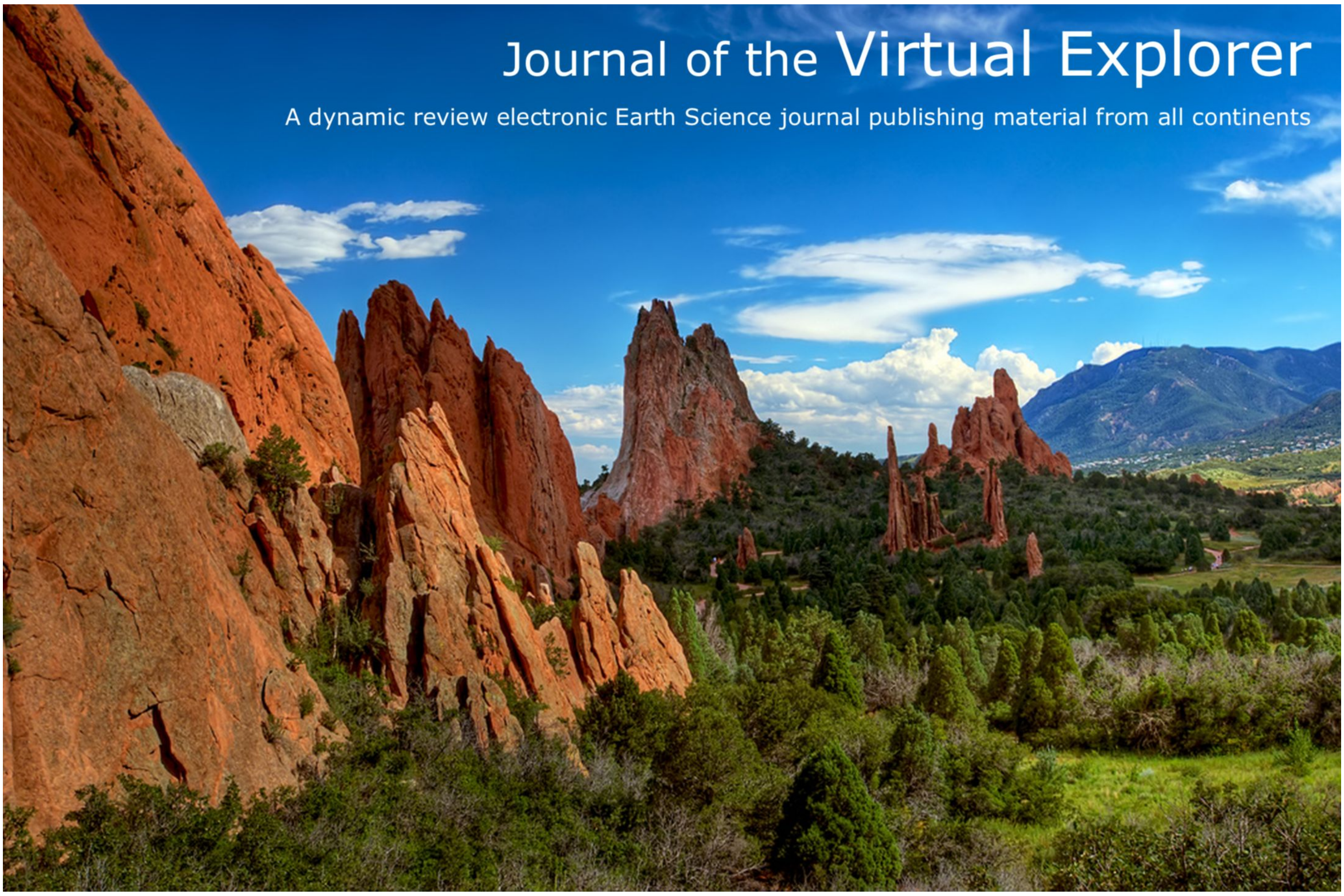


From ocean to subduction: the polyphase metamorphic evolution of the Frido Unit metadolerite dikes (Southern Apennine, Italy)

Maria T. Cristi Sansone, Paola Tartarotti, Giacomo Prosser, Giovanna Rizzo

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **41**, paper 3
In: (Eds.) Michele Zucali, Maria Iole Spalla, and Guido Gosso,
Multiscale structures and tectonic trajectories in active margins, 2012.

From ocean to subduction: the polyphase metamorphic evolution of the Frido Unit metadolerite dikes (Southern Apennine, Italy)

Maria T. Cristi Sansone
Università degli Studi della Basilicata, Dipartimento di Scienze Geologiche, Potenza, Italy.
Email: mariacristisansone@virgilio.it

Paola Tartarotti
Università degli Studi di Milano, Dipartimento di Scienze della Terra, Milano, Italy.

Giacomo Prosser
Università degli Studi della Basilicata, Dipartimento di Scienze Geologiche, Potenza, Italy.

Giovanna Rizzo
Università degli Studi della Basilicata, Dipartimento di Chimica, Potenza, Italy.

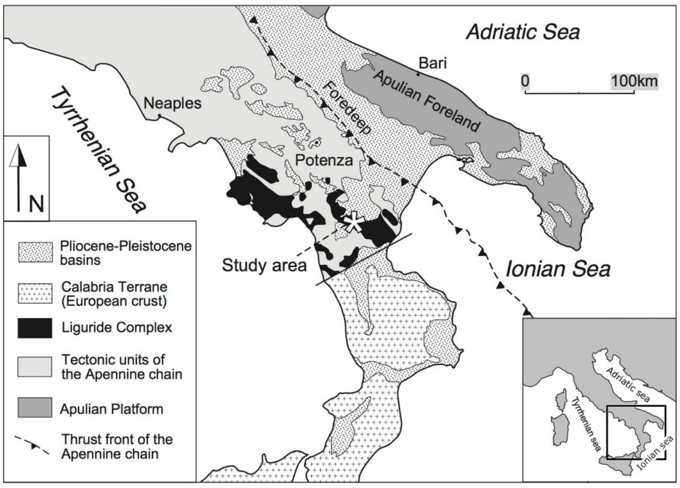
Abstract: The Liguride accretionary wedge in the Southern Apennine chain includes ophiolitic slices representing remnants of the Jurassic Tethyan ocean. In the northeastern slope of the Pollino Ridge (Calabria-Lucania border zone) ophiolitic rocks mostly consist of serpentinites crosscut by metadolerite dikes showing different types of textures, ranging from magmatic intersertal/intergranular and blastophitic to mylonitic and cataclastic. The metadolerite dikes have been affected by ocean-floor metamorphism under amphibolite to greenschists facies conditions. Subsequent subduction-related metamorphism under relatively HP/LT (blueschist facies) conditions affected the rocks during the formation of the Apennine accretionary prism. Late orogenic minerals of the prehnite-pumpellyite facies have crystallized in rocks and in veins. Such long-lasting metamorphic history, from the emplacement in the Jurassic western Tethys to the subsequent evolution in the Apennine accretionary wedge, is traced by pseudomorphic and coronitic textures of amphibole replacing igneous clinopyroxene. More specifically, this is attested to by the occurrence of brown amphibole coronas rimmed by green and blue-green to pale-green amphiboles that are statically replaced by Ca-Na-amphibole and subsequent Na-amphibole. The investigated textural domains still record such a long-lasting metamorphic evolution since metadolerites are almost unaffected by high strain zones due to deformation partitioning in the weaker serpentinite matrix or in low-grade metasediments during oceanic lithospheric stretching or during emplacement in the accretionary wedge.

Citation: 2012. From ocean to subduction: the polyphase metamorphic evolution of the Frido Unit metadolerite dikes (Southern Apennine, Italy). In: (Eds.) Michele Zucali, Maria Iole Spalla, and Guido Gosso, *Journal of the Virtual Explorer*, volume **41**, paper 3, doi: 10.3809/jvirtex.2011.00289

Introduction

Ophiolites of southern Apennines are obducted remains of a Late Cretaceous-Oligocene accretionary wedge (Knott, 1987; Monaco, 1993; Knott, 1994; Mazzoli, 1998; Cello and Mazzoli, 1999), resulting from a northwestward subduction of the Jurassic western Tethys below the European continental margin (Dewey *et al.*, 1989; Bortolotti and Principi, 2005). Fragments of the former European crust are now exposed in the Calabria Terrane (Fig. 1), representing the southernmost segment of the Apennine arc (Ogniben, 1969; Knott, 1987; Bonardi *et al.*, 2001).

Figure 1. Geological sketch map of southern Apennine chain, partly modified after Mazzoli (1998).



In this paper we have studied metadolerite dikes from the ophiolites of the southern Apennines in order to unravel their evolution from the emplacement in the Tethyan ocean and related ocean-floor metamorphism, to the HP/LT subduction-related metamorphism acquired during the growth of the Apennine accretionary wedge. A general overview of these metadolerites is given in Sansone (2010), Sansone *et al.* (2011) and Sansone and Rizzo (2012). These Authors suggest that the metadolerite dikes display both amphibolite and greenschists facies mineral assemblages, related to ocean-floor metamorphism, and lawsonite-glaucophane facies assemblages, typical of subduction-related metamorphism. However, textural relationships between minerals related to primary crystallization and to the subsequent metamorphic events have never been described in detail.

We have focused our study on undeformed microstructural sites where the orogenic evolution did not obliterate the original igneous structure and the oceanic mineral assemblages, leaving intact an almost complete record of their long-lasting evolution. For this purpose, we have analysed the microstructure and mineral chemistry of metadolerite dikes, with particular emphasis on the pseudomorphic and coronitic textures indicative of different metamorphic events. Detailed petrographical and microstructural data are provided to unravel the evolution from the ocean-floor metamorphism to the HP/LT orogenic overprint. Microstructural and mineral chemistry analyses, implemented with element compositional maps, have facilitated the identification of the primary (igneous) mineral assemblages related to the magmatic protolith, and of the metamorphic minerals crystallized during the subsequent metamorphic events.

