnes, 2011). They occur in scattered outcrops located mainly in the Alps and northern Apennines (Piccardo *et al*., 2014, and references therein). In thesouthern Apennines they only crop out in southern Basilicata and northern Calabria (Beccaluva *et al*., 1983; Spadea, 1994; Liberi *et al*., 2006; Cristi Sansone *et al*., 2011; Mazzeo *et al*., 2014). The northern Apennines ophiolitic massifs show widely variable lithological associations, textural, geochemical and mineralogical features, reflecting variable histories of petrological evolution undergone during the opening of the Ligurian Tethys (Rampone and Piccardo, 2000). For this reason they are divided into in peri-continental (marginal) and intra-oceanic (distal) ophiolites on the basis of their inferred paleogeographic position (Rampone *et al*., 2014, and references therein). In some cases, the oceanic lithosphere has been partially preserved not only in ophiolitic massifs, but also as olistoliths enclosed in terrigenous/carbonatic sedimentary units, like the Oligocene breccias and sandstones of the Val Marecchia Nappe in northern Italy (Perrone *et al*., 2014). In southern Italy, the presence of basaltic igneous rocks, intercalated/embedded into the Miocene succession of terrigenous turbidites, cropping out in the Cilento area (Campania) at Mount Centaurino and subordinately at Mount Sacro (Fig. 1A-B), is well known for more than fifty years (Ietto and Cocco, 1965; Cocco and Di Girolamo, 1970; Dietrich and Scandone, 1972; Di Girolamo *et al*., 1991). Various interpretations about their geochemical affinity, their stratigraphic/tectonic relationships with the surrounding sedimentary rocks, and, therefore, their geological significance have been proposed in literature. Based on field evidence, especially on a presumed metamorphic contact between igneous and sedimentary rocks, and biostratigraphic data, Cocco and Di Girolamo (1970) considered these igneous rocks as the product of a hawaiitic volcanic activity occurred simultaneously to the turbidite sedimentation. This idea was re-proposed by Amore *et al*. (1988) who hypothesized a link between these igneous rocks and the synorogenic magmatism recorded in the Betic Cordillera and African Maghrebides. However we want to

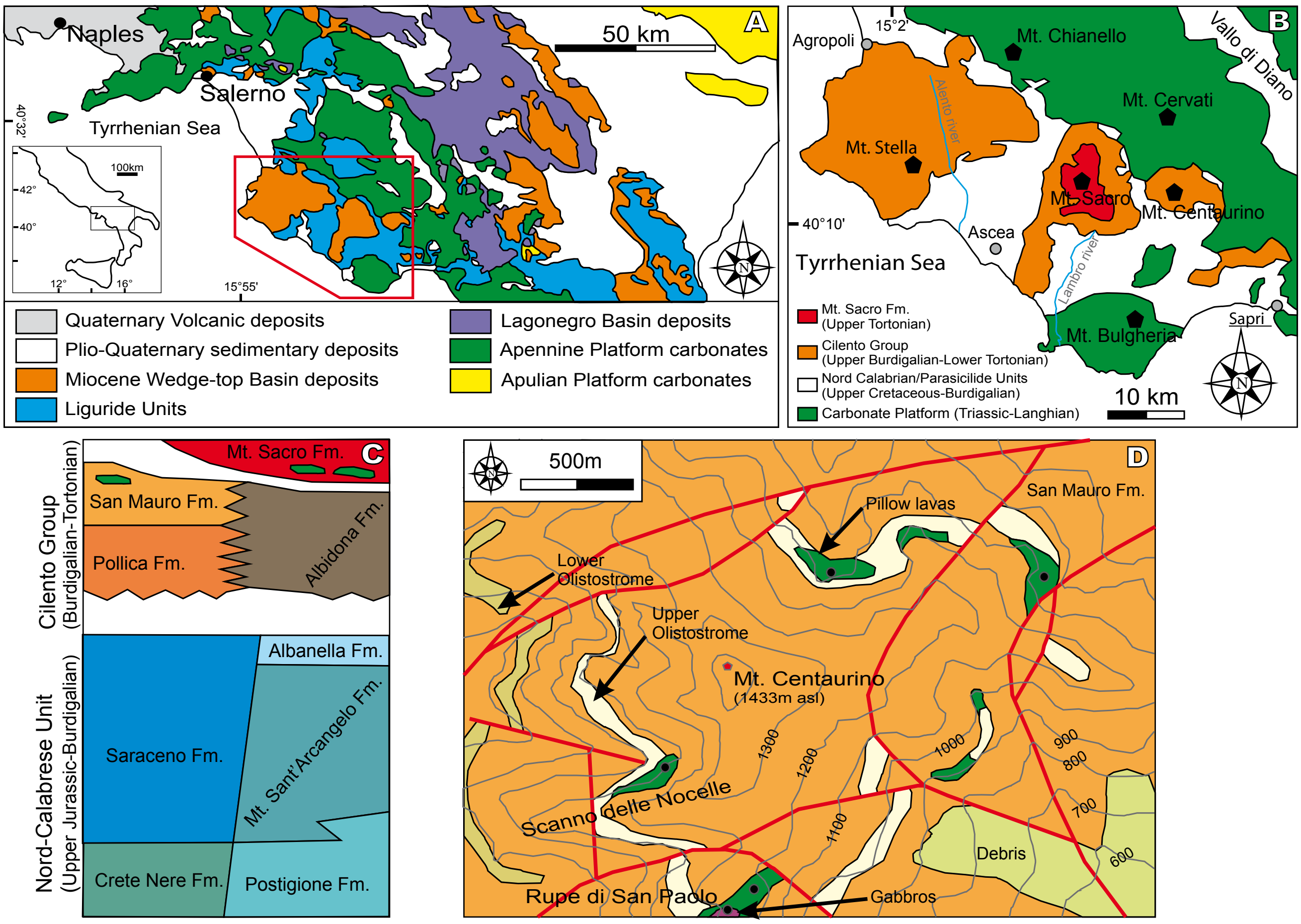

FIGURE 1. A) Tectonic sketch map of southern Apennines (redrawn after Vitale *et al*., 2011); B) geological sketch map of the Cilento area (redrawn after Vitale *et al*., 2011); C) sketch showing stratigraphic relationships of the different tectonic units cropping out in the Cilento area (modified after Vitale *et al*., 2011); D) simplified geological map of Mt. Centaurino, showing all investigated outcrop locations.

point out that the only hawaiitic volcanism with anorogenic geochemical characteristics of SE Spain occurs at the Tallante-Cartagena area, and has been dated at ~2.3–2.9Ma (Duggen *et al*., 2005), much later than the main orogenetic phases. The same situation is found in the Moroccan and Algerian Maghrebian Chain, where the anorogenic products, mostly with sodic alkaline affinity, are late Miocene–Quaternary in age (Coulon *et al*., 2002; Duggen *et al*., 2005). A completely different scenario is that proposed by Dietrich and Scandone (1972) who found no evidence of contact metamorphism between the Mt. Centaurino igneous rocks and the turbidite series, and proposed that they were ophiolitic olistoliths. Based on petrographic and geochemical data, Di Girolamo *et al*. (1991) recognized a Mid Oceanic Ridge Basalts (MORB) affinity in these rocks, supporting the hypothesis that they are olistoliths incorporated during sedimentation of the conglomerate-sandstone succession diffusely cropping out in the Cilento area. This interpretation has been newly supported by new field data provided by the Italian CARG Project, an update of the geological cartography at 1:50.000 scale launched in 1988 (Catenacci, 1995), in which the Mt. Centaurino area here investigated pertains to geological sheets n. 504, Sala Consilina (Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), 2010), and n. 520, Sapri (Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), in press). In this work we present petrographic, mineralogical and geochemical data on a new selection of pillow basalts and, for the first time, gabbroic rocks found in association with effusive ones. A comprehensive petrological investigation has been carried out using these data, including geothermometry estimates and trace element modeling, in order to shed new light on the origin and geological significance of the Mt. Centaurino igneous rocks in the framework of the Tertiary evolution history of this sector of the Mediterranean area.

