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### Geology map of the central area of Catena Costiera: insights into the tectono-metamorphic evolution of the Alpine belt in Northern Calabria

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## SCIENCE

### Geology map of the central area of Catena Costiera: insights into the tectono-metamorphic evolution of the Alpine belt in Northern Calabria

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The 1:25.000 scale geological map of the central area of Catena Costiera aims to provide a picture of the tectonic setting of the metamorphic units belonging to the Alpine collisional belt of Northern Calabria, Italy. The exposed successions of the study area have been investigated by structural analyses, petrographic, petrological and geochemical studies whose results are summarised in the geological map.

In this area, two HP-LT metamorphic, oceanic-derived units, referred as the Mongrassano and Cozzo Cervello units, have been distinguished on the base of their stratigraphic and tectono-metamorphic evolution. Both the oceanic-derived units show a polyphase deformation history developed under retrograde metamorphism in a subduction zone by underplating and exhumation into an accretionary wedge. These units are overthrust by continental-derived units, referred as the Sila and Castagna units, consisting of medium and high-grade metamorphic rocks. While the Castagna unit displays an Alpine HP/LT metamorphic overprint, the Sila unit escaped any subduction-related metamorphism.

**Keywords:** Calabria; Catena Costiera; HP/LT metamorphism; ophiolites; structural geology

#### 1. Introduction

In the present-day framework of the Central Mediterranean area, the Northern Calabria can be regarded as a ribbon of continental crust bounded south-eastward by the Ionian subduction zone and north-westward by the Tyrrhenian back-arc basin (Polonia et al., 2011 and quoted references). This ribbon of continental crust includes several metamorphic units interpreted as fragments of a collisional belt. This resulted from both the Variscan and Alpine orogenic events as well as from the subsequent extensional tectonics related to the opening of the Tyrrhenian basin from the Tortonian onwards (Kastens & Mascle, 1990). The result of this tectonic history is an intricate assemblage of tectonic units whose evolution is still matter of debate. In Figure 1, the Catena Costiera represents a key area of Northern Calabria where the most significant units of this Alpine collisional belt are preserved.

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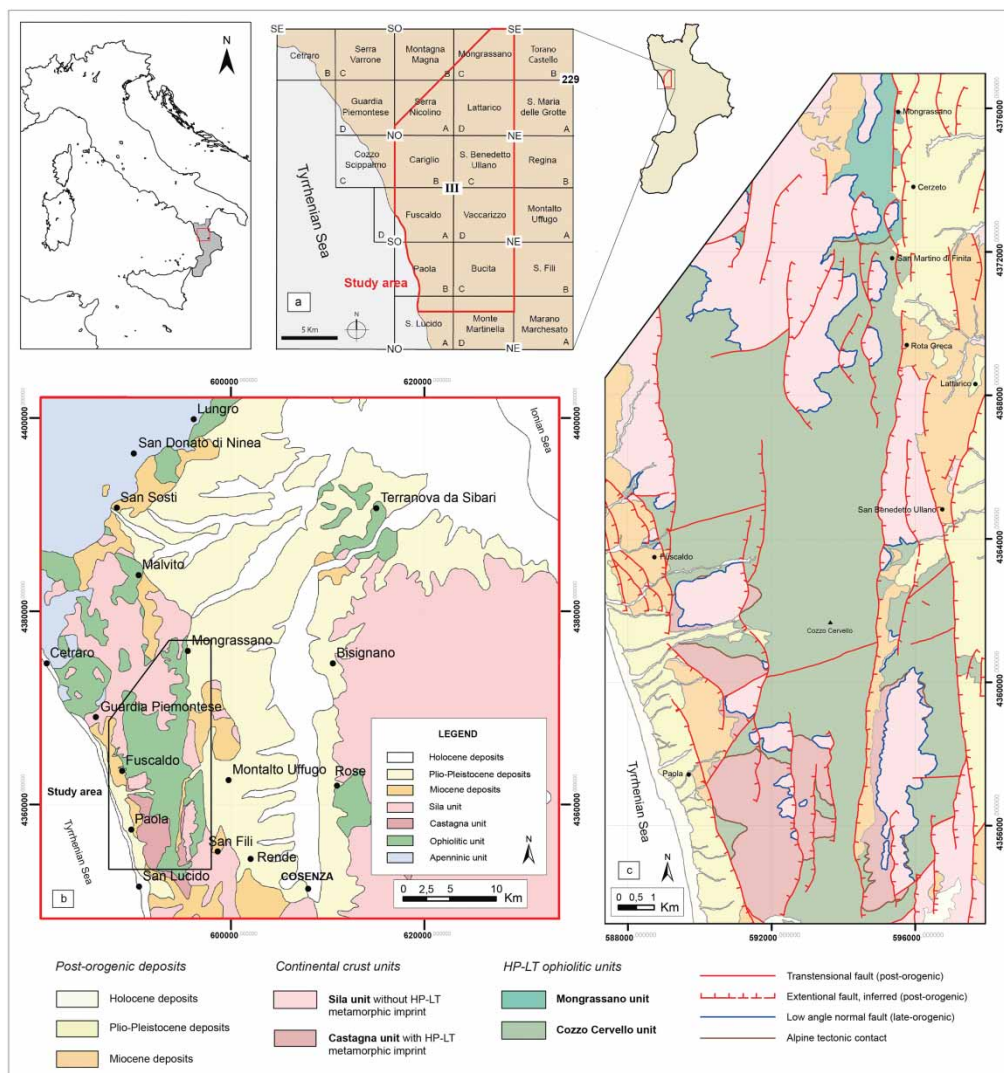


