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The Calabria-Peloritani Orogen, a composite terrane in Central Mediterranean; its overall architecture and geodynamic significance for a pre-Alpine scenario around the Tethyan basin

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Abstract

The Calabria-Peloritani Orogen is an arcuate segment of the peri-Mediterranean orogenic Alpine nappe system that comprises the whole Calabria and the north-eastern sector of Sicily. It comprises the Sila and Catena Costiera Massifs in northern Calabria, the Serre and Aspromonte Massifs in central and southern Calabria, and the Peloritani Mountains in Sicily.

In Sila and Catena Costiera Massifs, three tectonic complexes are recognisable: a) the basal Apennine Complex, which consists of carbonate platform sequences of passive continental margin; b) the intermediate Liguride Complex, made of oceanic-derived units, affected by HP/LT metamorphism; and c) the upper Calabride Complex, which represents a nearly entire section of continental crust. The Catanzaro Line separates the northern sector from the Serre Massif that also represents a nearly entire segment of Variscan continental crust unaffected by Alpine metamorphism. Further to the south, the Palmi Line separates the Serre from the Aspromonte Massif and the Peloritani Mountains. These two latter nappe edifices consist of either Variscan metamorphic units, Variscan units with Alpine overprint and units of continental derivation that are exclusively affected by Alpine metamorphism. The comparison between the geological evolutions of the various chain sectors, as well as their structural setting and their direction of tectonic transport, indicates that the Calabria-Peloritani Orogen is a composite terrane derived from the amalgamation of crustal blocks of different continental provenance. Northern Calabria represents a fragment of the Adria palaeomargin, whereas southern Calabria and northeastern Sicily are relics of an accretionary wedge resulting from the deformation of the European continental margin. As a consequence, nowadays a segment of the Europe-Adria collisional suture crops out in central Calabria.

Key Words: Variscan crystalline basements; Alpine orogeny; palaeogeography; Calabria and NE Sicily.

Introduction

The circum-Mediterranean Variscan chain, developed as a consequence of the late Paleozoic convergence between Gondwana and Laurussia, includes numerous fragments of pre-Mesozoic basements that, if pieced together, may be considered as a single terrane before the Mesozoic disaggregation of Pangea. The history of each fragment is delineated by the various metamorphic and magmatic events associated to either the Variscan or the Alpine orogenesis and, in many cases, also involving pre-Variscan basements. The main problem in the study of crystalline basements from collisional-type orogens is that of locating the main events in space and time, in the frame of plate tectonics;. to this aim, several efforts have been also made for the Calabria-Peloritani Orogen .

Since the first half of the 19th century, the abrupt interruption of the lithological continuity of the Italian peninsula passing from the relatively thin-skinned sedimentary slices of the Apennine chain to the deep-seated crystalline rocks of northern Calabria has stimulated a great interest of both Italian and foreign geologists, who envisaged the southernmost sector of the Italian peninsula as a fragment of the same crystalline basement widely exposed in the Alps and in the other Massifs of Europe (Figure 1 - Haccard et al., 1972). This southward shifted fragment of the European continent, initially known in the literature as Calabrian-Peloritani Arc and later as Calabria-Peloritani Orogen or Terrane, soon became a natural laboratory for Italian as well as European scientists. Its marginal geographic position did not diminish its importance: indeed the location in the central Mediterranean area and the important geological-petrographic open questions have been keeping alive and continuously animating the scientific debate.

Several authors elaborated a number of tectonic models where the whole orogen did bounce from one margin of the Tethyan basin to another one, with contrasting interpretations that, mostly over the last thirty years, nurtured a lively scientific debate. Papers published within this time span (e.g. Amodio Morelli et al., 1976; Ogniben, 1981; Bonardi et al., 2003; 2008; Stampfli, 2005; Van Dijck et al., 2000; Vai, 1990; 1992; Beccaluva et al., 2011; Cavazza and Ingersoll, 2005; Alvarez and Shimabukuro, 2009) share this joint purpose: to explain the complex geometries of the Calabria-Peloritani Orogen in the frame of the Central Mediterranean geodynamics.

This work is meant to review, debate as well as re-organise the strongholds of the entire Calabria-Peloritani Orogen architecture, by examining its constituting massifs in terms of tectono-metamorphic complexes. These latter, recording different stages of the orogenic history, altogether provide the key to define the geological significance of the orogen itself. This moved us to design a unitary model able to consistently integrate and synthesize all of the existing data for each segment, in order to facilitate the correlations among the various orogenic fragments that have been scattered by subsequent geological events.