FIELD RELATIONSHIPS OF IGNEOUS ROCKS AND TURBIDITIC SERIES

The studied area is located in the Cilento region (southern Campania; Fig. 1), which is representative of the main tectonic units forming the fold-and-thrust-belt structure of the southern Apennines (D'Argenio *et al*., 1973; Mostardini and Merlini, 1986; Mazzoli and Helman, 1994; Patacca and Scandone, 2007). The southern Apennine chain is the product of a tectonic overlap (from W to E), started in the late Oligocene, of oceanic and/or transitional basinal successions and carbonate platforms, occupying the western portion of the Alpine Tethys during the Mesozoic, between the European and African continental margins (Bonardi *et al*., 1988, 2001; Knott, 1994; Ciarcia *et al*., 2009, 2012; Vitale and Ciarcia, 2013). The terrains of these domains, detached from their basement and migrated eastwards, have been piled forming an Oligocene orogenic prism (Ligurian Accretionary Complex (LAC), Ciarcia *et al*., 2009). During the orogenic phases, these units overthrust the outer carbonate platform domain to the East, and were unconformably covered by the wedge-top uppermost Burdigalian-lower Tortonian turbidite flysch of the Cilento group (Bonardi *et al*., 1988, 2009), the Tortonian Piaggine sandstones (Sgrosso, 1981) and the upper Tortonian Monte Sacro Formation (Selli, 1962). The igneous rocks of Mt. Centaurino are embedded into the Langhian-lower Tortonian San Mauro Formation, forming the upper part of the Cilento group turbidite series. At this site, pillow lavas, hyaloclastites and pillow breccias form an apparently discordant outcrop because they cut the bedding of the succession (Fig. 2A, B, C). These field observations were inferred as indicators of a synorogenic effusive and sub- effusive magmatic event occurred during the deposition of the turbidites (Ietto and Cocco, 1965; Cocco and Di Girolamo, 1970). New field data indicate that these igneous rocks occur within a definite stratigraphic interval (Fig. 1D) and that those outcrops apparently cutting the succession are Quaternary debris deposits derived by denudation of the upper parts of the slope. The olistostromal level (identified with ol3 and ol4 in the Sala Consilina and Sapri geological sheets, respectively) is a chaotic deposit with masses of ophiolitic rocks, represented by effusive (pillow lavas, hyaloclastites and pillow breccias), intrusive (gabbros) and sedimentary (cherts and phthanites) material. In addition, intrusive granitoid rocks are reported by the old geological maps. The occurrence of granitoid rocks together with basaltic rocks is quite rare in ophiolitic mélanges (with exception for plagiogranitic type). Unluckily, due to the difficulty of reaching these outcrops, it has not been possible to take samples of granitoid rocks. These igneous rock masses are irregularly distributed within the olistostromal level. Locally they appear dominant up to form tower-shaped morphologies (*e.g*., Rupe San Paolo) or included as boulders or cobbles into a polychrome greyish-greenish-reddish clayey and marly matrix. A further proof of the olistostromal genesis of these rocks is the similarity with clasts of igneous rocks comprised in the homologous stratigraphic interval at the Mt. Sacro section, for which the sedimentary olistostromal genesis was undoubtedly established since the first geological surveys (Cocco and Pescatore, 1968). The average and the maximum thickness of the olistostromal level are 110 and 150m, respectively, at Mt. Centaurino, and 120 and 160m, at Mt. Sacro. The age is estimated not older than lower Tortonian.

SAMPLE PREPARATION AND ANALYTICAL TECHNIQUES

Representative samples of mafic (effusive and intrusive) rocks that crop out at Mt. Centaurino have been collected. The samples were cut with a saw and crushed in a jaw crusher. The chips were washed with deionized water and dried in oven at 120ºC. Subsequently the samples

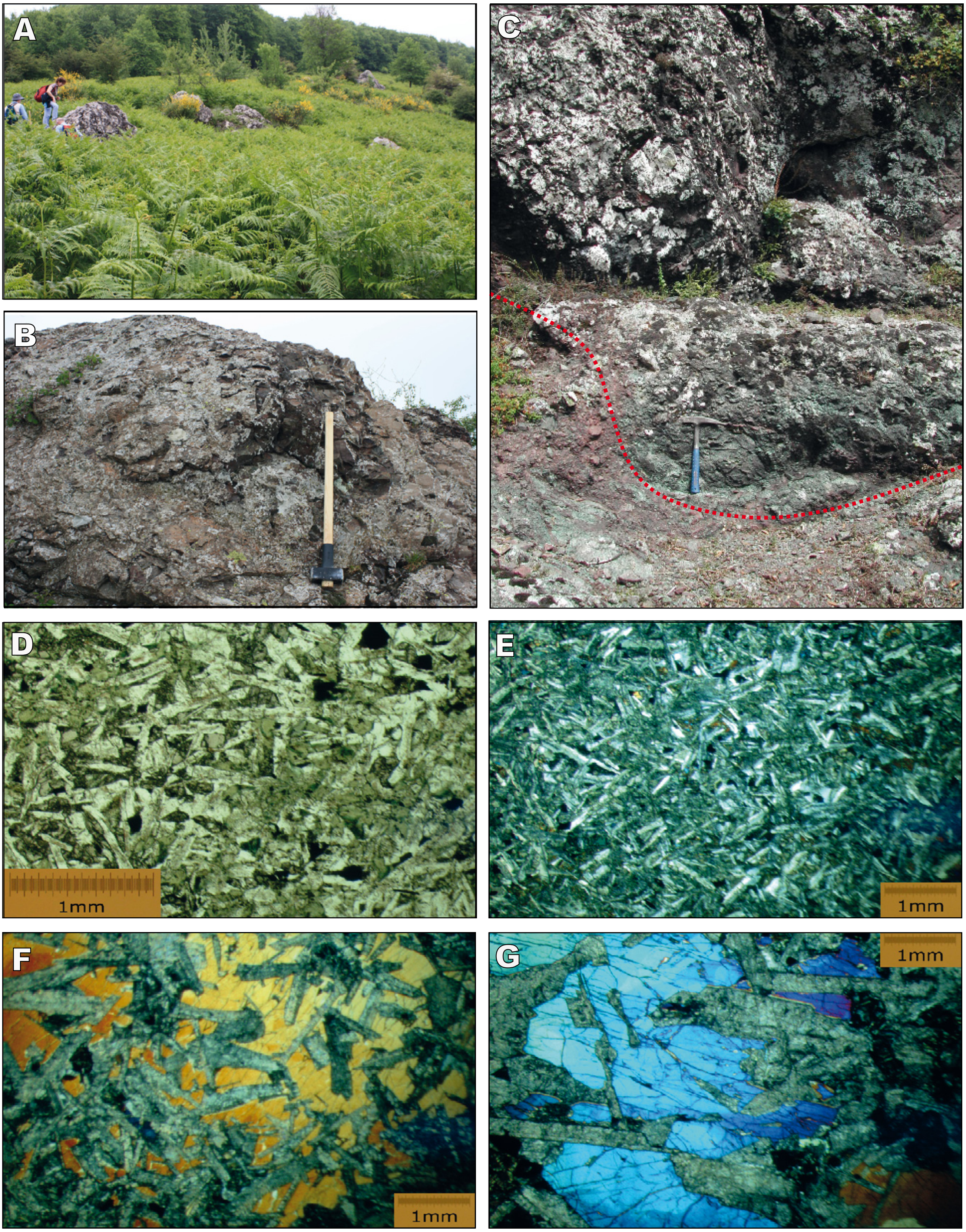

FIGURE 2. A and B) Outcrops of mafic igneous rocks at Mt. Centaurino; C) contact between basaltic rocks and pelitic-arenaceous succession at Mt. Centaurino; D and E) ophitic texture of the basaltic samples with crystals of plagioclase and clinopyroxene; F and G) coarse-grainedcumulitic texture in gabbros with plagioclase and large crystals of clinopyroxene as dominant phases.

were observed under a binocular microscope and only the freshest pieces were chosen for powdering. For each sample, about 40g of granulated rock were handpicked. The samples were washed again with deionized water and dried in oven at 120ºC. Sample powders were produced in a low-blank agate planetary ball mills. For each sample two pulverization steps were done with 20g of material each. Considering the strong replacement of the original paragenesis by secondary minerals (see above) we decided to use for the subsequent analytical steps, only the samples with a mass Loss On Ignition (LOI) less than 3wt.%. The volatile content (LOI) was measured using standard thermo-gravimetric methods at the Centres Científics i Tecnològics de la Universitat de Barcelona (CCiTUB) (Spain), by igniting rock powders at 1100ºC after drying them overnight at 120ºC. Major oxides and some trace elements (Sc, V, Cr, Ni, Rb, Sr, Ba, Y, Zr and Nb) were analyzed by X-ray fluorescence using a Philips PW2400 sequential X-ray spectrometer at the CCiTUB. Other trace elements including the Rare Earth Elements (REE) were analyzed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) using a Perkin Elmer Elan 6000 at the CCiTUB. For this purpose, powders of the whole rock were dissolved with high-purity HF + HNO3 + HClO4 mixtures. Relative precision was generally better than 1–2% for major oxides, and better than 5–10% for trace elements, verified by analysis of the JSy-1 and JB-3 standards of the Geological Survey of Japan (Imai *et al.*, 1995).