Geological Setting

The Southern Apennine chain is a fold-and-thrust belt (Fig. 1) formed between the upper Oligocene and Quaternary (Scandone, 1967; Ogniben, 1969; D'Argenio *et al.*, 1973, 1975; Pescatore and Slaczka, 1984; Mostardini and Merlini, 1986; Casero *et al.*, 1988; Roure *et al.*, 1991; Hippolyte *et al.*, 1994; Cello and Mazzoli, 1999; Cello *et al.*, 2000; Mazzoli *et al.*, 2001; Patacca and Scandone, 2007), resulting from the convergence between the African and European plates and the simultaneous rollback of the SE-directed Ionian subduction, which caused the opening of the Tyrrhenian back-arc basin (Gueguen *et al.*, 1998; Cello and Mazzoli, 1998; Doglioni *et al.*, 1999). Relicts of the late Creaceous-Oligocene accretionary wedge, resulting from subduction towards NW of the western Tethys Ocean, occur at the highest structural levels of the Apennine chain. The accretionary wedge includes the Liguride Complex, consisting of HP/LT metamorphic sequences (the Frido Unit; Vezzani, 1969, 1970), as well as sequences devoid of a metamorphic overprint (the North-Calabrian Unit; Bonardi *et al.*, 1988). Ophiolitic slices are present both in the Frido Unit and in the North-Calabrian Unit (Bonardi *et al.*, 1988). Ophiolites of the Frido Unit are characterized by a HP/LT metamorphic overprint (Lanzafame *et al.*, 1979; Spadea, 1982; Beccaluva *et al.*, 1982), whereas those of the North-Calabrian Unit do not exhibit any subduction-related metamorphism (Bonardi *et al.*, 1988).

The ophiolitic rocks studied in this paper belong to the Frido Unit (Fig. 2) consisting of serpentinites, derived from mantle lherzolite and subordinate harzburgite

(Sansone *et al.*, 2012), metagabbros, metabasalts, and their respective sedimentary cover, showing a very low-grade metamorphic overprint (Vezzani, 1970; Lanzafame *et al.* 1979; Spadea, 1982, 1994). Metabasalts either occur as metadolerite dikes intruded in the serpentinites or as volcanic rocks with a relict pillow structure (Lanzafame *et al.* 1979; Spadea, 1982, 1994). Dikes and serpentinites have been affected by ductile to brittle deformation connected to oceanic lithosphere stretching and to emplacement of the ophiolites in the orogenic wedge. For this reason, dikes are mostly preserved as 1 to 10 m-sized blocks enclosed in a strongly deformed serpentinite matrix (Fig. 3). Ophiolites are associated with tectonic slices essentially made up of medium-to high grade metamorphic rocks (such as amphibolite, gneiss and granofels).

Figure 2. Simplified geological map of the study area (see text), modified after Monaco *et al.* (1995).

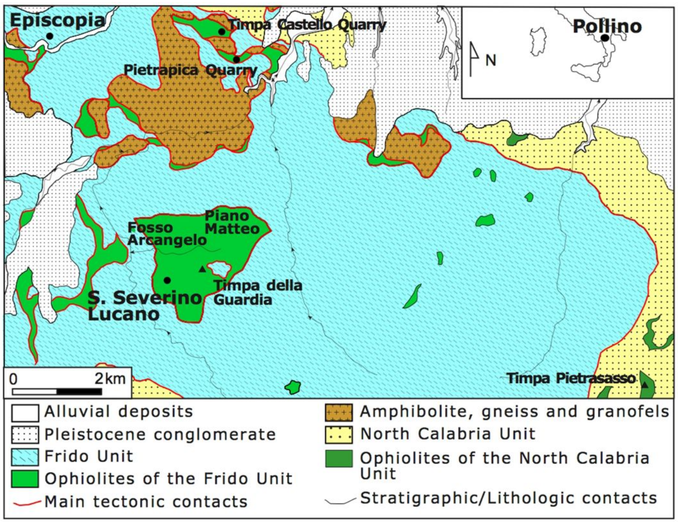
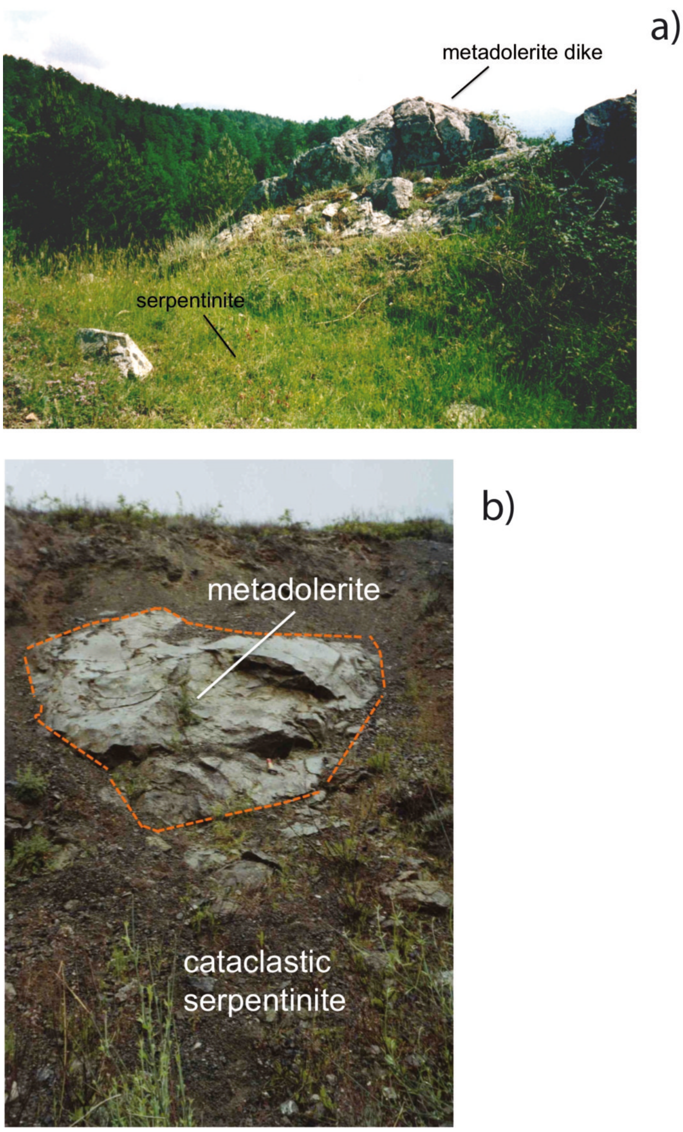


Figure 3. Examples of outcrops of metadolerite dikes in the study area.



a) Metadolerite dike protruding from serpentinites covered by grass at Timpa della Guardia. b) Dike surrounded by cataclastic serpentinites at the Timpa Castello quarry.

Metadolerite dikes hosted in serpentinized peridotites display different kinds of texture and degrees of re-crystallization (Sansone, 2010). Texture ranges from intersertal to grano-xenoblastic and mylonitic with increasing deformation. Metadolerites recorded two main metamorphic events: an ocean-floor metamorphism and an orogenic overprint (Sansone *et al.*, 2011). Ocean-floor metamorphism was accompanied by rodingitization and spilitization. In the study area rodingites are exposed as greyish-white, cm- to dm-thick dikes cutting through serpentinites (Spadea, 1982; Sansone *et al.*, 2011; Sansone and Rizzo, 2012). Garnet found in rodingites replaces plagioclase and retains high hydrogrossularite–grossularite contents (86 - 95 mol% Grs; 0.02 - 8 mol % Prp; 4 - 6 mol % Alm.; 0.2 - 0.4 mol % Sps; Sansone *et al.*, 2011).

The serpentinites of the Frido Unit derive from serpentinization of mantle peridotites with porphyroclastic texture (Sansone *et al.*, 2012). Serpentinization produced a pseudomorphic mesh texture defined by serpentine +magnetite that statically replace olivine crystals, and by yellow-brown bastite replacing orthopyroxene. Pseudomorphic texture is crosscut by various sets of submillimetric veins mostly filled with serpentine fibers. These serpentine veins are responsible for the foliation visible in the field.

Sampling and analytical methods

The Frido Unit metadolerites were collected at San Severino Lucano village, at Timpa Della Guardia, Piani Matteo and Fosso Arcangelo localities, located at the Calabria-Lucania border zone (Figs. 1, 2). These rocks occur mainly as m-sized blocks within strongly deformed serpentinite matrix (Fig. 3).

Petrographic and microstructural observations were carried out in selected samples (Table 1); electron microprobe analyses were performed on amphibole, clinopyroxene, pumpellyite, chlorite, and white mica by using a JEOL JXA-8200 probe, equipped with five WDS spectrometers and an EDS spectrometer, at the Dipartimento di Scienze della Terra “Ardito Desio” of the Università degli Studi di Milano. The analytical conditions were: 15 kV accelerating voltage and 15 nA beam current; count time 30 s at peak and 10 s at background. Natural oxides were used as standards.