Figure 1. (a) Cartographic elements at the scale 1:10.000 (Cassa per il Mezzogiorno – Legge speciale per la Calabria del 26/11/1955 n. 1177) with the location of the study area. (b) Simplified geological map of the Northern Calabria (modified after [Amodio-Morelli et al., 1976](#)); the black box is enlarged in (c). (c) Simplified tectono-metamorphic sketch map of the study area.

The Catena Costiera is characterised by the superposition of three main groups of tectonic units each issued from different paleogeographic domains. These units are, from bottom to top:

- the Apenninic units ([Amodio-Morelli et al., 1976](#)), represented by Triassic- Early Miocene successions representative of the Africa continental margin ([Amodio-Morelli et al., 1976](#); [Iannace et al., 2007](#); [Ogniben, 1973](#));
- the ophiolitic units, that consist of ophiolites and deep-sea deposits derived from the Western Tethys oceanic basin ([Amodio-Morelli et al., 1976](#); [Liberi, Morten, & Piluso, 2006](#); [Liberi and Piluso, 2009](#); [Ogniben, 1973](#); [Spadea, 1994](#));

- the continental units, representative of both lower and upper levels of the continental crust and small volumes of subcontinental upper mantle rocks (Liberi, Piluso, & Langone, 2011; Messina et al., 1994; Piluso & Morten, 2004; Piluso, Cirrincione, & Morten, 2000).

The study area is located in the central region of Catena Costiera where the structural setting mainly consists of the ophiolitic units overlapped by the continental units. The ophiolitic units are represented by the Mongrassano (MG) and Cozzo Cervello (CC) units, whereas the continental ones include, from bottom to the top, the Castagna (CS) and Sila (SL) units; the Apenninic units are absent in the study area. Finally, Tertiary to Quaternary sedimentary deposits, sedimented during the transtensional tectonic phases, unconformably cover the ophiolitic and continental units (Figure 1).

The purpose of this study is the use of a multidisciplinary approach by combining geological mapping, structural analyses, and petrographic, petrological and geochemical studies in order to unravel the tectonic setting of a key-area of the Catena Costiera. The results of this approach are summarised in the Main Map a 1:25.000 scale geological map of the studied area.

## 2. Methodology

Geological mapping was performed at a scale of 1:10.000 using topographic maps (Cassa per il Mezzogiorno – Legge speciale per la Calabria del 26/11/1955 n. 1177; Figure 1). The collected lithological and structural data were drawn and stored using ESRI ArcGIS 9.3 and Adobe Illustrator which allowed for the extraction of a pdf format image of the geological map. A Digital Elevation Model (DEM) derived topographic map, characterised by 25 m contour interval, has been used as a base map. Three geological cross sections were drawn perpendicular to the structural contacts and the regional foliation trends.

The stereo diagrams reported in the geological map are equal-area projections plotted in the lower hemisphere using the software GEORient and represent the structural features related to the different deformation phases identified in the study area. Conventional thermobarometry and petrogenetic grids were used to reconstruct the P-T diagrams. Abbreviations are as follows: D for deformation phase, S for syn-metamorphic foliation or axial plane of folds, Sm for mylonitic foliation, L for mineral/stretching lineations and F for fold axes and intersection lineations, while numbers denote the relative deformation phase. Minerals abbreviations are given according to Kretz (1983) with the update of Bucher and Frey (2002), and Whitney and Evans (2010).

## 3. Lithostratigraphy

The lithostratigraphy of the tectonic units outcropping in the study area is described from the lowermost, i.e. MG and CC ophiolitic units, towards the upper ones represented by the continental units.