The mineral compositions were obtained with a Cameca SX100 SEM-WDS microprobe at CCiTUB, equipped with four INCA X-act detectors, operating at a 15kV beam voltage, with a 50–100mA filament current, variable spot size and 50s net acquisition time. Precision and accuracy were controlled using internal standards. Trace element content in clinopyroxene (cpx) was determined by Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICP- MS) at CNR–Istituto di Geoscienze e Georisorse (IGG, Pavia, Italy). The microprobe consist of an Elan DRC-e quadrupole mass spectrometer coupled with a Q-switched Nd: YAG laser source (Quantel Brilliant). The fundamental emission of the laser source (1,064nm, in the near-IR region) was converted to 266nm by two harmonic generators. Spot diameter was varied in the range of 40–60µm. NIST SRM 610 standard was used as external standard, Ca measured by EMPA was used as internal standard. Precision and accuracy (both better than 10% for concentrations at ppm level) were assessed by means of repeated analyses of NIST SRM 612 and BCR-2g standards.

PETROGRAPHY

Basalts from Mt. Centaurino (Fig. 2D, E) show a very fine-grained ophitic texture, with crystals of plagioclase, often clustered and albitized, zoned clinopyroxene sometimes completely replaced by chlorite, amphibole with a fibrous appearance and yellow to light green pleochroism, and olivine altered along fractures to iddingsite. In the groundmass, opaque minerals and clinopyroxene, often observed at the rims of olivine or enclosed in plagioclase, and apatite complete the mineralogical association. In many samples, the presence of secondary mineral phases such as serpentine, chlorite, talc, glauconite, iddingsite and calcite are significant. Gabbros have been distinguished for their coarser grain-size and ophitic texture (Fig. 2F, G). Plagioclase is the dominant phase and forms euhedral to subhedral, rarely preserved grains (modal 50–55%). Clinopyroxene (modal 25–35%) occurs as subhedral grains and as interstitial grains between large plagioclase crysts. Small amounts of olivine, generally altered along fractures to serpentine (some crystals are completely serpentinized) and iddingsite, and opaque oxides (in some cases included in olivine) complete the mineralogical association. The observed crystallization order in gabbros is olivine ± opaque oxides + plagioclase + clinopyroxenes, which is typical of MORB melts.

WHOLE ROCK CHEMISTRY

Major and trace element analyses of the Mt. Centaurino igneous rocks are reported in Table I. The studied samples are basalts according to the Total Alkalis *vs.* Silica (TAS) diagram, and on the basis of their CIPW norms can be classified as hyperstene tholeiites (normative Hy is ~15wt.% for gabbros and ~21wt.% for basalts). Their chemical composition is different from that of other igneous products cropping out in nearby volcanic districts, such as Somma-Vesuvius and Phlegrean Volcanic District. Instead, they fall within the compositional field defined by the ocean floor basalts cored into the Tyrrhenian Sea basin. Basaltic pillow lavas have low SiO_2 (<51wt.%) and alkali contents (2.7–3wt.%) with Na_2O>K_2O (K_2O/Na_2O ratios ~0.1), and high Al_2O_3 (>15wt.%) and CaO (>10wt.%) contents. They have low Mg# values (56–58, calculated assuming Fe_2O_3/FeO = 0.15; Middlemost, 1989). Moreover, they have high Ni (~200ppm), Cr (~350ppm), V (~300ppm), and almost similar Sr (~270ppm) and Ba (~330ppm) contents. The other trace element content is comparably low. Mt. Centaurino basaltic rocks show an almost flat chondrite normalized REE pattern (Fig. 3), with a slight enrichment in light Rare Earth Elements (LREE) compared with middle Rare Earth Elements (MREE) and heavy Rare Earth Elements (HREE), showing low La_N/YbN ratios (~1.7) and no europium anomalies (Eu/Eu*~1). Also, they have a chondrite normalized REE pattern falling within the compositional field of the Alpine-Corsica ophiolitic basalts (Venturelli *et al.*, 1981; Ottonello *et al.*, 1984; Vannucci *et al.*, 1993; Rampone *et al.*, 1998; Saccani *et al.*, 2008) and southern Italy ophiolitic basalts (Liberi

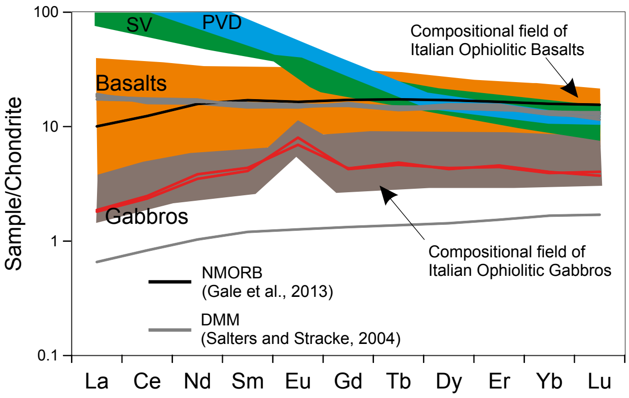

FIGURE 3. Chondrite-normalized Rare Earth Element patterns for Mt. Centaurino mafic igneous rocks, compared to those of SV-PVD (abbreviations a sincaption of Figure 3), of the average N-MORB (Gale *et al.*, 2013), the composition of other Italian ophiolitic basalts (Venturelli *et al.*, 1981; Ottonello *et al.*, 1984; Vannucci *et al.*, 1993; Rampone *et al.*, 1998; Liberi *et al.*, 2006; Saccani *et al.*, 2008; Mazzeo, 2014) and of the composition of other Italian ophiolitic gabbroic rocks (Montanini *et al.*, 2006; Rampone *et al.*, 1998; Tribuzio *et al.*, 1999, 2000 and 2004; Piccardo and Guarnieri, 2011; Mazzeo, 2014). The chondrite values used for normalization are taken from Boynton (1984).

et al., 2006; Mazzeo, 2014). Gabbros have high MgO ~8wt.%, TiO_2 = 0.2–0.3wt.%, Al_2O_3 ~17wt.%, CaO ~11wt.%, low Ni (~200ppm) and high Cr (~900ppm) contents. They have low REE content (2–8 times chondrite; Fig. 3), with patterns showing moderate HREE depletion (LaN/YbN ~0.7) and positive Eu anomalies (Eu/Eu*= 1.6–1.9). Large-Ion Lithophile Elements LILE are enriched relative to LREE (Ba/La~4), and both LILE and LREE are enriched relative to High Field Strength Elements (HFSE) (Ba/Nb~23–44 and La/Nb~6–10). The high Al_2O_3, Sr and Eu concentrations reflect the high modal plagioclase content. Like basalts, gabbros from the Mt. Centaurino have a chondrite-normalized REE pattern falling within the compositional field of the other Italian ophiolitic gabbros (Montanini *et al.*, 2006; Rampone *et al.*, 1998; Tribuzio *et al.*, 1999, 2000, 2004; Piccardo and Guarnieri, 2011; Mazzeo, 2014).