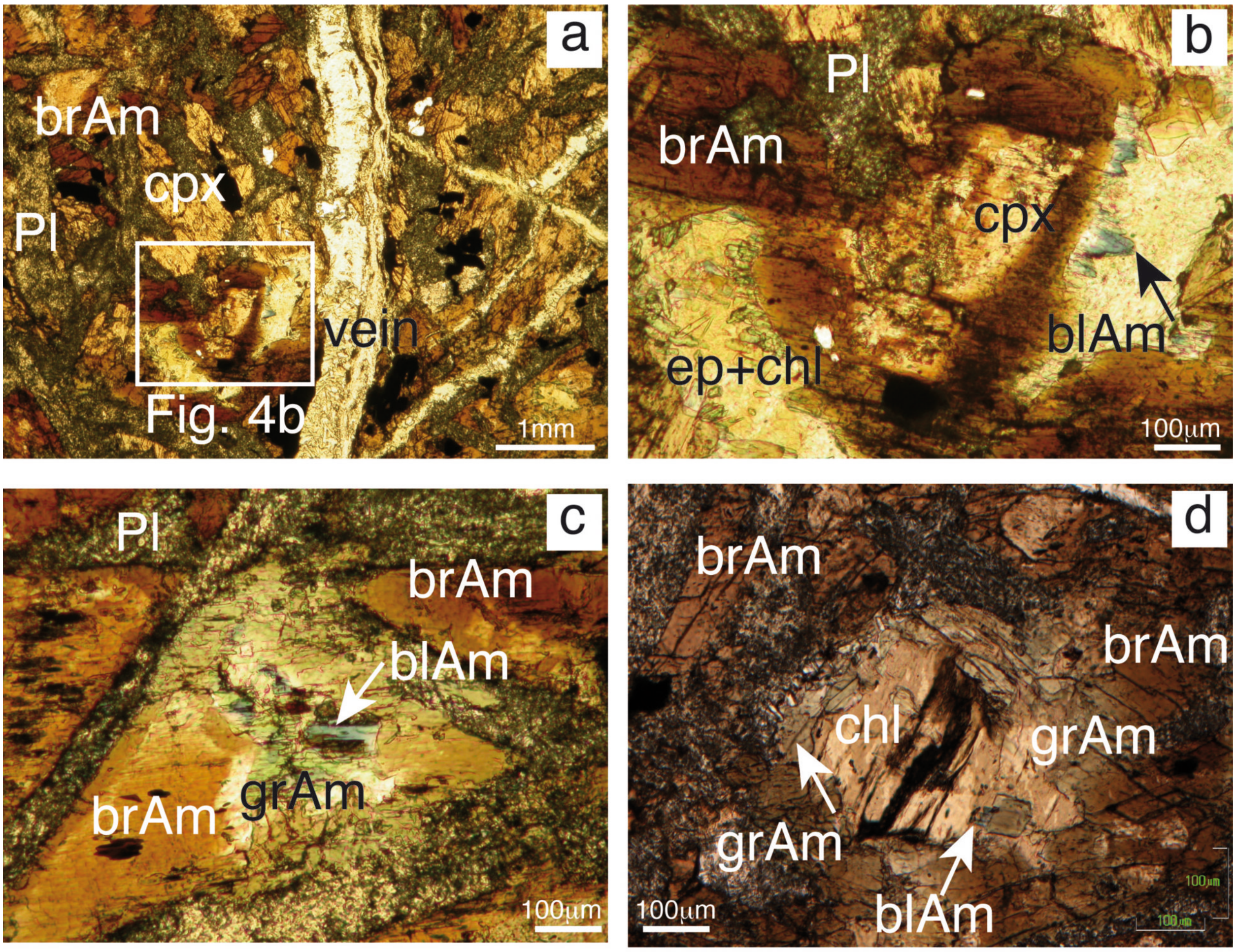
Symbols for minerals recommended by Siivola and Schmid (2007) were used in the text, tables, and figures. The exceptions are indicated by the following symbols: brAm (brown amphibole), grAm (green amphiboles), blAm (blue amphibole), bl-grAm (blue-green amphibole), Dbt (diabantite); Pc-Chl (pycnochlorite), and Wm (white mica).

Petrography

The studied metadolerite dikes show various textures in response to the extent of dolerite recrystallization and deformation (Table 1). These textures range from intersertal or intergranular and blastophitic to mylonitic and cataclastic. Metadolerite dikes with intersertal/intergranular and blastophitic texture consist of plagioclase, clinopyroxene, and opaque minerals (Fig. 4a), which represent the primary (igneous) minerals. Plagioclase is commonly sericitized or saussuritized or is completely replaced by fine-grained aggregates of pumpellyite, prehnite, chlorite, and epidote. Fresh clinopyroxene occurs as twinned or zoned crystals showing undulose extinctions. More often clinopyroxene is partially replaced by chlorite, white mica, and various types of amphibole (mainly brown-, green-, and blue-amphibole). Brown amphibole is present as single crystals (Fig. 4a), as pseudomorph after clinopyroxene (Figs. 4a-4d), or it forms coronas rimming clinopyroxene. Green amphibole crystallized as single crystals, as pseudomorph after clinopyroxene, or it forms coronas rimming brown amphibole or clinopyroxene (Figs. 4c, 4d). Pale-green amphibole may form pseudomorphs after clinopyroxene (together with chlorite and white mica). Most commonly, uncoloured or pale-green amphibole rims the brown amphibole and is in turn rimmed by blue-green amphibole (Fig. 4b). Blue amphibole commonly rims the brown amphibole or the green amphibole (Fig. 4c). On the basis of amphibole type and texture, several occurrences were distinguished and summarized in Figure 5.

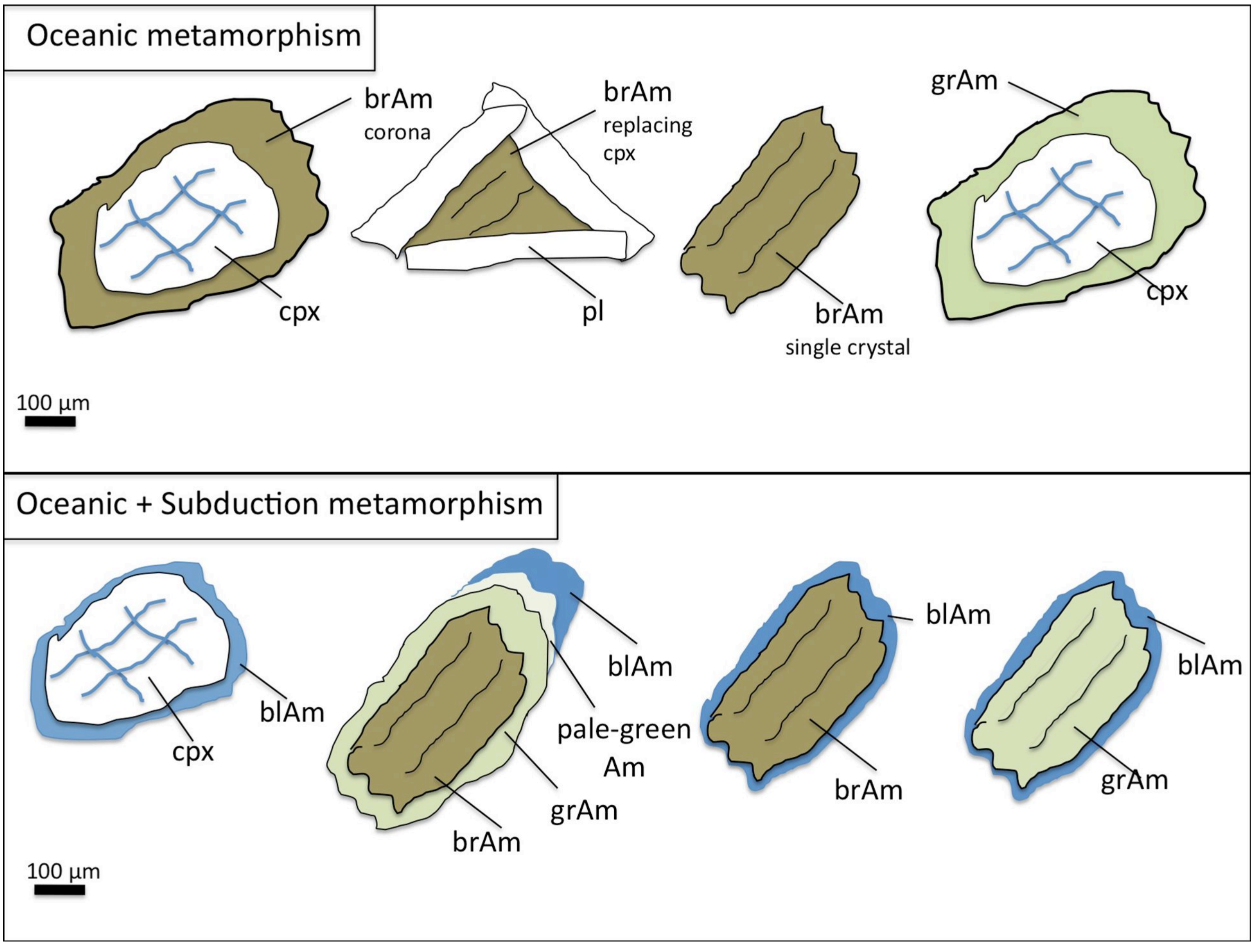
Metadolerite with mylonitic and cataclastic textures characterize the most deformed domains. In these rocks, the primary mineralogy and structure have been obliterated, with the exception of porphyroclastic clinopyroxene which displays a sigmoidal shape.