The ophiolitic units of the Northern Calabrian Arc are represented by metabasalts with a tholeiitic affinity and T-MORB geochemical signatures and metasedimentary cover (Figure 2); metaultramafic rocks are present in the Gimigliano-Monte Reventino unit only, whilst gabbros and the sheeted-dike complex are completely absent (Amodio-Morelli et al., 1976; Liberi et al., 2006; Liberi & Piluso, 2009; Spadea, 1979). The Calabrian ophiolites, as well as those from Corsica, Northern Apennines and Alps, are described as incomplete ophiolitic sequences characterised by quite heterogeneous metasedimentary covers showing a noticeable terrigenous supply (Liberi & Piluso, 2009).

Two different ophiolitic units have been recognised in the study area. The CC unit includes metabasalts topped by thin levels of volcanoclastic metasediments. In Vallone Berarda and

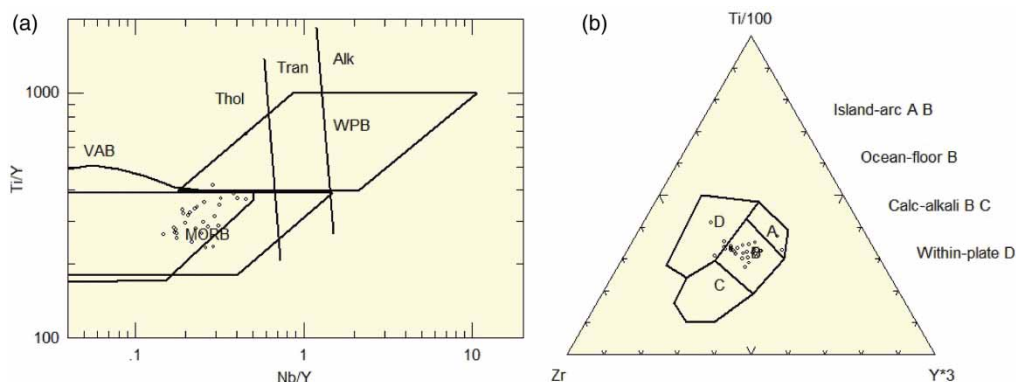


Figure 2. (a) Ti/Y versus Nb/Y (Pearce, 1982) and (b) Zr-Ti/100 versus Y\*3 (Pearce and Cann, 1973) tectonomagmatic discrimination diagrams for the metabasalts of the CC and MG ophiolitic units in the study area.

Cozzo Cervello localities, the volcanoclastic metasediments are represented by alternating levels of ophiolitic metarenites and metapelites. These metasediments show a gradual transition to rare metacarbonates topped by a thick succession of metapelites, metarenites and metarudites, characterised by a remarkable increase in the marble levels moving northward in the study area (Liberi & Piluso, 2009). Instead, the MG unit is characterised by metabasalts and volcanoclastic metasediments topped by calcschists with thin levels of metapelites. Locally, in the northernmost part of the study area, centimetric layer of metaradiolarites can be observed at the top of the metabasalts.

The ophiolitic units are overthrust by the continental units, represented by the CS and the SL units. The SL unit consists of medium to high-grade metamorphic para- and ortho- gneisses cut by aplite and pegmatite dykes. Bodies of pyroxene-bearing granulites and migmatites characterised by the occurrence of garnet, sillimanite and cordierite can also be observed. Small stocks of monzogranites of Permian age (Messina et al., 1994) have been identified mainly in the southern areas of the map. This unit is regarded as representative of a continental crustal section including small volumes of the subcontinental mantle rocks that preserved the records of the late Variscan deformations (Graessner & Schenk, 2001; Piluso & Morten, 2004; Piluso et al., 2000) as well as the following extensional events during Permo-Triassic time span (Caggianelli, Liotta, Prosser, & Ranalli, 2007; Liberi et al., 2011). These rocks are affected only by the Variscan metamorphism and deformation (Amodio-Morelli et al., 1976; Graessner & Schenk, 2001; Piluso & Morten, 2004; Piluso et al., 2000). The CS unit underwent both Variscan and Alpine tectonometamorphic evolutions (Amodio-Morelli et al., 1976; Colonna & Piccarreta, 1976; Rossetti et al., 2001); it is constituted by a thick succession of mylonitic to ultramylonitic from original Paleozoic orthogneisses and paragneisses (Amodio-Morelli et al., 1976). Boudins of amphibolites, metatonalites, metagabbros and gneissic rocks occasionally occur within the mylonites.