MINERAL CHEMISTRY

Representative mineral compositions are given in the Electronic Appendix I, available at www.geologica-acta.com. Olivine in basalts shows a fairly restricted range of composition from Fo_{83} to Fo_{78}, and is characterized by high MnO content (0.4–0.6wt.%). In comparison, olivine in gabbros shows a wider range of composition, from Fo_{87} to Fo_{80}. NiO ranges from 0.11 to 0.33wt.%, CaO ranges from 0.2 to 0.4wt.%, MnO is highly variable and ranges from 0.09 to 0.4wt.%, slightly increasing as MgO decreases. Clinopyroxene (Fig. 4A) in basalts is augite ($Wo_{33-43}En_{56-43}Fs_{6-17}$). The Mg# value ranges from 83 to 69. It has variable TiO_2 (0.7–1.6wt.%), Al_2O_3 (1.8–6wt.%), FeO (6.7–12.8wt.%), Na_2O (0.1–0.6wt.%) and Cr_2O_3 (0.1–1.4wt.%) contents. With decreasing Mg# the content of Cr_2O_3 decreases, that of TiO_2 and FeO increases, while the Al_2O_3 and Na_2O contents tend to increase until Mg# = 76, decreasing afterwards (Fig. 4B-F). Clinopyroxene in gabbros is also classified as augite (Fig. 5A) and shows a chemical composition similar to that of clinopyroxene in basaltic samples but with smaller variations. The Mg# values range from 82 to 77. Al_2O_3 varies from 0.7 to 2.9wt.%, TiO_2 from 1.14 to 1.64wt.%, FeO_t from 7.5 to 8.9wt.%, Cr_2O_3 from 0.1 to 0.55wt.% and Na_2O from 0.26 to 1.43wt.%. No correlation between these elements and Mg# value can be observed (Fig. 4B-F). The chemical variation shown by clinopyroxenes in gabbros are represented within the compositional field of clinopyroxenes in oceanic mafic cumulates. The only exception is shown by the TiO_2 content of clinopyroxene, which is much higher than that typically observed in clinopyroxene of oceanic cumulitic rocks. Clinopyroxenes in gabbros have slight LREE depletion (Fig. 5A; La_N/Sm_N = 0.16–0.22), and small negative Eu anomalies (Eu/Eu*= 0.75–0.95). The chondrite-normalized REE pattern of clinopyroxene in gabbros from Mt. Centaurino is very similar to that of clinopyroxenes in gabbros from External Ligurides ophiolitic massifs while it is very different from that of the clinopyroxenes in gabbros from Internal Ligurides ophiolitic massifs, mainly with regard to LREE concentration (La_N<0.1 times chondritre). The primitive mantle-normalized incompatible trace element patterns of the clinopyroxenes show Th, Nb and Sr depletion relative to the other trace elements (Fig. 5B). Pigeonite crystals have been found only in basaltic samples (Fig. 4A). They show a narrow compositional range ($Wo_{8-14}En_{56-50}Fs_{29-38}$). The Mg# values range from 66 to 56. Plagioclase is mainly bytownite-labradorite ($An_{76.5-60.5}Ab_{23.5-39.5}Or_{0-0.5}$) in all rock samples (Fig. 6A) and shows a normal compositional zoning. The SrO and BaO contents are extremely low, often below the instrument detection limit. FeO_t content ranges from 0.4 to 0.9wt.% (Fig. 6B). Ti-magnetite is the dominant spinel phase and has low Al_2O_3 (<6wt.%). Cr-Spinel has been found as inclusion in the most Fo-rich olivines (Fo>85) and has high Cr_2O_3 (35–43wt.%) and FeO (17–22wt.%) contents (Fig. 6C). The TiO_2 content ranges from 0.5 to 1.2wt.%. Cr# ranges from 42 to 58. Ilmenite has a limited range of chemical variation in both rock types with low MgO (0.9-1.6wt.%) and Al_2O_3 (0.15–1wt.%) contents (Fig. 6D).

TEMPERATURE AND OXYGEN FUGACITY ESTIMATES

To estimate the temperature of the basaltic magmas from which the Mt. Centaurino igneous rocks have crystallized, we used several geothermometers based on mineral-liquid equilibration. The temperature values calculated using the

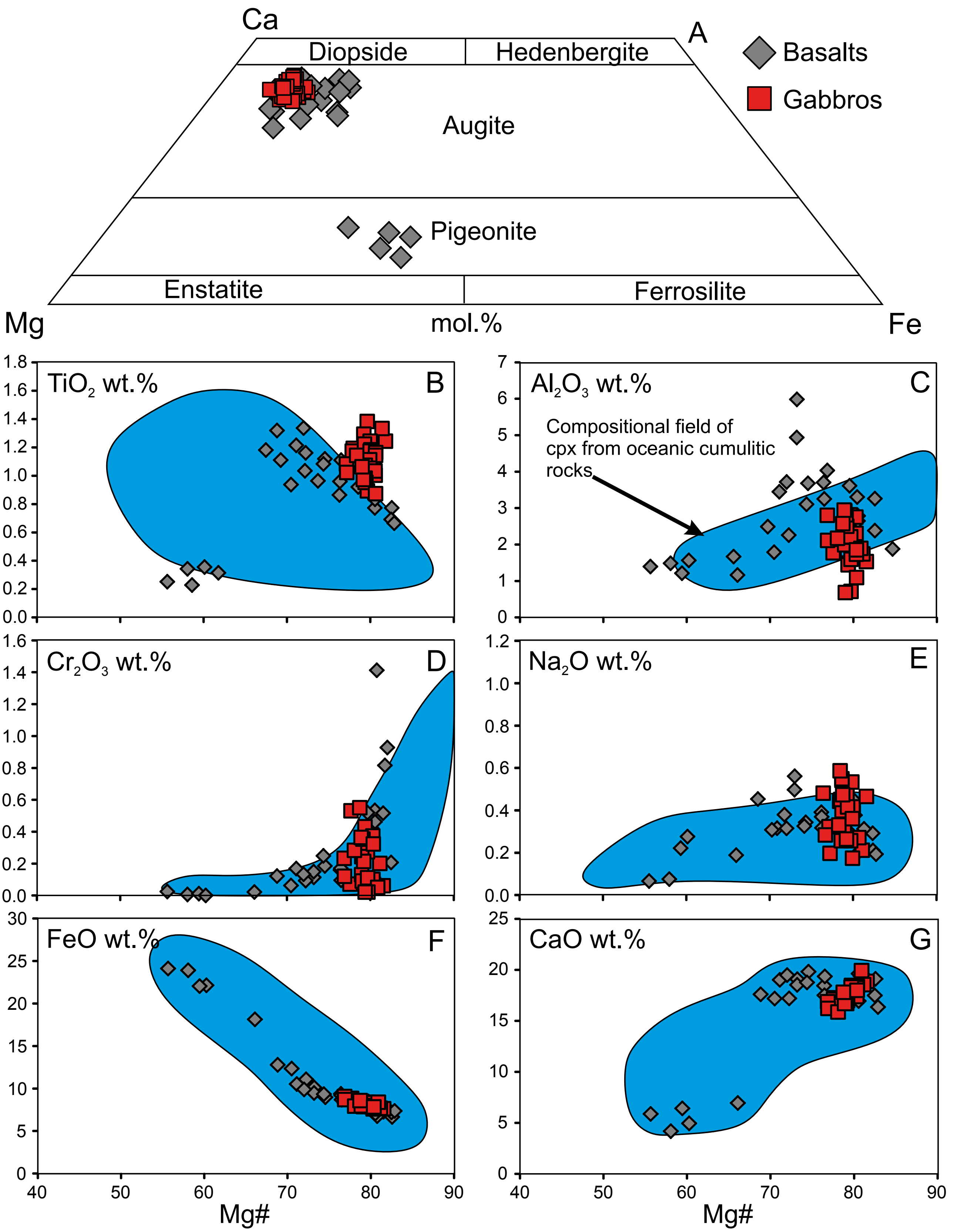

FIGURE 4. A) Classification of pyroxene from Mt. Centaurino mafic igneous rocks (after Morimoto, 1988); B–G) binary diagrams showing the compositional variations of the pyroxene with decrease of Mg#. Compositional fields of clinopyroxene from ocean-derive digneous rocks are redrawn after Elthon *et al.* (1992).

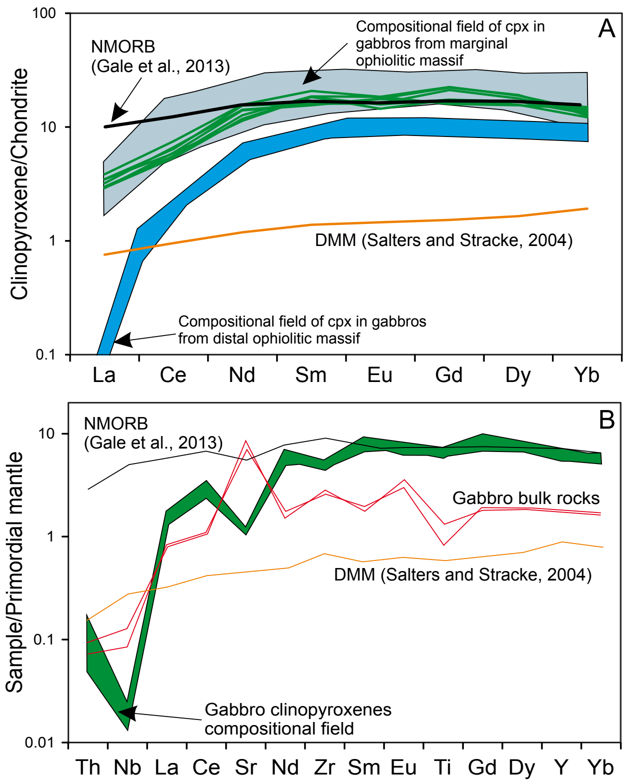

FIGURE 5. A) Chondrite-normalized Rare Earth Elements (REE) abundance of clinopyroxenes in the analyzed gabbroic rocks. Normalization values from Boynton (1984). Compositional field of clinopyroxene in other Italian ophiolitic massif are redrawn from Rampone and Piccardo (2000) and Piccardo and Guarnieri (2011); B) primitive mantle-normalized trace elements abundance of gabbro whole rocks and clinopyroxenes compared to N-MORB average composition (Gale *et al.*, 2013). Normalization values from Lybetskaya and Korenaga (2007).