Figure 4. Photomicrographs of metadolerite dike (sample MC81).



a) General view of the rock showing intersertal structure (altered plagioclase and clinopyroxene), cut by a vein filled with chlorite+epidote. Brown amphibole occurs as single crystal (upper left) or partly replacing clinopyroxene. Plane polarized light. b) Enlargment of fig. 4a showing brown amphibole (replacing clinopyroxene) rimmed by pale-green and blue amphiboles. Plane polarized light. c) Altered plagioclase, brown amphibole (replacing clinopyroxene) rimmed by green amphibole which is rimmed by blue amphibole. Plane polarized light. d) Brown amphibole grading to green amphibole rimmed by blue amphibole growing in the textural site of clinopyroxene. Chlorite grows at the core of the cpx site. Plane polarized light.

Figure 5. Simplified sketch of amphiboles in metadolerite samples.



Simplified sketch summarizing the textures of amphiboles crystallized during oceanic and subduction-related metamorphism in metadolerite samples with intersertal/intergranular and blastophitic textures (see text for explanation and mineral abbreviations).

Additional metamorphic minerals were observed in all metadolerite types and include quartz, albite, titanite, apatite, and typical blueschist facies minerals such as blue-amphibole and lawsonite (Table 1). Metadolerites are commonly cut by veins filled with metamorphic minerals as pumpellyite, chlorite, prehnite, albite, tremolite/actinolite, white mica, quartz, calcite, epidote, lawsonite, glaucophane, and chrysotile, which occur with various combinations within the same vein (see also Sansone *et al.*, 2011; Sansone and Rizzo, 2012).

Petrographic and microstructural observations carried out on metadolerite samples allowed us to reconstruct the textural and metamorphic evolution of dolerite dikes intruding serpentinites in the Frido Unit. The results are summarized in Table 2, which refers to the entire set of investigated samples, although we focused our analysis on metadolerites characterized by intersertal/intergranular and blastophitic texture. In particular, one sample (sample MC81; Table 1) was selected for the description of pseudomorphic and coronitic domains. These domains (as small as about 500µm) trace in detail the mineralogical and textural changes induced by oceanic and subduction-related metamorphism. The results are illustrated and discussed after presentation of the mineral chemistry data.

Mineral chemistry

In selected samples of metadolerites (samples MC70, MC77, MC81; Table 1) electron microprobe analyses were carried out on relict igneous clinopyroxene and metamorphic minerals, as amphibole, chlorite, pumpellyite, and white mica. The results are reported in Tables 3, 4, 5.

Clinopyroxene

Structural formula of clinopyroxene was calculated on the basis of 6 oxygens and classified by using the pyroxene nomenclature suggested by Morimoto (1988, 1989); the chemical compositions of clinopyroxene are reported in Table 3. Clinopyroxene is enriched in augite and augite-diopside components and displays high Al and Fe contents (Al_2O_3= 4.95-6.86 wt %; FeO=6.05-18.80 wt %; Table 3). The only exception is represented by acicular clinopyroxene crystals with aegirine-augite composition (e.g. Na_2O=6.90 wt %; Table 3, sample MC81-21; see also Fig. 7a).

Amphiboles

Structural formula of amphibole was recalculated on the basis of 23 oxygens and classified by using the amphiboles nomenclature suggested by Leake *et al.* (1997, 2004). The chemical compositions of the analysed amphiboles are reported in Table 4. They include Ca-amphiboles (Figs. 6a, 6b), Na-Ca-amphiboles (Fig. 6c), and Na-amphiboles (Fig. 6d). The analysed amphiboles are: brown, green, pale-green/colorless, blue, and blue-green amphiboles.

Brown amphiboles with $(Na+K)_A$<0.50 have magnesiohornblende and ferrotschermakite compositions (Fig. 6a). Brown amphiboles with $(Na+K)_A$≥0.50 and Ti<0.50 show magnesiohastingsite, edenite, and pargasite compositions (Fig. 6b). Green and pale green/uncoloured amphiboles with $(Na+K)_A$<0.50 show magnesiohornblende, actinolite, and tschermakite compositions (Fig. 6a), whilst green amphiboles with $(Na+K)_A$≥0.50 and Ti<0.50 show magnesiohastingsite, hastingsite, and edenite compositions (Fig. 6b). The blue-green amphiboles with $(Na+K)_A$≥0.50 and Ti< 0.50 have magnesiohastingsite composition, while those with $(Na+K)_A$<0.50 show a tschermakite composition. The sodic-calcic amphibole shows a winchite composition (Fig. 6c): it occurs at the rim of brown amphibole and is in turn rimmed by blue amphibole corona. Blue amphibole exhibits glaucophane and magnesioriebeckite compositions (Fig. 6d).

Figure 6. Chemical composition of amphiboles according to the nomenclature of Leake *et al.* (2004).

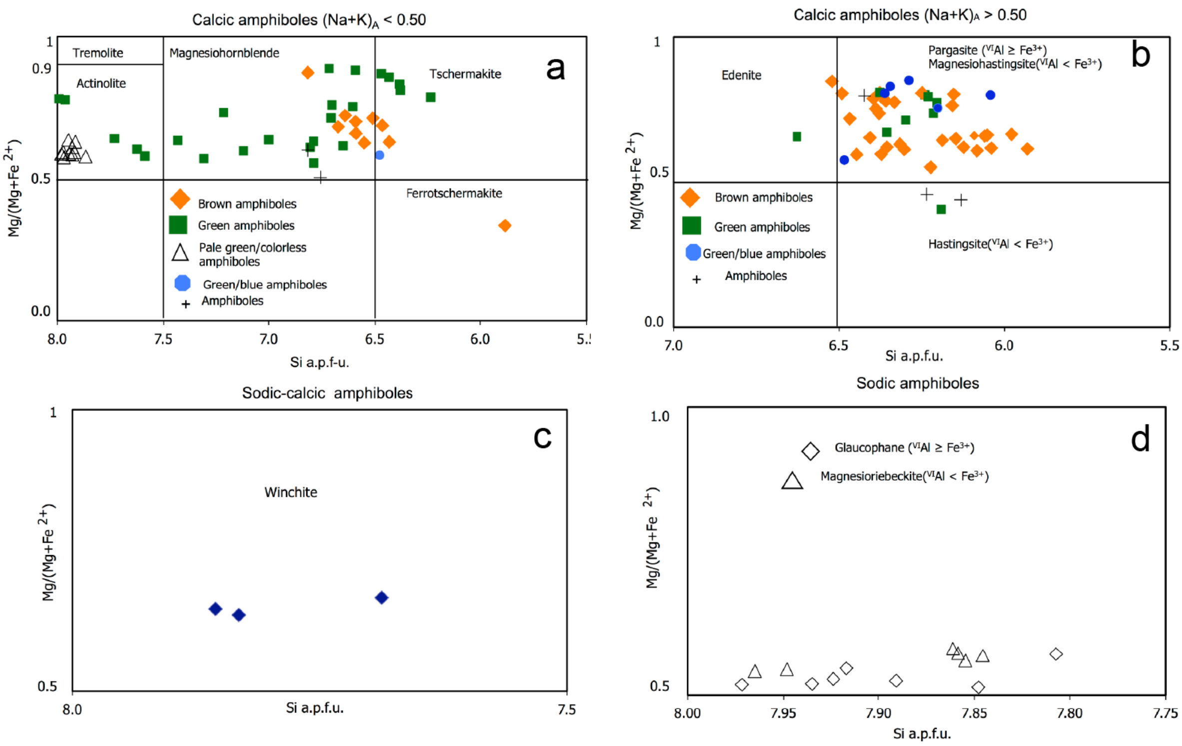
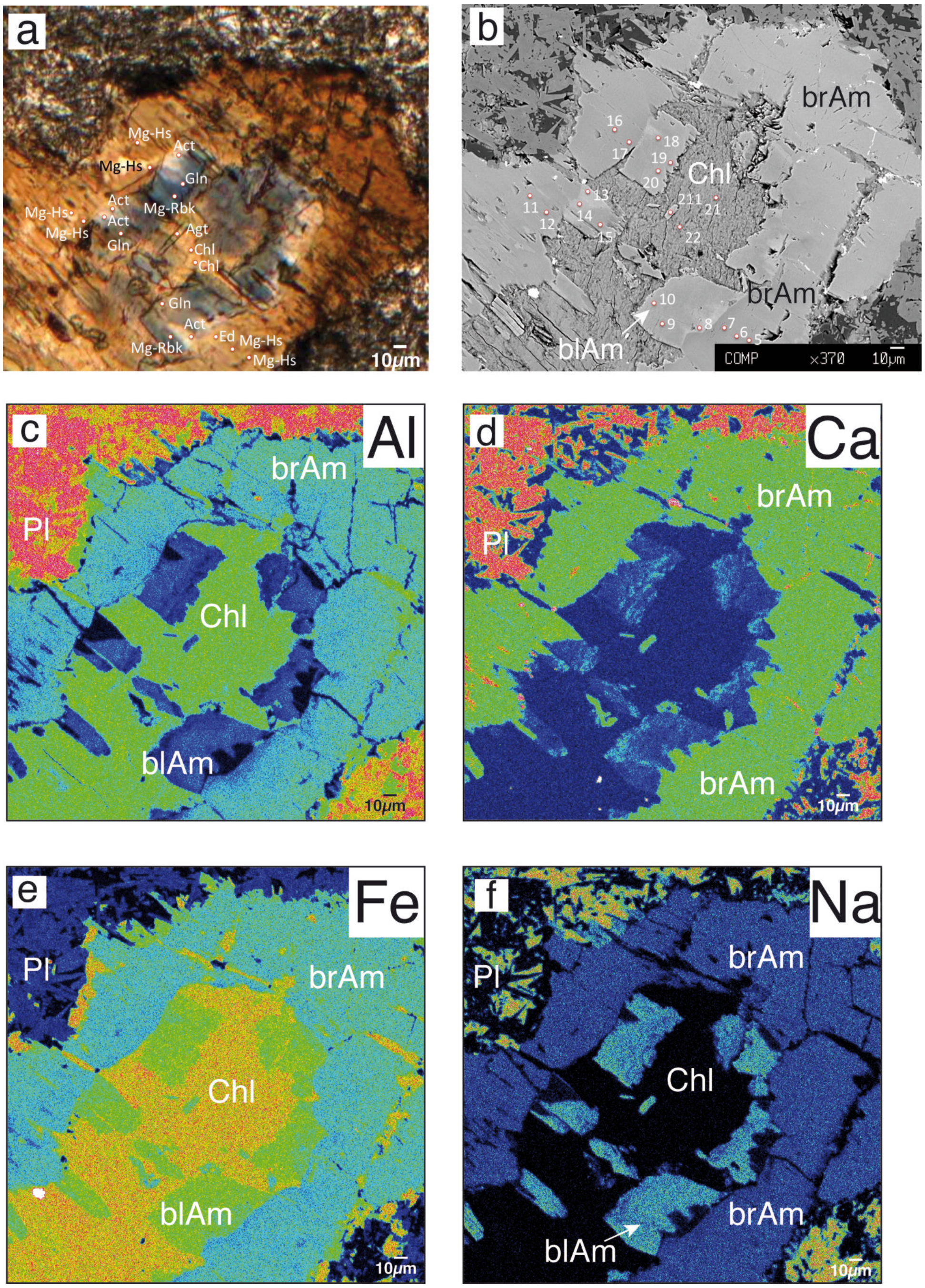