#### 4. Deformation history

The analysis of the deformation history has been carried out mainly on the CC and MG units as well as on the CS unit, i.e. the units that underwent HP-LT metamorphic overprint during the Alpine deformation. Therefore, the deformation history of the SL unit, which escaped Alpine tectonics, and the post-orogenic tectonics are here briefly discussed. The photos at the meso-scale of the deformation features of the studied tectonic units are inserted in the geological map.



The oldest geological structures observed in the study area refer to the SL unit. In fact, although severely fractured and altered, the rocks belonging to this unit show a gneissic foliation developed under granulitic facies conditions, as testified by the blastesis of sillimanite along the foliation. It is difficult to determine a structural trend for this phase, as the outcrops are very discontinuous and the attitude data of the gneissic foliation do not display any preferential orientation in the study area. At regional scale, this tectonometamorphic event is related to the Variscan orogenic cycle (Graessner et al., 2000; Piluso & Morten, 2004). The gneisses are intruded by late Variscan granites and cross-cut by several peraluminous dykes (Messina et al., 1994).

The Variscan basement rocks are placed on the HP oceanic and continental-derived units (CC, MG and CS units) along very low-angle brittle tectonic contacts. Kinematic data are doubtful, however this contact has been described as an original Alpine contractional structure reworked during the pre- to syn-collisional extensional tectonics during Oligo-Miocene times (Cello & Mazzoli, 1999; Rossetti, Goffè, Moniè, Faccenna, & Vignaroli, 2004; Rossetti et al., 2001; Thomson, 1998; Wallis et al., 1993).

The CC and MG units show common deformation histories that will be described together. Both these units underwent Alpine polyphase deformation history that can be subdivided into four (D1-D4) deformation phases.

The D1 phase is characterised by a S1 foliation (Figure 3), which represents the main structural surface observed in the field. The NW-SE striking S1 foliation shows both NE and SW plunge. The L1 lineations, represented by stretched quartz and feldspars crystals, show a clear ENE-WSW trend. The isoclinal F1 folds show N-S trending axes and boudinaged limbs. Mylonitic shear zones developed parallel to the S1 foliation in both CC and MG units. The kinematic indicators, as S-C structures, reveal a top-to-west sense of shear for these structures. The D2 phase is characterised by asymmetric, open to close F2 folds showing a NE-SW trending axes. A SE-dipping, axial plane foliation S2 as well as a developed crenulation cleavage can be observed at the mesoscale. The L2 lineations, given by the stretched albite and quartz crystals, can be locally observed on the S2 foliation. During the D2 phase, cataclastic-mylonitic shear zones were developed, sometimes as structures that overprint the pre-existing mylonites. The D3 phase is characterised by open F3 folds showing NW-SE trending axes. The axial plane foliation is represented by a disjunctive cleavage. The D4 phase can be observed only at the map-scale as km-scale F4 open folds with N-S trending axes.

With regard to the CS unit, the meso- and microstructural analyses allowed to recognise four main deformation phases (D1 to D4 phases). The D1 deformation phase is represented by a S1 relict foliation, which can be observed only in few small outcrops or at the microscopic scale, in low strain domains that escaped the ductile shear related to the following phase. The D2 phase (Alpine) is responsible for the development of a NW-SE-striking Sm2 mylonitic foliation, which represents the most pervasive fabric at both the meso- and microscale. Along the Sm2 foliation, WSW-ENE trending Lm2 lineations, defined by stretched quartz and feldspar minerals, are common. At the mesoscale, the Sm2 foliation is characterised by ductile kinematic indicators such as  $\sigma$ -type porphyroclasts, quartz veins sigmoids, S-C structures and C'-type shear bands, all coherent with a top to the W-SW sense of shear. At the microscopic scale, mineral fish and minerals sigma structures occur with the same sense of shear (Figure 4c–e). Along Sm2 foliation tight and/or isoclinal F2 folds developed, showing WNW-ESE trending axes and dipping mainly to E-SE. Boudins of metatonalites, amphibolites, metagabbros and gneissic rocks are commonly aligned along the Sm2 foliation.