Geological outline

The term Calabria-Peloritani Orogen (CPO) is referred to an arcuate ribbon-like segment of the peri-Mediterranean orogenic Alpine nappe system that comprises the whole Calabria and the north-eastern sector of Sicily (Figure 2). It is geographically identifiable as an orogen located between the Pollino Fault Zone (PFZ),

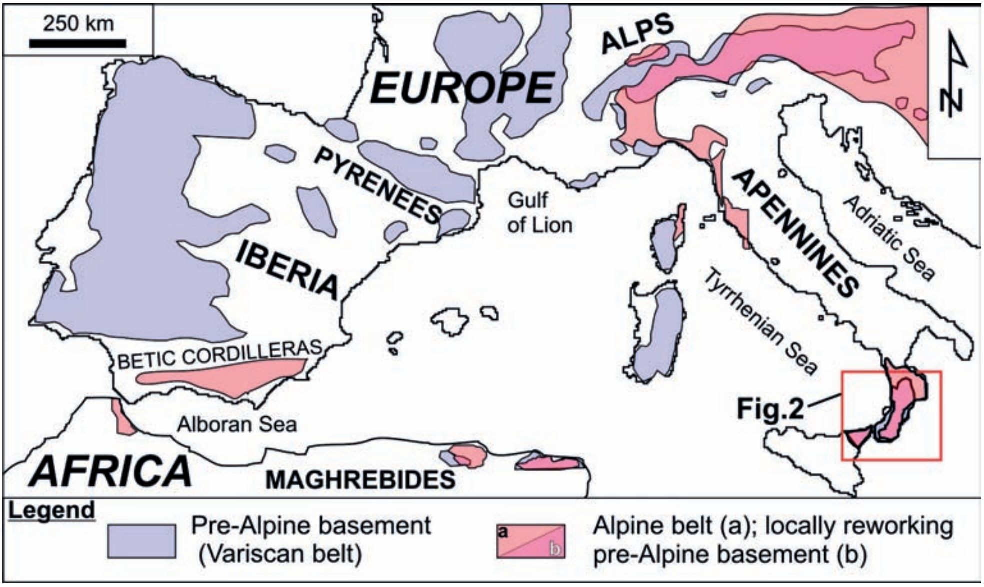


Figure 1. Distribution of the Alpine and Pre-Alpine Basement in Western Europe (redrawn after Cirrincione et al., 2012a).

to the north, and the Taormina Line (TL) to the south, acting as a connecting element between the Apennine thrust-and-fold belts of southern Italy and the Maghrebian chain in Sicily (Figure 2a - Bonardi et al., 1980a; Tortorici, 1982; Carminati et al., 1998). The overall architecture of the CPO is made up of a series of basement nappes and ophiolite-bearing tectonic units that are considered to be remnants of the Cretaceous-Paleogene Europe verging Eo-Alpine chain involved, during the Neogene, in the building of the Apennine orogenic belt. Thrusting has been related to the slab roll-back of the African subducting plate, accompanied by the progressive back-arc opening of the Tyrrhenian sea (Figure 2a) and the consequent southeastward migration of the entire belt in the present-day geographic coordinates (Rossetti et al., 2001; Cifelli et al., 2008; Carminati et al., 2010). From a physiographic point of view, the CPO is clearly constituted by the amalgamation of two different sectors, subdivided by the Catanzaro line (CL) (Figure 2b): a northern sector, composed by the Sila Massif and the Catena Costiera and a southern one, formed by the Serre and Aspromonte massifs together with the Peloritani Mountains, in Sicily. From a geological point of view, on the other hand, the origin and evolution of these chain sectors is still matter of debate: some authors argue that the CPO would entirely derive from the European continental margin of the neo-Tethys (Ogniben, 1973; Bouillin, 1984; Knott, 1987; Dietrich, 1988; Dewey et al., 1989; Thomson, 1998), while others hypothesize that it can be considered a portion of the Austroalpine domain belonging to the African plate (Haccard et al., 1972; Alvarez et al., 1974; Amodio-Morelli et al., 1976; Scandone, 1979; Bonardi et al., 1982; 1993); other authors still propose a derivation from a micro-continent located between African and European plates (Guerrera et al., 1993; Cello et al., 1996; Perrone, 1996; Critelli and Le Pera, 1998). Lastly, it has been also considered as the result of the accretion of six different crustal micro-plates (Vai, 1992). The subdivision into