Putirka (2008) geothermometer based on the olivine-liquid equilibrium at 0.1kbar, range from 1156ºC to 1203ºC. The geothermometer based on the plagioclase-liquid equilibrium (Thy *et al.*, 2013) yields a temperature range of 1170±26ºC, very similar to the pigeonite thermometer calculation (Ishii, 1975), that yields a temperature of 1162±17ºC. Calculated equilibration temperatures and oxygen fugacity provided by the magnetite-ilmenite equilibrium pairs (Lepage, 2003) range from 1089 to 967ºC and from -10.5 to -11.3log units, respectively, plotting close to the Quartz-Fayalite-Magnetite (QFM) buffer , quite typical for MORB magmas.

GEOCHEMICAL AFFINITY AND CRYSTALLIZATION CONDITIONS

On the basis of their textural features (*e.g.* opaque oxides only in groundmass and plagioclase before clinopyroxene), the major element contents (low TiO_2 and K_2O), and the relatively flat pattern, the basalts and gabbros cropping out at the Mt. Centaurino show a tholeiitic character, evidenced also by the presence of normative hyperstene. The low Na_2O and Al_2O_3 contents of clinopyroxene in basalts, as well as the presence of a Ca-poor pyroxene (pigeonite) in association with augitic clinopyroxene are features typical of rocks that crystallize from tholeiitic melts at low pressure in different tectonic settings (*e.g.*, Elthon *et al.*, 1992; Melluso *et al.*, 2006; Cucciniello *et al.*, 2014). However, clinopyroxenes in gabbros show TiO2 concentrations higher than those normally observed in clinopyroxene from oceanic rocks (Fig. 4B). This feature, already observed in other cases, is commonly associated with high concentration of Na_2O (Elthon *et al.*, 1992; Dick *et al.*, 2002; Stone and Niu, 2009), but it is not observed in our case. These unexpected composition of clinopyroxene can be attributed to:

i) crystallization of evolved liquids trapped in a cumulate, that can affect mineral compositions during a later stage of cooling (Coogan *et al.*, 2000);

ii) crystallization of small amounts of opaque oxides from a MORB melt (Dick *et al.*, 2002);

iii) pressure-dependent partition coefficients of these elements, because $Kd^{cpx\text{-}liq}$ for Ti and Na are higher at P>3kbar (Elthon *et al.*, 1992).

We are prone to exclude the first possibilities because they are common process in rocks that derive from evolved liquids and the Mt. Centaurino mafic igneous rocks are not residual rocks. Also the second hypothesis is ruled out. Indeed, the late appearance of opaque minerals as liquidus phases can increase the TiO_2 content in the residual liquid but, in this case we should expect a Ti-enrichment in the Mt. Centaurino rocks, something that does not occur because they are not residual rocks as mentioned above. In our case, it is quite plausible to state that there is no dependence of Na and Ti concentration from pressure, considering that the pressure of 3kbar correspond roughly to the base of the oceanic crust. The chemical composition of plagioclase and clinopyroxene coexisting in both basalts and gabbros are typical of rocks with MORB affinity, as they are represented in the compositional fields described by minerals of ocean-derived rocks (Fig. 7A). The maximum Mg# value of olivines (Fig. 7B) and calcic clinopyroxenes (Fig. 7C) in the studied samples decreases with decreasing of whole rock Mg# (considered representative of the liquid in equilibrium with the mineral phases), suggesting that these rocks are derived by a fractional crystallization process from primitive melts. The calculated distribution coefficients of Fe and Mg for olivine (${}^{Fe/Mg}Kd^{Ol\text{-}liq}$= 0.27–0.33; Roeder and Emslie, 1970) and clinopyroxene (${}^{Fe/Mg}Kd^{cpx\text{-}liq}$= 0.24–0.30; Grove and Bryan, 1983) indicate that some mafic

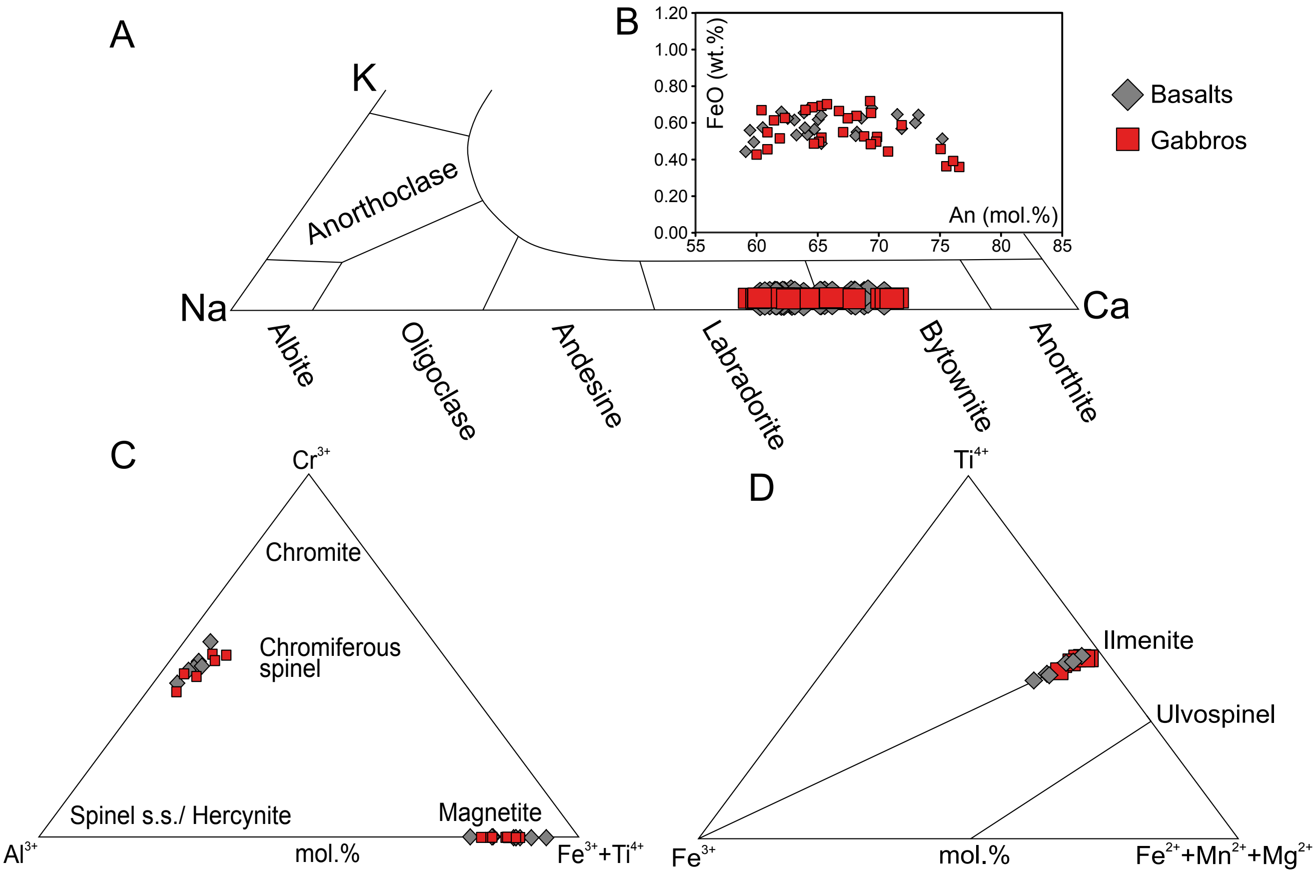

FIGURE 6. A) Classification of plagioclase from Mt. Centaurino mafic igneous rocks; B) An (mol.%) *vs.* FeO (wt.%) binary diagrams showing the compositional variations oftheplagioclase; C and D) classification diagrams showing the composition of oxide minerals from Mt. Centaurino mafic igneous rocks.

minerals, generally clinopyroxene, are not in equilibrium with the host rock as they are represented below the clinopyroxene-liquid equilibrium field (Fig. 7C). This feature may be due to the fact that the clinopyroxene likely form from more evolved melts, because generally clinopytroxenes has lower Mg# compared to the expected value in equilibrium with the melt.

Mt. Centaurino mafic rocks are very similar to MORB, due to the slight LREE enrichment and flat HREE in the chondrite-normalized REE pattern (Fig. 3). The similarity between these rocks and the typical MORB is confirmed also by the incompatible trace element contents, and especially their ratios: Nb/Yb= 0.7–1, Nb/Ta= 12–14, Zr/Hf= 35–42; Th/Nb~0.1. The diagrams in Figure 8 show that these ratios fit well within the range of N-MORB worldwide (Sun and McDonough, 1989; Salters and Stracke, 2004; Workman and Hart 2005; Gale *et al.*, 2013). Moreover, the compositional difference between the Mt. Centaurino mafic rocks and the other igneous products cropping out in nearby volcanic districts of southern Italy appears once again, as they fall within the compositional field defined by the ocean floor basalts of the Tyrrhenian Sea Basin, although the latter are related to a much younger (*i.e.* Plio-Pleistocene) magmatic episode.