These boudins formed during the D2 deformation phase as they show WSW-ENE trending long axes parallel to the stretching lineations Lm2. D3 phase is characterised by F3 asymmetric folds, showing NE-SW trending axes. The axial plane foliation of the F3 folds is represented by a well-developed crenulations cleavage. At places, stretched quartz crystals define a

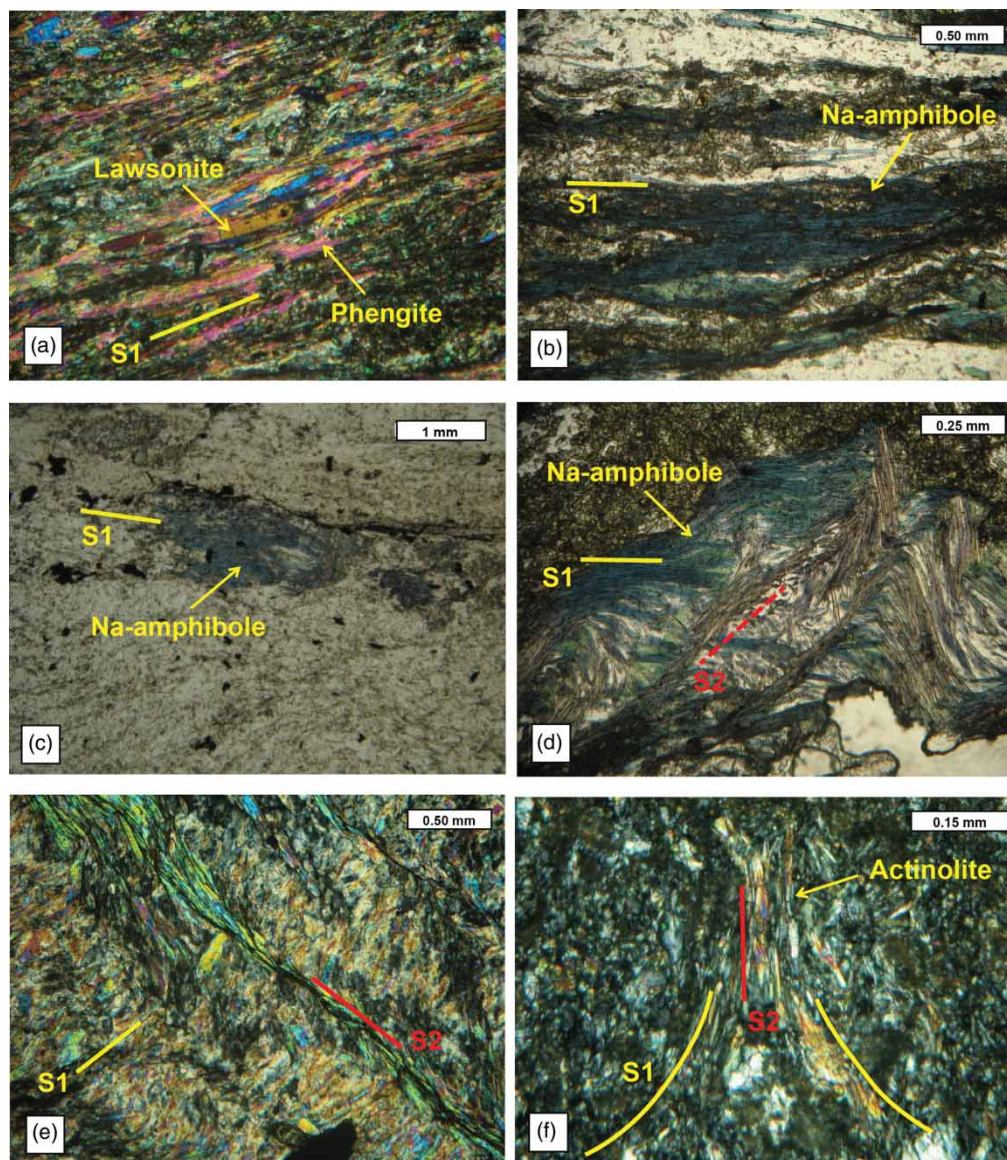


Figure 3. Cozzo Cervello and Mongrassano units microstructures. a) Lawsonite and phengite along S1 foliation within metabasalts; Microphoto in polarised light, crossed nicols; b) Blastesis of Na-amphibole along S1 in the metabasalts. Microphoto in polarised light, parallel nicols; c) Na-amphibole along S1 foliation in the metarenites. Microphoto in polarised light, parallel nicols; d) Na-amphibole crenulated during D2 event in the metabasalts. Microphoto in polarised light, parallel nicols; e) Blastesis of white mica and development of S2 foliation. Microphoto in polarised light, crossed nicols; f) Blastesis of actinolite along S2 foliation in the metabasalts of the CC unit. Microphoto in polarised light, crossed nicols.

NW-SE-trending L3 lineation. The D4 phase shows features similar to those recognised in the MG and CC units.

In the study area, the post-orogenic tectonics is represented by N-S and NE-SW trending high-angle extensional faults. The N-S faults border, on both side, the Catena Costiera structural high.