Figure 7. Textural features and microchemical composition of metadolerite MC81.



a) Photomicrograph of a selected microstructural site showing amphiboles replacing magmatic clinopyroxene (middle) and altered plagioclase (upper side); plane polarized light. The shape of magmatic clinopyroxene (now replaced by brown amphibole) is still recognizable. Brown amphibole is rimmed by uncoloured and blue amphiboles growing towards the core of the microstructural site. Location of the analysed spots is also indicated. b) BSE image of the same sample portion with location of the analysed spots (analysis number as in Table 4). c-f): elemental maps relative to Al, Ca, Fe and Na distribution, respectively.

One sample (MC81; Table 1) was selected for showing microstructural domains characterized by pseudomorphic and coronitic textures. Microchemical composition and location of the analysed spots are reported in Figures 7a and 7b, and in Table 4. In such domains, brown amphibole (Mg-hastingsite) is pseudomorphic after clinopyroxene (replacive amphibole) and is rimmed by pale green/uncoloured amphibole (actinolite). The brown and pale green amphiboles are rimmed by blue amphibole (glaucophane and Mg-riebekite). The core of these domains consists of chlorite + aegirin-augite (Fig. 7a) which probably replaced magmatic clinopyroxene. Detailed microchemical analyses and elemental maps were performed on these domains as illustrated in Figures 7c-7f. The elemental maps clearly show that Al and Ca decrease from the brown to the blue amphibole (Figs. 7c and 7d), whilst Na and Fe increase from the brown amphibole to the blue amphibole (Figs. 7e and 7f).

Chlorite

Chlorite was recalculated on the basis of 28 oxygens. Selected analyses are reported in Table 5. Chlorite is classified according with Hey (1954)'s nomenclature. The analysed chlorite occurs at the core of textural sites near blue amphibole rimming brown amphibole (see Figs. 7a, 7b; analyses 21 and 22 in Table 5) and in veins associated with colourless amphibole (analysis 160 in Table 5).

Pumpellyite

Pumpellyite occurs in veins and as pseudomorph after magmatic plagioclase. Pumpellyite composition is characterized by relatively high content of Al (Al_2O_3=22.68-26.04 wt %) and Fe (FeO=2.83-7.43 wt %); MgO content is between 2.31-3.43 wt %. Pumpellyite shows a linear and negative Fetot vs Al_2O_3 .

White mica

The structural formula of white mica was recalculated on the basis 11 oxygens. Using the calculations suggested by Bousquet *et al.* (2002), white mica in the Frido Unit metadolerites shows a phengitic composition (Si = 3.133-3.425 a.p.f.u.).

Textural and Metamorphic Evolution of the Frido Unit Metadolerite Dikes

Metadolerite dikes crosscutting serpentinites in the Frido Unit ophiolites are characterized by a wide range of textures going from well-preserved igneous intersertal/integranular and blastophitic textures to cataclastic and mylonitic. The microstructural and metamorphic evolution of the investigated metadolerites is summarized in Table 2. In the least deformed metadolerite samples showing intersertal/intergranular and blastophitic texture, plagioclase, clinopyroxene and opaque minerals represent the relict igneous phases ("Igneous" stage in Table 2). Clinopyroxene is replaced by brown amphibole (mainly Mg-hornblende and Mg-hastingsite) rimmed by green amphibole with similar compositions. The brown and green (or blue-green) amphiboles are often rimmed by uncoloured actinolite. We interpret these Ca-amphiboles as being related to oceanic metamorphism in the Jurassic Tethys Ocean that occurred under amphibolite to greenschists facies conditions (e.g. Liou *et al.*, 1974; Spear, 1981; stage "Oceanic 1" in Table 2). Brown and red/brown amphiboles have been described in oceanic gabbros (e.g. Prichard and Cann, 1982; Mével, 1988; Coogan *et al.*, 2001) and ophiolitic gabbros (e.g. Mével *et al.*, 1978; Tribuzio *et al.*, 1995, 1999) and attributed to either magmatic or late magmatic crystallization (e.g. Tribuzio *et al.*, 2000) or to HT-oceanic alteration (e.g. Gaggero and Cortesogno, 1997) or both (e.g. Coogan *et al.*, 2001), depending on textural features and composition of trace elements. In the Northern Apennine ophiolite, brown amphibole associated with green and blue-green amphiboles has been found in dolerites and attributed to oceanic metamorphism (Cortesogno and Oliveri, 1974). Green and pale-green Ca-amphiboles replacing clinopyroxene and veins filled with actinolite, actinolitic hornblende, and Mg-hornblende have been found in dolerites drilled in the modern oceanic crust from the Pacific ocean (lower sheeted dike complex; Laverne *et al.*, 1995; Tartarotti *et al.*, 1995; Alt *et al.*, 1996; Vanko *et al.*, 1996) indicating relatively high temperatures (>400°C), typical of greenschists to amphibolite facies conditions.

Plagioclase phenocrysts in the Frido metadolerites are replaced by pseudomorphs of sericite or saussurite, pumpellyite, prehnite, chlorite, and epidote. These metamorphic minerals can be interpreted either as oceanic (stage "Oceanic 2" in Table 2) or as orogenic (see Table 2), since minerals of the prehnite-pumpellyite facies as well as of the greenschists (or sub-greenschists) facies have been described in both the present-day oceanic crust (e.g. Alt *et al.*, 1986, 1996, 2010 and refs. therein) and in orogenic environments (e.g. in the Apennines; Cortesogno and Oliveri, 1974; Cortesogno, 1980; Beccaluva *et al.*, 1982). As far as pumpellyite, its textural features and the high Al_2O_3 content suggest that it probably crystallized under blueschists or lawsonite-albite facies conditions (Cortesogno *et al.*, 1984, Sansone and Rizzo, 2012), supporting the hypothesis of an orogenic (subduction-related) origin.