GENESIS OF THE PARENTAL MAGMAS

The genesis of ocean ridge tholeiitic melts (Mid-Ocean Ridge Basalts, MORB) is believed to be the result of partial melting of a spinel-bearing, depleted asthenospheric mantle (DMM, Depleted MORB Mantle; Niu, 1997; Salters and Stracke, 2004; Workman and Hart, 2005; Gale *et al.*, 2013). Starting from this assumption, a non-modal partial melting model has been developed, in order to determine the degree of partial melting that could have generated the basalts cropping out at Mt. Centaurino. The used parameters and obtained results are provided in the Electronic Appendix II. As illustrated in Figure 9A, the chemical composition of the Mt. Centaurino basalts is consistent with magmas generated by variable degrees of non-modal fractional partial melting, totaling not more than 10%, of a spinel-facies, DMM-type asthenospheric mantle. The calculated degree of partial melting value is consistent with that obtained for ophiolitic basalts of Alps and starting from the chemical composition of olivine, clinopyroxene and plagioclase (all parameters and results in Electronic Appendix). The composition of the calculated melts is highly variable, though including that of basalts from Mt. Centaurino (Fig. 10). Also, the trace element concentrations of clinopyroxene of gabbros have been used to calculate the trace elements composition of the parental liquid (see Electronic Appendix), using the experimentally determined partition coefficients of Ionov *et al.* (2002). The synthetic liquids in equilibrium with the clinopyroxene in gabbros show REE concentrations about 10–20 times the chondritic values, with slight fractionation in LREE (La_N/Yb_N = 0.8–0.9). These synthetic melts are, however, very different from the

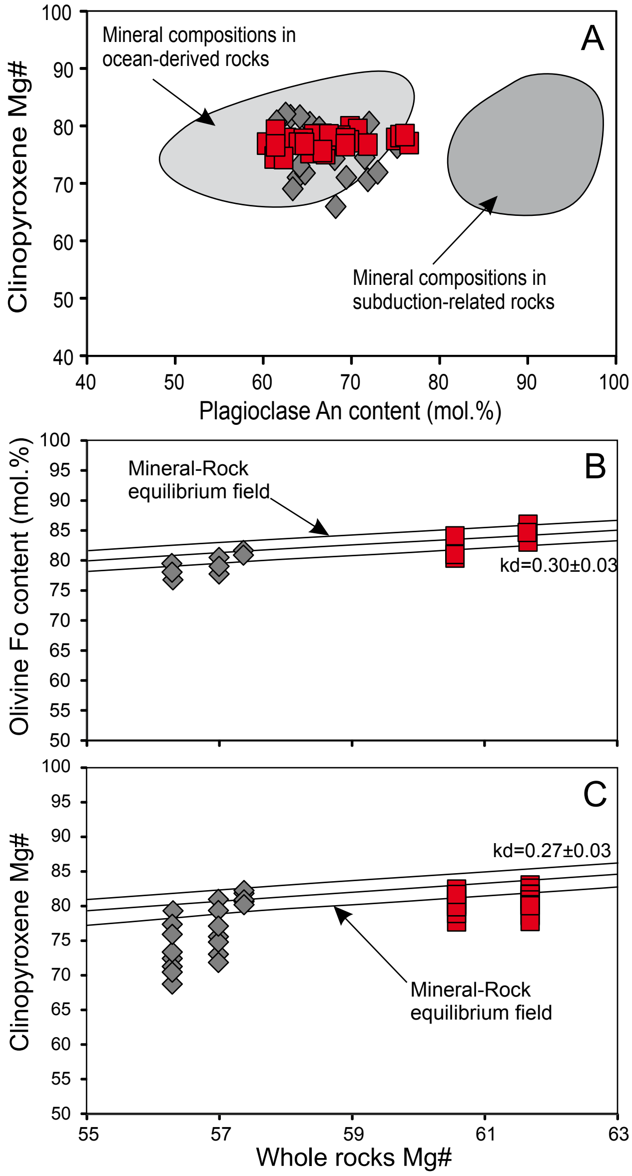

FIGURE 7. A) Plagioclase An (mol.%) *vs.* clinopyroxene Mg#, binary diagram showing the compositional affinity of these minerals with the oceanic crust-derived rocks (compositional field redrawn after Stone and Niu, 2009); B) Fe-Mg partitioning between olivine and hostrock ($^{Fe/Mg}Kd^{Ol\text{-}liq}$= 0.27–0.33; Roeder and Emslie, 1970); C) Fe-Mg partitioning between clinopyroxene and host rock ($^{Fe/Mg}Kd^{cpx\text{-}liq}$= 0.24–0.30; Grove and Bryan,1983).

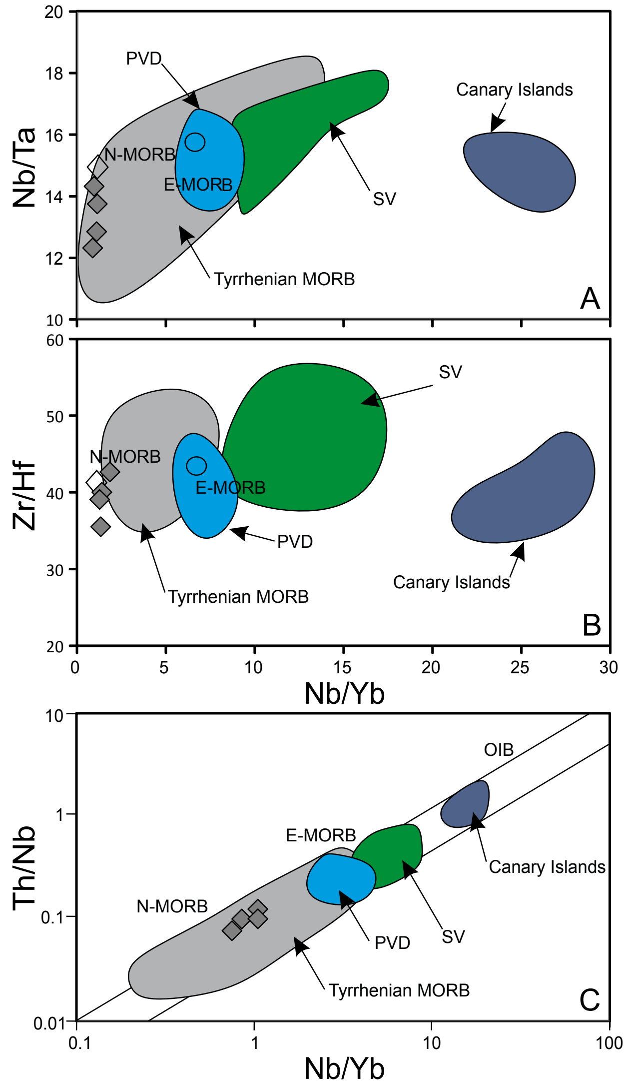

FIGURE 8. A–C) variation diagrams using ratios of HFSE. The geochemical composition of Mt. Centaurino mafic igneous rocks is very close to that of MORB all over the world (Gale *et al.*, 2013) and the Tyrrhenian Sea, while differing from that of the SV and PVD volcanic centers (compositional fields from Mazzeo *et al.*, 2014).

Northern Apennines, estimated to be ~5-15% (Venturelli *et al.*, 1981; Vannucci *et al.*, 1993; Saccani *et al.*, 2008), and other ophiolitic basalts of southern Apennine that crop out at Mt. Pollino (Calabria-Basilicata boundary), estimated at about 10–15% (Mazzeo, 2014). Major and trace elements concentration of minerals in gabbros can be used to calculate the composition of the parental liquids. To calculate the major oxide composition of the gabbro parental melts, we used the experimentally determined partition coefficients of Herzberg and O'Hara (2002) and Villiger *et al.* (2007)

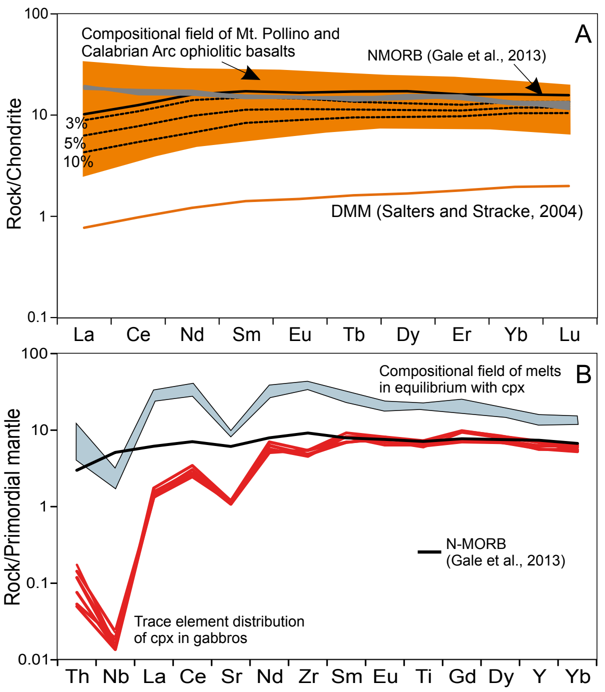

FIGURE 9. A) chondrite-normalized REE diagram for the Mt. Centaurino basalts. The chondrite-normalized REE abundance calculated for melts obtained by variable degrees of spinel-facies fractional melting of spinel-facies Depleted MORB Mantle (DMM) are reported for comparison (see Supplementary Electronic Material for parameters and results). Normalization values from Boynton (1984); B) primitive mantle-normalized trace element abundance of clinopyroxenes in the analyzed gabbros compared with the calculated composition of melts in equilibrium (see text for more information and Supplementary Electronic Material for parameters and results). Normalization values from Lybetskaya and Korenaga (2007).