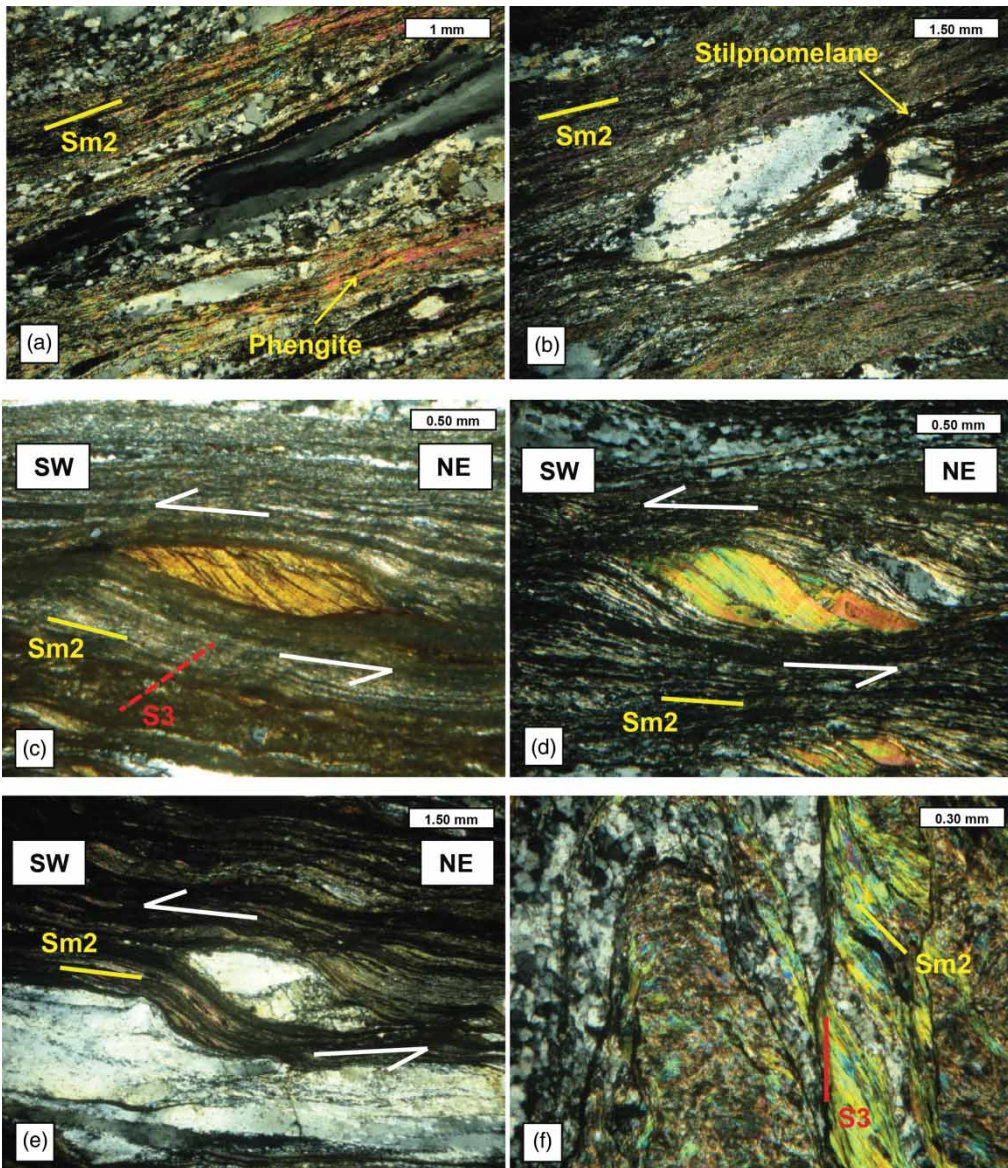


Figure 4. Castagna unit microstructures. (a) Mylonitic foliation Sm2 marked by the blastesis of phengites and quartz ribbon; (b) Sigma structure along Sm2 with syn-kinematic growth of stilpnomelane during Dm2; (c) Biotite fish along Sm2 with top to the southwest sense of shear. Note S3 incipient foliation; (d) Mica fish along Sm2 with top to the southwest sense of shear; (e) Sigma along Sm2 with top to the southwest sense of shear; (f) S3 foliation development marked by the blastesis of white mica; Microphotos in polarised light, crossed nicols.

These faults are responsible for the opening of late Miocene to Quaternary extensional basins, filled by Messinian to Quaternary marine and continental clastic deposits (Cifelli, Rossetti, & Mattei, 2007; Mattei et al., 2002; Tortorici, Monaco, Tansi, & Cocina, 1995). In fact, since middle Miocene, the northern Calabrian Arc was affected by post-orogenic extension associated to the opening of the Tyrrhenian basin (Sartori, 1990).