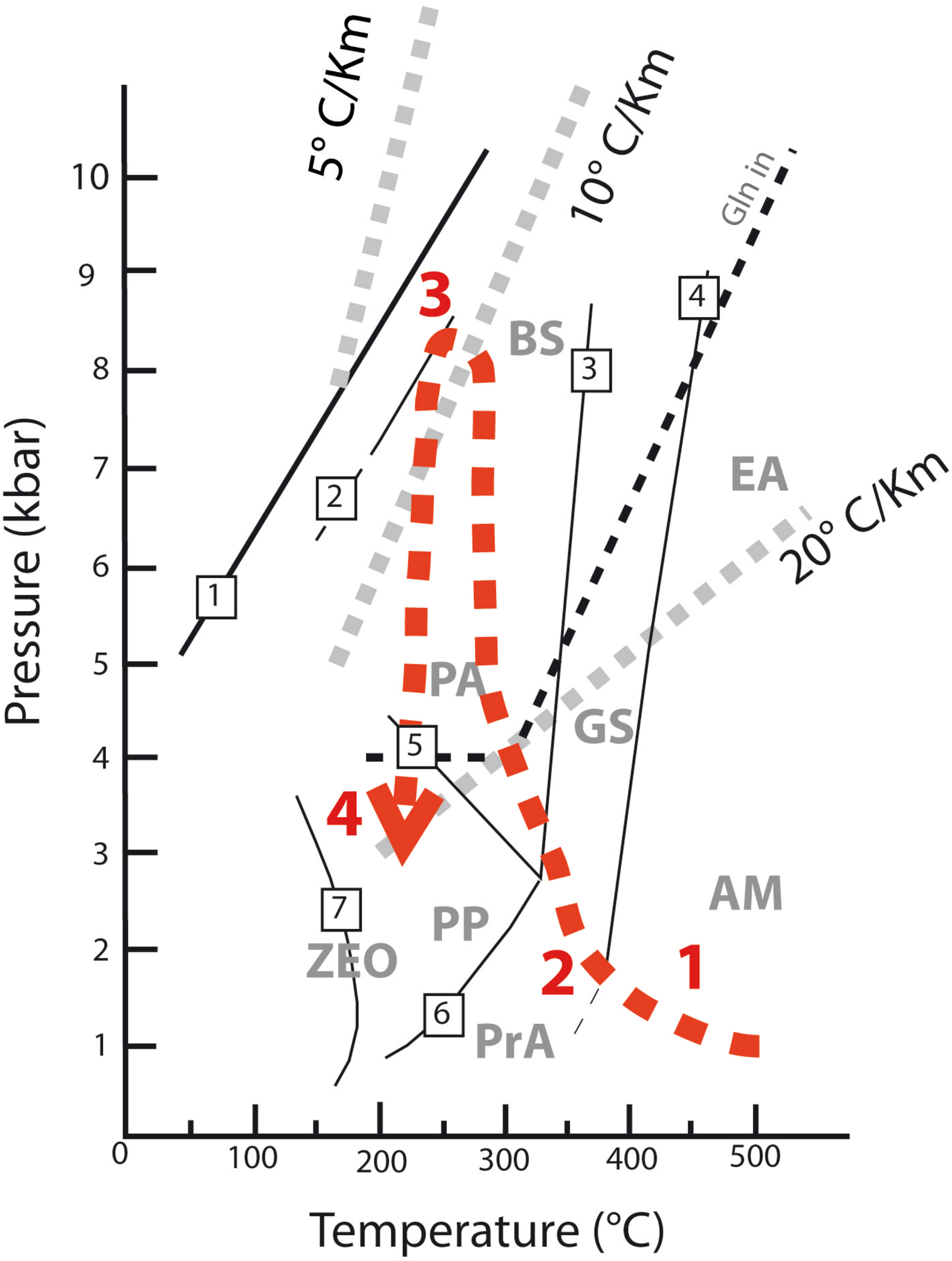
Blue amphibole (glaucophane and Mg-riebekite), that commonly grows at the rim of Ca-amphiboles replacing clinopyroxene in the Frido metadolerites, is here interpreted as being of orogenic origin (stage “Subduction-related” in Table 2): it crystallized during subduction under HP-LT conditions in the Apennine accretionary wedge, as already discussed in Spadea (1994) and Sansone *et al.* (2011). Ca-Na amphibole (winchite) at the contact between green and blue amphiboles might be interpreted as a reaction product formed during the initial stage of the subduction phase (“Win” in Table 2). In fact, winchite has been described in eclogites from the Western Alps (Gran Paradiso and Sesia-Lanzo unit; Ungaretti *et al.*, 1983; Benciolini *et al.*, 1994). Lawsonite in our samples commonly fills veins. It is also interpreted as being a subduction-related mineral (Table 2). White mica filling veins has a phengitic composition and can be also ascribed to a subduction-related stage (Bousquet *et al.*, 2002).

In textural domains where the suite “brown- green- and blue-amphibole” occurs, we also observed the association of chlorite+aegirin-augite (see Figs. 7a, 7b). These two minerals are interpreted as being crystallized under blueschist facies (or epidote-blueschist facies as defined by Evans, 1990) conditions. Aegirin-augite has been observed in blueschists facies rocks from the North Cascades and from New Zealand (e.g. Brown, 1974). However, secondary aegirin-augite of oceanic origin has been also described in basalts from the Pacific Ocean (Laverne, 1987); consequently, an oceanic origin for this pyroxene cannot be completely ruled out.

Additional metamorphic minerals found in the studied samples also include quartz, albite, apatite, titanite, and minor calcite and chrysotile (see also Sansone *et al.*, 2011). These minerals occur either as pseudomorphs (or replacive) crystals after igneous phases or more often as vein infilling. Mineral associations within veins may be various; in fact, within a vein, mineral assemblages typical of the prehnite-pumpellyite as well as of the lawsonite-glaucophane facies may occur together, as already stated by Sansone *et al.* (2011) and Sansone and Rizzo (2012). However, since veins cut through all the previous textures of the rock, they are interpreted as being formed during the entire orogenic evolution of the Frido ophiolite within the Apennine accretionary wedge, from subduction to late orogenic stages (see Table 2). Similar metamorphic mineral assemblages have been described in the Franciscan subduction complex (California), where mafic blocks in the mélanges are mostly composed of LT-blueschist facies minerals including albite, chlorite, pumpellyite, lawsonite, Na-pyroxene, quartz, sphene (and no garnet; e.g. Cloos, 1985 and refs. therein). This is different from most of the lawsonite-bearing rocks occurring at active margins, being lawsonite eclogites (e.g. Tsujimori *et al.*, 2006; Zucali & Spalla, 2011).

Summing up, we may infer that the studied metadolerites have been affected by rock-seawater (or seawater-derived fluids) interaction in the Jurassic Tethys Ocean, producing oceanic alteration under amphibolite to greenschists and facies conditions. Oceanic hydrothermal alteration may have induced element mobility (e.g. LREE), although the studied rocks have all an N-MORB affinity (Sansone *et al.*, 2011). These oceanic rocks have been subsequently involved in the Apennine accretionary prism, as attested by the occurrence of blueschist facies minerals and by late prehnite-pumpellyite facies mineral assemblages (see Table 2). A qualitative P-T path for the investigated rocks is illustrated in Figure 8. The oceanic evolution of the metadolerite dikes is constrained by the crystallization of amphiboles under amphibolite and greenschist facies conditions (steps 1 and 2 in Fig. 8) at low pressure. The early orogenic evolution is marked by crystallization of (LT-) blueschist facies minerals, namely lawsonite and glaucophane related to subduction (“subduction-related” stage in Table 2). Pressure and temperature are difficult to determine however, as the glaucophane stability field (“Gln in” curve in Fig. 8) constrains the upper T boundary (Maresch, 1977), while the occurrence of lawsonite in the studied samples suggests minimum pressures of 3 kbar (Thompson, 1971; Liou, 1971). Lawsonite in the metadolerite dikes occurs inside veins and is mostly associated with LT-blueschist facies minerals. Consequently, the reaction curve Lws+Gln = Pmp+Chl+Ab+Qtz+fluid by Liou *et al.* (1985) was chosen to constrain the upper pressure boundary for the studied samples (curve 2 in Fig. 8). The presence of albite instead of jadeite and quartz (curve 1 in Fig. 8) suggests a maximum pressure for the subduction-related metamorphism of 8 to 10 kbar in the temperature range of 100 to 250°C (Newton & Smith, 1967). Late orogenic minerals observed in our samples (“late orogenic stage” in Table 2) suggest a decompressional retrograde path toward the prehnite-pumpellyite facies (stage 4 in Fig. 8).

Figure 8. P-T diagram showing the metamorphic evolution of the Frido Unit metadolerites.



Metamorphic evolution of the Frido unit metadolerites plot in a P-T diagram showing petrogenetic grid for low-grade metamorphic facies in a basaltic system (redrawn after Liou *et al.*, 1985 and after Maresch, 1977 for the glaucophane stability field). A proposed qualitative P-T path is illustrated (red arrowed-trajectory). Red numbers (1 through 4) refers to Oceanic 1, Oceanic 2, Subduction-related, and Late orogenic stages, as defined in Table 2, respectively (see text and Table 2 for comments). Numbered lines are the following univariant lines (according to Liou *et al.*, 1985): (1) Jd+Qtz = Ab; (2) Lws+Gln = Pmp+Chl+Ab+Qtz+fluid; (3) Pmp+Chl+Qtz = Zo+Tr+fluid; (4) Zo+Chl+Tr+Qtz = Hbl+fluid; (5) Pmp+Tr+Qtz = Prh+Chl+fluid, (6) Pmp+Qtz = Zo+Prh+Chl+fluid; (7) Ab+fluid = Anl+Qtz. “Gln in”: upper stability field for glaucophane according to Maresch (1977). Metamorphic facies: PP=prehnite-pumpellyite; PrA=prehnite-actinolite; GS=greenschist; BS=blueschist; EA=epidote-amphibolite; AM=amphibolite. Geothermal gradients of 5°C/Km, 10°C/Km, and 20°C/Km are also shown. Mineral abbreviations according to Siivola and Schmid (2007).

The retrograde path did not necessarily take place at a lower temperature than the prograde one during the subduction; thus the downward and upward paths could have been almost identical. However, we suggest that the retrograde path did not proceed under a higher temperature than the prograde path, since relatively high temperatures would have led to the lawsonite breakdown. Consequently, the inferred qualitative P-T-path follows a counter-clockwise trajectory. Counter-clockwise trajectories for subducted terranes are commonly attributed by numerical modeling to early subduction stages in an accretionary prism (e.g. Cloos, 1982; Gerya *et al.*, 2002; Gerya, 2011), such as the Franciscan Complex (Cloos, 1985). Well-developed counter-clockwise paths have been proposed for fast subduction by Roda *et al.* (2010), where burial flow dominates over the upwelling flow. Additional field and analytical studies are needed to better constrain and quantify the metamorphic evolution of the Frido unit.

Conclusions

The metadolerites from the Frido Unit have been affected by ocean-floor metamorphism under amphibolite to greenschists facies conditions. Subsequent subduction-related metamorphism under relatively HP/LT (blueschist facies) conditions affected the rocks during the formation of the Apennine accretionary prism. Late orogenic minerals of the prehnite-pumpellyite facies have crystallized in rocks and in veins. Such long-lasting metamorphic evolution accompanying the rocks investigated here, from their emplacement in the Jurassic western Tethys to the tectonic history in the Apennine accretionary wedge, is easily readable within microstructural domains characterized by pseudomorphic textures. The zoned structure of amphiboles replacing igneous clinopyroxene records the entire metamorphic evolution, as attested by the occurrence of Ca-amphiboles (brown amphibole rimmed by green and blue-green to pale-green amphiboles) that are statically replaced by Ca-Na-amphibole and subsequent Na-amphibole. The investigated textural domains still record such a long-lasting metamorphic evolution since the rock was relatively unaffected by high strain zones (undeformed pods), due to deformation partitioning in the weaker serpentinite matrix or in low-grade metasediments during oceanic lithospheric stretching or during emplacement in the accretionary wedge.