N-MORB melts, having higher REE concentrations (Fig. 9B). This suggests that clinopyroxenes in gabbros might have derived from more evolved melts compared to those that produced the pillow, compatible with the observation that the clinopyroxene have lower Mg# than what is expected, using literature partition coefficient Kd Fe/Mg, as is the case of gabbroid suites cropping out in the ophiolitic massif of the Monte Maggiore in Corsica (Piccardo and Guarnieri, 2011). Furthermore, it is important to emphasize that the synthetic liquids in equilibrium with clinopyroxene of gabbros have low contents of Sr, Ti and Nb, a feature that may be due to fractionation of plagioclase and opaque oxides, coherently with the relatively evolved composition of the clinopyroxene.

PALEOGEOGRAPHIC AND GEODYNAMIC INFERENCES AND CONCLUSION

The new petrological and geochemical data, especially those achieved in detail for the first time on the gabbroic rocks, firmly support the idea that the mafic igneous rocks cropping out at the Mt. Centaurino were derived from an oceanic basin and embedded as olistoliths within the turbiditic succession of the Cilento group, as proposed by Di Girolamo *et al.* (1991). However, these authors have not investigated the reasons of the presence of these olistoliths embedded into sedimentary wedge top basin deposits. Mafic olistoliths have been found also in the Alps and Northern Apennines, where they occur embedded within a Late Cretaceous sedimentary succession and often associated with continental crust basement rocks (granulite, gneiss and amphibolite). Some authors (Marroni *et al.*, 1998; Principi *et al.*, 2004; Perrone *et al.*, 2014) believe that the Late Jurassic ophiolitic breccias arise from gravitational collapses originated from topographic highs associated with activation of normal/transform faults of the Ligurian Tethys in slow spreading ocean ridge segments, allowing exhumation of the lithospheric mantle and its exposure along unstable slopes during the subduction of the Ionian oceanic lithosphere below the European continental lithosphere likely started at around 50–45Ma (Alvarez and Shimabukuro, 2009; Lustrino *et al.*, 2009; Shimabukuro *et al.*, 2012; Mazzeo *et*

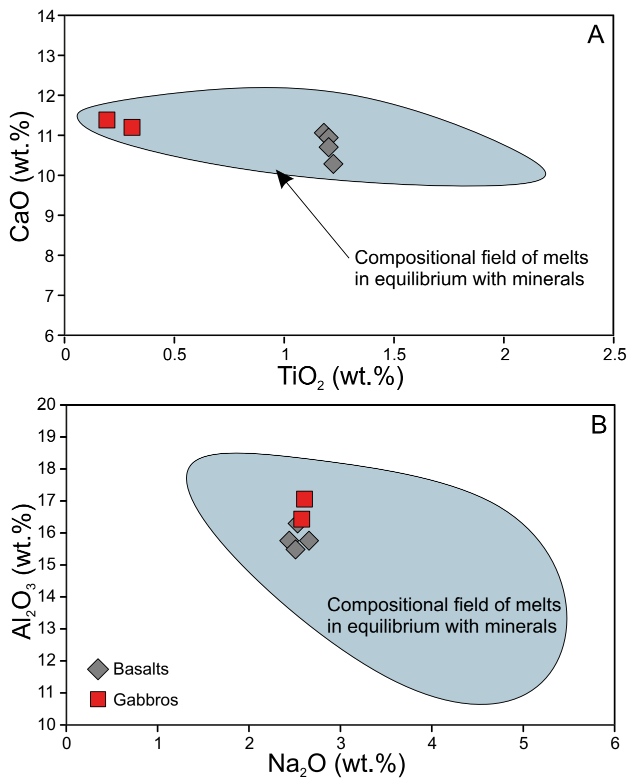

FIGURE 10. A and B) binary variation diagrams comparing the bulk composition of Mt. Centaurino mafic igneous rocks and the composition of melts in equilibrium with mineral phases (see text for more information, and Supplementary Electronic Material for parameters and results).

al., 2014). If we applied the same scenario to the Mt. Centaurino igneous olistoliths (Fig. 11A, B) we must assume that the slides involving the oceanic crust rocks have roughly the same age of the turbiditic succession within which the olistoliths are embedded, *i.e.*, the Miocene Cilento group (that is uppermost Burdigalian-lower Tortonian). Only after the deposition, these igneous rocks and the turbidites were involved in the phases of building of the southern Apennine Chain. In that respect, the ophiolitic basalts and gabbros of the Mt. Centaurino represent, along with the other outcrops of ophiolitic rocks scattered in Basilicata and Calabria, precious witnesses of the past geodynamic evolution history of this sector of the Mediterranean area. This, however, appears somewhat unrealistic in our case. As previously reported, the Miocene Cilento group is a wedge-top sedimentary succession and, according to several authors (Ciarcia *et al.*, 2009, 2012; Vitale *et al.*, 2010, 2011), no oceanic crust was exposed at the time of its formation. However, it is possible that during the early stages of the new orogenic phase, an accretionary wedge made up of oceanic lithologies-only might have formed. With the progress of subduction this accretionary wedge was dismantled and its remains were deposited in the adjacent Liguride basin (Vitale and Ciarcia, 2013 and references therein). It is possible that portions of this prism had survived to the initial stages of the new W-dipping subduction, and were later embedded during the deposition of the Cilento group (Fig. 11C, D).