5. Metamorphic evolution

Geothermobarometric estimates for the Alpine mineral assemblages are based on selected conventional thermobarometry and petrogenetic grids (Carlson, 1980; Filice et al., 2013; Liou, 1971; Liou et al., 1985; Maruyama et al., 1986; Massonne, 1992; Massonne, 1995; Nitsch, 1971, 1972). The P-T paths follow a typical HP-LT clockwise evolution and are reported in the Main Map. Although the ophiolitic units are characterised by the same structural evolution, they display different metamorphic peak conditions and subsequent retrogression (Table 1). Physical conditions of 1.1 GPa, P and 350°C, T and 0.9 GPa, P and 320°C, T have been calculated for the D1 phase metamorphic peak for the CC and MG units, respectively, both for the metabasalts and metasediments. The inferred peak metamorphic pressure has been determined using the Si<sup>IV</sup> content of phengites (Massonne & Schreyer, 1987). Therefore, the HP metamorphic event develops in the blueschist facies conditions characterised by the mineral paragenesis: phengite + lawsonite for the MG unit and phengite + lawsonite + Na-amphibole (crossite – Mg-riebeckite) for the CC unit (Table 1, Figure 3a–d). The subsequent decompression during the D2 phase is characterised by the blastesis of white mica + actinolite + albite + chlorite along the S2

Table 1. Mineralogical assemblage characterising each deformation phase in the ophiolitic (CC and MG) and Castagna (CS) units. Minerals abbreviations according to Kretz (1983), Bucher and Frey (2002), and Whitney and Evans (2010).

UNIT	DEFORMATION PHASE	LITHOLOGY AND MINERAL ASSEMBLAGES
Cozzo Cervello unit (CC)	D1	<i>Metabasalt</i> : Ab + Ep + Chl + Phe ± Qtz + Na-Amph (Mrb and Crt) + Lws ± Cal ± Ttn ± Hem <i>Volcanoclastic metasediments (ophiolitic metarenites)</i> : Chl + Ab ± Hem <i>Metacarbonate</i> : Cal + Dol + Qtz ± Phe ± Chl <i>Metapelite</i> : Qtz + Chl + Phe ± Ep + Ttn <i>Metapelite-Calcschist</i> : Qtz + Phe + Cal + Stp + Chl ± Ab ± Ep ± Ttn ± Hem <i>Metarenite and Metarudites</i> : Qtz + Ab + Phe + Na-Amph (Mrb and Crt) + Stp + Chl + Ep + Ttn + Py
	D2	<i>Metabasalt</i> : White mica + Act + Chl ± Ab <i>Metapelite</i> : White mica + Chl <i>Metapelite-Calcschist</i> : White mica + Chl
	D3	<i>Metapelite</i> : Chl + Pmp
	D1	<i>Metabasalt</i> : Ab + Chl + Phe + Ep + Lws + Qtz ± Ttn <i>Volcanoclastic metasediments (ophiolitic metarenites)</i> : Chl + Ab ± Hem <i>Calcschist</i> : Cal ± Qtz ± Ab ± Ep ± Phe ± Stp + Hem
Mongrassano unit (MG)	D2	<i>Metabasalt</i> : White mica + Chl ± Ab <i>Calcschist</i> : Cal + White mica
	D3	metamorphic blastesis absent
Castagna unit (CS)	D1 (protolite)	<i>Ortogneiss</i> : Qtz + Pl + Ms ± Grt + Bt + Ap + Ttn ± Rt <i>Paragneiss</i> : Qtz + Pl + Ms + Grt + Bt + Chl ± Crd ± Sil
	Dm2	<i>Mylonite</i> : Qtz + Ab + Phe + Chl + Ep + Stp ± Hem
	D3	<i>Mylonite</i> : White mica + Chl + Qtz + Hem

foliation in the metabasalts of the CC unit (Table 1, Figure 3e, f), and white mica + albite + chlorite in the MG unit. The blastesis of actinolite (Table 1, Figure 3f) documents a slight heating during decompression, which appear to be more prominent in the CC unit respect to the MG unit. The crystallisation of chlorite and pumpellyite in the metasediments indicates the transition to the lower greenschist facies conditions during the D3 phase.