Acknowledgements

Thanks go to R. Oberhänsli for his helpful comments. The paper has benefited from the comments of the Editor M. Zucali, whom we are grateful to. This work was supported by national funding PRIN2008 (Università degli Studi di Milano). We also wish to thank Andrea Risplendente for his technical assistance at the microprobe.

References

Alt J. C., Honnorez J., Laverne L., and Emmermann R., 1986 - Hydrothermal alteration of a 1 km section through the upper oceanic crust, DSDP Hole 504B: The mineralogy, chemistry, and evolution of seawater-basalt interactions. J. Geophys. Res., 91, 10309–10335, 10.1029/JB091iB10p10309

Alt J.C., Laverne C., Vanko D.A., Tartarotti P., Teagle D.A.H., Bach W., Zuleger E., Erzinger J., and Honnorez J., Pezard P.A., Becke, K., Salisbury M.H., and Wilkens R.H., 1996 - Hydrothermal alteration of a section of upper oceanic crust in the Eastern Equatorial Pacific: a synthesis of results from site 504 (DSDP Legs 69, 70, and 83, and ODP Legs 111, 137, 140, and 148). In: J.C. Alt, H. Kinoshita, L.B. Stokking, J.P. Michael, Proceeding of the Ocean Drilling Program, Scientific Results, College Station, TX, 148, 417-434.

Alt J.C., Laverne C., Coggon R.M., Teagle D.A.H., Banerjee R.N., Morgan S., Smith-Duque C.E., Harris M., Galli L., 2010 - Subsurface structure of a submarine hydrothermal system in ocean crust formed at the East Pacific Rise ODP/IODP Site 1256. Geochemistry Geophysics Geosystem, 11, 10.1029/2010GC003144

Amodio-Morelli L., Bonardi G., Colonna V., Dietrich D., Giunta G., Ippolito F., Liguori V., Lorenzoni S., Paglianico A., Perrone V., Piccarreta G., Russo M., Scandone P., Zanettin-Lorenzoni E. and Zuppetta A., 1976 - L'arco Calabro-Peloritano nell'orogene Appenninico-Maghrebide. Mem. Soc. Geol. It., 17, 1–60.

Beccaluva L., Macciotta G., Spadea P., 1982 – Pretrology and geodynamic significance of the Calabria-Lucania ophiolites. Rend. Soc. It. Min. Petr., 38 (3), 973-987.

Benciolini L., Martin S., Tartarotti P., 1984 - Il metamorfismo eclogitico nel basamento del Gran Paradiso ed in Unità Piemontesi della Valle di Campiglia. Mem. Soc. Geol. It., 29,127–151.

Bonardi G., Amore F.O., Ciampo G., De Capoa P., Miconnét P. and Perrone V., 1988 - Il Complesso Liguride Auct.: Stato delle conoscenze attuali e problemi aperti sulla sua evoluzione Pre-Appenninica ed i suoi rapporti con l'Arco Calabro. Mem. Soc. Geol. It., 41, 17–35.

Bonardi G., Cavazza W., Perrone V., Rossi S., 2001 - Calabria-Peloritani terrane and northern Ionian sea. In: Vai, G.B., Martini, I.P. (Eds), Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins. Kluwer Academic Publishers, Dordrecht, Boston, London, pp. 287-306.

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

Bousquet R., Goffe B., Vidal O., Oberhänsli R., Patriat M., 2002 - The tectono-metamorphic history of the Valaisan domain from the Western to Central Alps: new constraints on the evolution of the Alps. Geol. Soc. Amer. Bulletin, 114, 207-225.

Brown E.H., 1974 – Comparison of the mineralogy and phase relations of Blueschists from the North Cascades, Washington and Greenschists from Otago, New Zealand. Geol. Soc. Amer. Bullettin, 85, 333-344.

Casero P., Roure F., Endignoux L., Moretti I., Muller C., Sage L., and Vially R., 1988 – Neogene geoynamic evolution of the Southern Apennines. Mem. Soc. Geol. It., 41, 109-120.

Cello G. and Mazzoli S., 1999 - Apennine tectonics in southern Italy: A review. J. of Geodynamics, 27, 191–211.

Cello G., Gambini R., Mazzoli S., Read A., Tondi E., Zucconi V., 2000. Fault zone characteristics and scaling properties of the Val d'Agri Fault System (Southern Apennines, Italy), J. of Geodynamics, 29, 293-307.

Cloos M., 1985 – Flow melanges: Numerical modeling and geologic constraints on their origin in the Franciscan subduction complex, California. Geol. Soc. Am. Bull., 93, 330-345.

Coogan L.A., Wilson R.N., Gillis K.M., MacLeod, C.J., 2001 - Near-solidus evolution of oceanic gabbros: Insights from amphibole geochemistry. Geoch. Cosmoch. Acta, 65, 4339-4357.

Cortesogno L., 1980. Il metamorfismo giurassico nelle ofioliti dell'Appennino settentrionale: due distinti cicli metamorfici in ambiente oceanico. Ofioliti, 5, 5-18.

Cortesogno L. and Oliveri F., 1974. Fenomeni metamorfici di alta temperatura ed evoluzione polimetamorfica in ambiente "oceanico" e orogenico diabasi, brecce e sedimenti associati, affioranti presso Framura (Liguria Orientale). Rend. Soc.It. Min. Petr., 30, 931-959.

Cortesogno L., Lucchetti G., and Spadea P., 1984 – Pumpellyite in low-grade metamorphic rocks from Ligurian and Lucanian Apennines, Maritime Alps and Calabria (Italy). Contrib. Mineral. Pétrol., 85, 14-24.

Dewey J.F., Helman M.L., Knott S.D., Turco E., Hutton D.H.W., 1989 - Kinematics of the western Mediterranean. In: Coward M.P., Dietrich D., Park R.G. (Eds.), Alpine Tectonics. Geological Society, London, Special Publications, 45, 265-283.

D'Argenio B., Pescatore T., and Scandone P., 1973 - Schema geologico dell'Appennino meridionale (Campania e Lucania). In: Atti del convegno: Moderne vedute sulla geologia dell'Appenino. Acc. Nazion. Lincei,182, 49-72.

D'Argenio B., Pescatore T., and Scandone, P., 1975 - Structural pattern of the Campania-Lucania Apennines. In: Ogniben, L., Parotto, M., Praturlon, A. (eds.), Structural Model of Italy. Quad. Ric. Sci. 90, 313–327.

Doglioni C., Gueguen E., Harabaglia P. and Mongelli F., 1999 - On the origin of west-directed subduction zones and applications to the western Mediterranean. In: The Mediterranean basins: Tertiary extension within the alpine orogen. (eds): B. Durand, L. Jolivet, F. Horváth and M. Séranne, Special Publications Geological Society, London, 156, 541–561.

Evans B.W., 1990 – Phase relations of epidote-blueschists. Lithos, 25, 3-23.

Gaggero L. and Cortesogno L., 1997 - Metamorphic evolution of oceanic gabbros: recrystallization from subsolidus to hydrothermal conditions in the MARK area (OPD Leg 153). Lithos, 40, 105-131.

Gerya T. V., 2011 – Future directions in subduction modeling. J. Geodynamics, 52, 344-378.

Gerya T. V., Stöckert B., Perchuk A.L., 2002 – Exhumation of high-pressure metamorphic rocks in a subduction channel: a numerical simulation. Tectonics, 21 (6), 1056, 10.1029/2002TC001406

Gueguen E., Doglioni C., and Fernandez M., 1998 - On the post-25 Ma geodynamic evolution of the western Mediterranean. Tectonophysics, 298, 259–269.

Hey M. H., 1954 - A new review of the chlorites. Mineralogical Magazine, 30, 224-292.

Hippolyte J. C., Angelier J. and Roure F., 1994 - A major geodynamic change revealed by Quaternary stress patterns in the Southern Apennines (Italy). Tectonophysics, 230, 199-210.

Knott S.D., 1987 - The Liguride Complex of Southern Italy-a Cretaceus to Paleogene accretionary wedge. Tectonophysics, 142, 217–226.

Knott S.D., 1994 - Structure, kinematics and metamorphism in the Liguride Complex, Southern Apennine, Italy. J. Struct. Geology, 16, 1107–1120.

Lanzafame G., Spadea P. and Tortorici L., 1979 - Mesozoic ophiolites of northern Calabria and Lucanian Apennine (Southern Italy). Ofioliti, 4, 173–182.

Laverne C., Tartarotti P., Alt J.C., Vanko D.A., 1995 - Chemistry and geothermometry of secondary minerals from the deep sheeted dike complex, Hole 504B (East-Pacific). In: J. Erzinger, K. Becker, H.J.B. Dick, and L.B. Stokking (Eds.), Proc. ODP, Sci. Results, 137/140: College Station, TX (Ocean Drilling Program), 167-189.

Laverne, C. (1987), Unusual occurrence of aegirine-augite, fassaite and melanite in oceanic basalts (DSDP Hole 504B), Lithos, 20, 135–151.