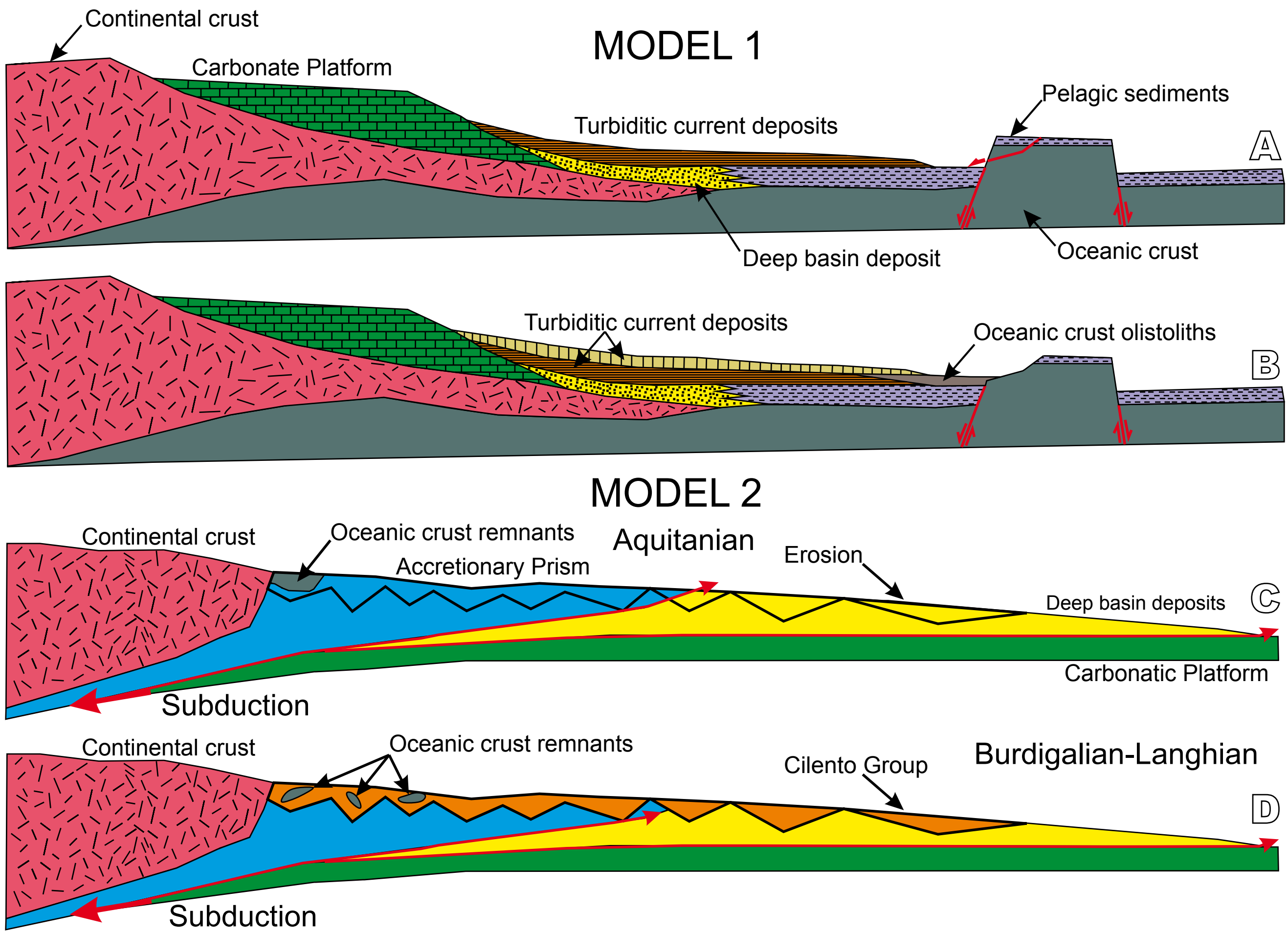

FIGURE 11. Cartoon showing the hypothetical formation and geological evolution of the Mt. Centaurino mafic olistoliths. According to exposure and gravitational instabilities of oceanic crust slope model of Perrone *et al.* (2014). A) The exhumation of the lithosphere and its exposure along unstable lopes is followed by B) gravitational collapses and deposition in adjacent deep basin (Model 1). This reconstruction appears not realistic in the studied case because no oceanic crust was exposed at the deposition time of the Cilento Group (uppermost Burdigalian–lower Tortonian). According to the paleogeographic reconstruction and geological evolution in Vitale *et al.* (2011) we suggest a second hypothesis (Model 2) C) during the early stages of the W-dipping subduction (Oligocene), an accretionary wedge made up of oceanic lithologies-only might have formed, being dismantled by the progress of subduction; D) portions of this prism could have survived and later embedded during the deposition of the Cilento Group in a thrust top basin.

ACKNOWLEDGMENTS

The authors wish to gratefully thank A. Zanetti (CNR, Pavia) for providing the LA-ICP-MS analyses. The friendly support of P. Petrosino (University of Naples) during field activity is greatly appreciated. This research has been carried out partly with a PhD bursary of the University of Naples to Fabio Carmine Mazzeo and with the financial support CGL2011-28022 fund by Spanish Ministerio de Ciencia y Educación to D. Gimeno.

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Manuscript received October 2015;
revision accepted April 2016;
published Online July 2016.

ELECTRONIC APPENDIX I

TABLE 1. Chemical composition of the Mt. Centaurino mafig igneous rocks

	40°13'12.48"N	40°13'10.90"N	[illegible]	40°12'30.34"N	40°11'5895"N	40°11'59.01"N
Longitude	15°28'44.54"E	15°29'37.53"E	15°28'22.82"E	15°27'59.04"E	15°28'13.88"E	15°28'15.86"E
Rock type	Basalt	Basalt	Basalt	Basalt	Gabbro	Gabbro
SiO_2	50.56	50.55	50.86	50.25	50.48	50.67
TiO_2	1.19	1.18	1.22	1.21	0.30	0.18
Al_2O_3	15.46	15.60	15.76	16.30	17.06	16.43
$Fe_2O_3(t)$	11.27	11.13	11.28	11.00	9.98	10.42
MnO	0.07	0.09	0.13	0.09	0.14	0.08
MgO	7.55	7.48	7.33	7.47	8.10	8.08
CaO	10.93	10.99	10.28	10.70	11.13	11.33
Na_2O	2.28	2.33	2.45	2.33	2.61	2.58
K_2O	0.55	0.45	0.56	0.48	0.17	0.19
P_2O_5	0.14	0.19	0.12	0.17	0.03	0.03
Sum	100.00	100.00	100.00	100.00	100.00	100.00
LOI	2.34	1.89	2.09	1.76	2.18	1.88
Na_2O+K_2O	2.83	2.78	3.01	2.82	2.78	2.77
K_2O/Na_2O	0.14	0.10	0.13	0.11	0.07	0.07
CaO/Al_2O_3	0.71	0.70	0.65	0.66	0.65	0.69
FeO(t)	10.14	10.02	10.15	9.90	8.98	9.38
Mg#	57.04	57.12	56.29	57.36	61.66	60.56
FeOt/MgO	1.34	1.34	1.38	1.33	1.11	1.16
V	270	276	291	308	374	375
Cr	310	390	330	320	877	978
Ni	168	260	185	176	197	218
Co	14	8	12	17	37	41
Rb	31	30	32	33	0.19	0.21
Sr	273	261	258	273	176	177
Ba	332	337	319	312	2.1	2.6
Y	27	23	21	22	8.0	8.3
Zr	83	86	89	88	31	29
Nb	2.70	2.10	2.30	3.04	0.09	0.06
Ta	0.21	0.17	0.16	0.22	0.01	0.01
Hf	2.10	2.00	2.56	2.21	0.37	0.45
Pb	1.40	1.30	1.60	1.90	0.26	0.21
Th	0.32	0.21	0.26	0.27	0.01	0.01
U	0.08	0.12	0.06	0.08	0.01	0.01
La	4.65	4.86	4.98	4.77	0.56	0.58
Ce	14.20	13.78	12.99	14.01	1.90	2.00
Pr	0.96	0.88	0.76	0.95	0.35	0.38
Nd	10.35	9.60	9.55	9.97	2.10	2.30
Sm	2.92	2.98	2.87	3.02	0.80	0.85
Eu	1.08	1.09	1.09	1.11	0.59	0.51
Gd	3.16	3.13	3.02	2.93	1.10	1.12
Tb	0.68	0.69	0.71	0.66	0.22	0.23
Dy	4.99	5.04	4.80	4.66	1.40	1.37
Ho	1.10	1.19	1.21	1.17	0.33	0.34
Er	3.02	3.26	3.14	3.19	0.93	0.96
Tm	0.47	0.51	0.61	0.57	0.13	0.11
Yb	2.66	2.78	2.81	2.79	0.82	0.84
Lu	0.39	0.37	0.41	0.43	0.13	0.12

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TABLE 1. Continued

	CENT 1	CENT 4	CENT 10	CENT 7	CENT 5	CENT 8
Latitude	40°13'12.48"N	40°13'10.90"N	40°12'6.08"N	40°12'30.34"N	40°11'5895"N	40°11'59.01"N
Longitude	15°28'44.54"E	15°29'37.53"E	15°28'22.82"E	15°27'59.04"E	15°28'13.88"E	15°28'15.86"E
Rock type	Basalt	Basalt	Basalt	Basalt	Gabbro	Gabbro
Eu/Eu*	0.95	0.95	0.98	0.99	1.92	1.60
La/Yb	1.75	1.75	1.77	1.71	0.68	0.69
Ba/La	71.40	69.34	64.06	65.41	3.75	4.48
Ba/Nb	122.96	160.48	138.70	102.63	23.60	44.07
La/Nb	1.72	2.31	2.17	1.57	6.29	9.83
Nb/Yb	1.02	0.76	0.82	1.09	0.11	0.07
Zr/Hf	39.52	43.00	34.77	39.82	83.78	64.44
Nb/Ta	12.86	12.35	14.38	13.82	14.83	11.80
Nb/Yb	1.02	0.76	0.82	1.09	0.11	0.07
Th/Yb	0.12	0.08	0.09	0.10	0.01	0.01
CIPW						
or	2.05	1.50	2.09	1.67	1.02	1.14
ab	20.98	21.37	22.48	21.43	22.08	21.82
an	30.03	30.48	30.03	32.26	34.32	32.69
di	19.03	18.63	16.54	16.10	16.88	19.08
hy	20.86	21.28	22.31	20.67	14.97	14.99
ol	1.52	1.15	1.02	2.31	7.49	7.15
mt	1.94	1.92	1.95	1.90	1.72	1.80
il	2.27	2.24	2.32	2.29	0.58	0.35
ap	0.34	0.46	0.29	0.41	0.07	0.07
Sum	2.05	1.50	2.09	1.67	1.02	1.14

Major elements, alkalis, calculated FeOt and LOI (loss on ignition) are reported as oxides wt.%. Normative composition is in wt.%. Trace elements are reported as ppm. FeOt and Mg# are calculted assuming Fe_2O_3/FeO = 0.15