The physical conditions of the metamorphic climax in the CS unit, during the D2 phase, have been calculated on the basis of the celadonitic content of the phengites ( $\text{Si}^{\text{IV}} = 3.5$  a.p.f.u.), at about 1.0–1.1 GPa, P (interpreted as a minimum pressure estimate) and 350°C, T. The HP metamorphic peak during the D2 phase is characterised by the blastesis of phengite + stilpnomelane (Table 1, Figure 4a, b). During the D3 phase a nearly isothermal decompression developed at 0.4 GPa, P and 320°C, T as suggested by greenschist facies assemblages made of white mica + chlorite + quartz + hematite, developed (Table 1, Figure 4f).

## 6. Discussions and conclusions

The geological map of the study area indicates that the tectonic setting of central Catena Costiera (northern Calabria) is characterised by an assemblage of three units. The deformation history and the associated HP-LT metamorphism of these units are regarded as indicative of their accretion and subsequent exhumation in an accretionary wedge within a subduction zone. Two units, the CC and MG units, are oceanic-derived, whereas the CS unit is regarded as a continental crust domain.

The occurrence of T-MOR basalts with a tholeiitic affinity in both the CC and MG units indicates their origin from the Western Tethys oceanic domain, analogously to the other ophiolite sequences cropping out within the northern Calabrian Arc (Liberi & Piluso, 2009; Liberi et al., 2006). The two ophiolitic units are characterised by thick metasedimentary covers including ophiolitic metarenites and metapelites, previously interpreted as belonging to a pre-Mesozoic continental basement (Bagni unit of Amodio-Morelli et al., 1976; Dietrich & Scandone, 1972). These units are affected by a structural history characterised by four deformation phases. The overall features of the D1 phase indicate that deformation occurred during underplating and accretion connected with a subduction zone. The top-to the west mylonitic shear zone recognised within the MG and CC units developed during the underplating. The D2 phase can be instead regarded as developed during the exhumation of these units under different P and T conditions, as suggested by the occurrence of actinolite along the S2 foliation of the CC unit only. The MG and CC units were probably coupled at the final stages of the D2 phase, when the cataclastic-mylonitic shear zones developed. It is noteworthy the occurrence of m-thick slices of metacarbonates into the D2 phase cataclastic-mylonitic shear zone inside the CC unit. This occurrence can be explained by reworking of the pre-existing weakness zone at the boundary of the metaophiolites and its metasedimentary cover. In this framework, the metacarbonates can be interpreted as extensional allocthonous of upper continental crust inherited during the phase of asymmetric rifting that predated the opening of the western Tethys, as observed for instance in Northern Apennine (e.g., Marroni & Pandolfi, 2007; Marroni & Tribuzio, 1996). The D3 phase is likely related to the very late stages of accretion of the Alpine units. The last deformation event is represented by the D4 phase mainly characterised by large-scale, very open folds that can be related to late orogenic contractional phases. Alternatively, they can be interpreted as roll-over folds connected with the post-orogenic extensional events.

The age of the HP/LT metamorphism is not well constrained, as few radiometric age data are available for the ophiolitic rocks belonging to the Gimigliano-Monte Reventino unit, exposed in the Sila Piccola area, and for the HP units cropping out north of the study area (Rossetti et al., 2001, 2004). The geochronological analyses gives ages ranging between 33–38 Ma and



18–22 Ma, which are interpreted respectively as the lower and upper limit ages for the HP-LT metamorphism.

Also the CS unit shows deformation and metamorphism that can be regarded as the involvement of a thinned continental crust, or small slices of continental crust, into a subduction zone. This interpretation is supported by the occurrence of the pervasive mylonitic foliation under HP/LT metamorphic conditions. The structural analysis of the CS unit allows to determine a top-to-the W-SW sense of shear during this HP/LT event.

The collected data allow us to propose some regional correlations:

- (i) the CC unit shows lithological and petrological features close to those described for the Gimigliano-Monte Reventino unit (Amodio-Morelli et al., 1976; Liberi et al., 2006) cropping out in the Sila Piccola area;
- (ii) the MG unit metasedimentary cover can be correlated with that of the Malvito ophiolitic unit (sensu Amodio-Morelli et al., 1976), cropping out in the northernmost area of the Catena Costiera;
- (iii) the subdivision between the Bagni and Gimigliano-Monte Reventino units, as proposed by Dietrich and Scandone (1972) and Amodio-Morelli et al. (1976) for the study area, is not supported by the evidence of the geological map, which indicates that the metarenites and metapelites belong to the sedimentary cover of the ophiolitic units.

## Software

The geological maps were drawn using ESRI ArcGIS 9.3. The structural data were analysed and plotted with GEORient. The cross sections presented in the geological map and the photographs were compiled with Adobe Illustrator.

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