Leake B.E., Woolley A.R., Arps C.E.S., Birch W.D., Gilbert M.C., Grice J.D., Hawthorne F.C., Kato A., Kisch H.J., Krivovichev V.G., Linthout K., Laird J., Mandarino J.A., Maresch W.V., Nickel E.H., Rock N.M.S., Schumacher J.C., Smith D.C., Stephenson N.C.N., Ungaretti L., Whittaker E.J.W., and Youzhi G., 1997 - Nomenclature of amphiboles: Report of the Subcommittee on Amphiboles of the International Mineralogical Association, Commission on New Minerals and Mineral Names. American Mineralogist, 82, 1019–1037.

Leake B.E., Woolley A.R., Birch W.D., Burke E.A.J., Ferraris G., Grice J.D., Hawthorne F.C., Kisch H.J., Krivovichev V.G., Schumacher J.C., Stephenson N.C.N. and Whittaker E.J.W., 2004 - Nomenclature of amphiboles: Additions and revisions to the International Mineralogical Association's amphibole nomenclature. American Mineralogist, 89, 883–887.

Liou J.G., 1971 – P-T stabilities of laumontite, wairakite, lawsonite, and related minerals in the system Ca Al2Si2O8-SiO2-H2O. J. Petrology, 12, 370-411.

Liou J.G., Kuniyoshi S., and Ito K., 1974 – Experimental studies of the phase relations between greenschist and amphibolite in a basaltic system. Amer. J. Sci, 274, 613-632.

Liou J.G., Maruyama S. and Cho M., 1985 – Phase equilibria and mineral parageneses of metabasites in low-grade metamorphism. Mineral. Mag., 49, 321-333.

Maresch W.V., 1977 – Experimental studies on glaucophane: an analysis of present knowledge. Tectonophysics, 43, 109-125.

Mazzoli S., 1998 - The Liguride units of southern Lucania (Italy): structural evolution and exhumation of high pressure metamorphic rocks. Rendinconti Lincei, 9, 271-291.

Mazzoli, S., Barkham, S., Cello, G., Gambini, R., Mattioni, L., Shiner, P., and Tondi, E., 2001 - Reconstruction of the continental margin architecture deformed in the contraction of the Lagonegro Basin, Southern Apennines, Italy. J. Geol. Soc. London 158, 309–319.

Mével C., 1988. Metamorphism in oceanic layer 3, Gorringe Bank, eastern Atlantic. Contrib. Mineral. Petrol., 100, 496-509.

Mével C., Caby R., and Kienast J.R., 1978 - Amphibolite facies conditions in the oceanic crust: example of amphibolitized flaser-gabbro and amphibolites from the Chenaillet ophiolite massif (Haute Alpes, France). Earth Planet. Sci. Letts., 39, 98-108.

Monaco C., 1993 - Le Unità Liguridi nel confine Calabro-Lucano (Appennino Meridionale): controllo dei dati esistenti, nuovi dati ed interpretazione. Boll. Soc. Geol. It., 112,751-769.

Monaco C., Tortorici L., Morten L., Critelli S., Tansi C., 1995 – Geologia del versante Nord-Orientale del Massiccio del Pollino (Confine Calabro Lucano): Nota illustrativa sintetica alla scala 1:50.000. Boll. Soc. Geol. It., 114, 277-291.

Morimoto N., 1988 - Nomenclature of pyroxenes. Mineralogy and Petrology, 39, 55–76.

Morimoto N., 1989 - Nomenclature of pyroxenes. Canadian Mineralogist, 27, 143–156.

Mostardini F., and Merlini S., 1986 - Appennino Centro Meridionale. Sezioni Geologiche e Proposta di Modello Strutturale, Mem. Soc. Geol. It., 35(1), 177-202.

Newton R.C. and Smith J.V., 1967 – Investigations concerning the breakdown of albite at depth in the earth. J. Geology, 75, 268-286.

Ogniben L., 1969 - Schema introduttivo alla geologia del confine calabro-lucano. Mem. Soc. Geol. It., 8, 453–763.

Patacca E. and Scandone P., 2007 - Geology of the southern Apennines. In: Results of the CROP Project, Sub-project CROP-04 Southern Apennines (Italy). (eds): A. Mazzotti, E. Patacca and P. Scandone. Boll. Soc. Geol. It., Special Issue, 75–119.

Pescatore T. and Slaczka A., 1984 – Evolution models of two flysch basins: The Northerns Carpathians and the Southern Apennines. Tectonophysics, 106, 49-70.

Prichard H.M. and Cann J.R., 1982 - Petrology and mineralogy of dredged gabbro from Gettysburg Bank, eastern Atlantic. Contrib. Mineral. Petrol., 79, 46-55, 10.1007/BF00376960

Roda M., Marotta A.M., Spalla M.I., 2010 – Numerical simulations of an ocean-continent convergent system: Influence of subduction geometry and mantle wedge hydration on crustal recycling. Geochemistry, Geophysics, Geosystem, 10.1029/2009GC003015

Roure F., Casero P., and Vially R., 1991 - Growth processes and melange formation in the Southern Apennines accretionary wedge. Earth Planet. Sci. Lett., 102, 395-412.

Sansone M.T.C., 2010 – Serpentinites and metadolerites from Frido Unit: genesis, evolution and environmental problems. Plinius, 36, 1-6.

Sansone M.T.C. and Rizzo G., 2012 - Pumpellyite veins in the metadolerite of the Frido Unit (Southern Apennines, Italy). Periodico di Mineralogia. 81, 75-92. 10.2451/2012PM005

Sansone M.T.C., Rizzo G. and Mongelli G., 2011 - Petrochemical characterization of mafic rocks from Ligurian ophiolites, southern Apennines. International Geology Review, 53, 130-156., 10.1080/00206810902954993

Sansone M.T.C., Prosser G., Rizzo G., and Tartarotti P., 2012 – Spinel-peridotites of the Frido Unit ophiolites: evidence for oceanic evolution. Periodico di Mineralogia. 81, 35-59. 10.2451/2012PM0003

Scandone P., 1967 - Studi di geologia lucana: la serie calcareo-silico-marnosa ed i suoi rapporti con l'Appennino calcareo. Boll. Soc. Nat. in Napoli, 76 (2): 301-469.

Siivola J. and Schmid R., 2007 - List of mineral abbreviations-Recommendations by the IUGS Subcommission on the Systematics of Metamorphic Rocks: 12. Web version 01.02.07.

Spadea P., 1982 - Continental crust rock associated with ophiolites in Lucanian Apennine (Southern Italy). Ofioliti, 7, 501–522.

Spadea P., 1994 - Calabria-Lucania ophiolites. Bollettino di Geofisica Teorica ed Applicata, 36, 271-281.

Spear F.S., 1981 – An experimental study of hornblende stability and compositional variability in amphibolite. Amer. J. Sci., 281, 697-734.

Tartarotti P., Allerton S., Laverne C., 1995 - Vein formation mechanisms in the sheeted dike complex from Hole 504B (Legs 137/140). Proceeding of the Ocean Drilling Program, vol. 137/140, Scientific Results, 231-243.

Thompson A.B., 1971 – Laumontite equilibria and seolite facies. Am. J. Sci., 269, 267-275.

Tribuzio, R., Riccardo, M. P., and Ottolini, L., 1995 - Trace element redistribution in high-temperature deformed gabbros from East Ligurian ophiolites (Northern Apennines, Italy): Constraints on the origin of syndeformation fluids. J. Metam. Geol. 13, 367–377.

Tribuzio, R., Tiepolo, M., Vannucci, R., and Bottazzi, P., 1999 - Trace element distribution within olivine-bearing gabbros from the Northern Appenine ophiolites (Italy): Evidence for post-cumulus crystallistion in MOR-type gabbroic rocks. Contrib. Mineral. Petrol. 134, 123–133.

Tribuzio R., Tiepolo M., Thirwall M.F., 2000 - Origin of titanian pargasite in gabbroic rocks from the Northern Apennine ophiolites (Italy): insights into the late magmatic evolution of a MOR-type intrusive sequence. Earth Planet. Sci. Letters, 176, 281-293.

Tsujimori T., Sisson V.B., Liou J.G., Harlow G.E., Sorensen S.S., 2006 - Very-low-temperature record of the subduction process: A review of worldwide lawsonite eclogites. Lithos, 92, 609-624.

Ungaretti L., Lombardo B., Domeneghetti C., and Rossi G., 1983 - Crystal-chemical evolution of amphiboles from eclogitised rocks of the Sesia-Lanzo Zone, Italian Western Alps. Bull. Miner., 106, 645-672.

Vanko D.A., Laverne C., Tartarotti P., Alt J.C., 1996 - Chemistry and origin of secondary minerals from the deep sheeted dikes cored during ODP Leg 148, Hole 504B. In Alt, J.C., Kinoshita, H., Stokking, L.B., et al., Proc. ODP, Sci. Results, 148, College Station, TX (Ocean Drilling Program), 71-86.

Vezzani L., 1969 - La Formazione del Frido (Neocomiano-Aptiano) tra il Pollino ed il Sinni. Geologica Romana, 8, 129-176.

Vezzani L., 1970 - Le ofioliti della zona tra Castelluccio Inferiore e S. Severino Lucano (Potenza). Accademia Gioenia di Scienze Naturali in Catania, 7, 1-49.

Zucali M. and Spalla M.I., 2011 – Prograde lawsonite during the flow of continental crust in the Alpine subduction: Strain vs. metamorphism partitioning, a field-analysis approach to infer tectonometamorphic evolutions (Sesia-Lanzo Zone, Western Italian Alps). J. Struct. Geol., 33, 381-398.