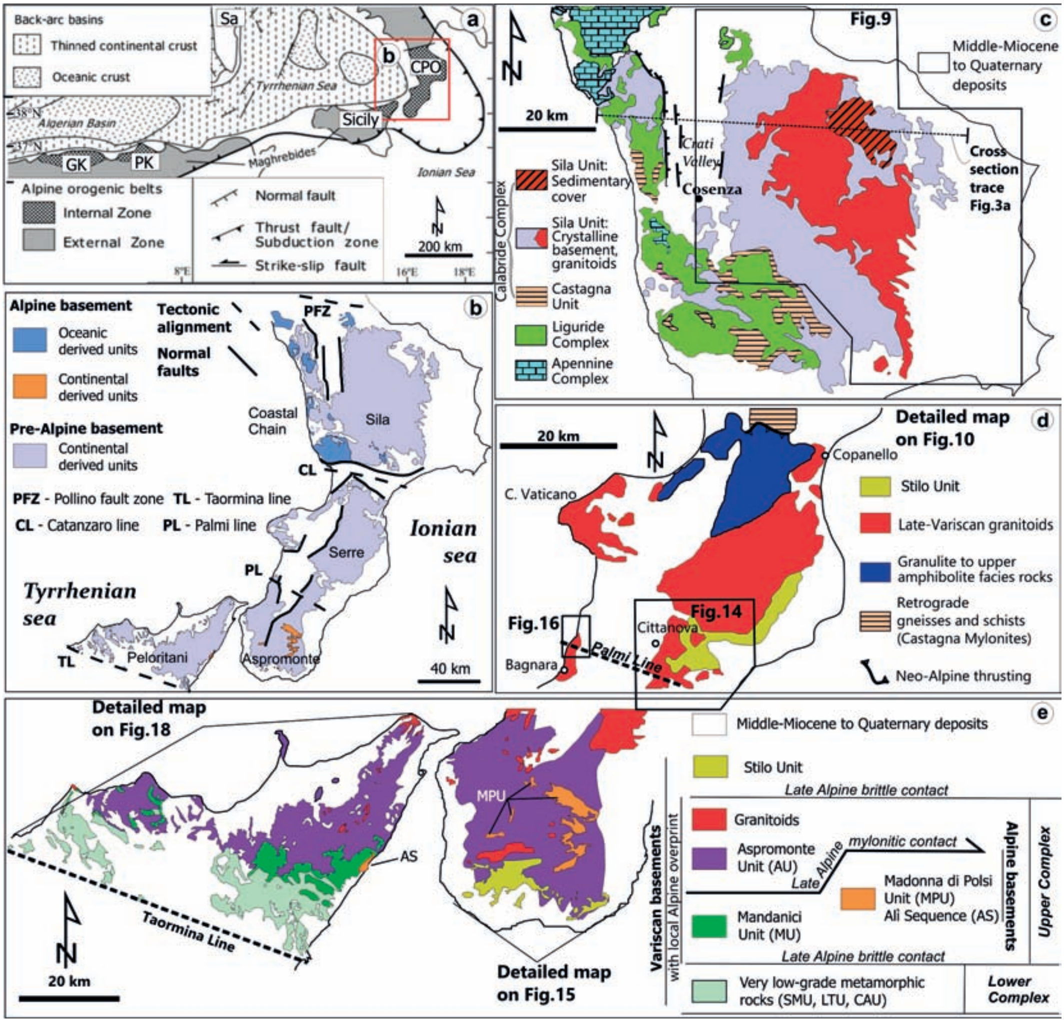


Figure 2. Geological map representations of the Calabria-Peloritani Orogen: a) Schematic map of the Alpine belt in the southern Mediterranean area (GK= Grande Kabylie; PK = Petit Kabylie; Sa = Sardinia; CPO = Calabrian Peloritani Orogen) (modified after Carminati et al., 1998); b) Geological sketch map of the Calabria-Peloritani Orogen with distribution of its massifs and related Alpine and pre-Alpine basement rocks (modified after Angì et al., 2010; c) Geological sketch map of the Sila and Catena Costiera Massifs; d) Geological sketch map of the Serre Massif; e) Geological sketch map of the Aspromonte Massif and Peloritani Mountain Belt.

northern and southern sector, suggested for the first time by Tortorici (1982) on the basis of the alleged absence of Alpine metamorphic overprint as well as by the lack of Liguride units in the southern one, has been also continuously re-discussed. In fact, several units exclusively characterised by Alpine metamorphic evolution have been successively recognised also in the southern sector (Cirrincione and Pezzino, 1991; Pezzino et al., 2008; Cirrincione et al., 2008a;2012a). Nevertheless, this subdivision can be still considered geologically significant since it separates two sectors with remarkably different geological histories. The northern sector is represented by an Europe verging nappe-like edifice of pre-Lutetian age (Dietrich, 1988; Cello et al., 1996) overlapped during early-Miocene onto the African continental margin. The nappe edifices of the CPO southern sector show instead exclusive Africa verging transport, since early Oligocene and up to Miocene, with associated deposition of a huge flyschioid succession known as Stilo-Capo d'Orlando Formation (Cavazza and Ingersoll, 2005), whose basal conglomerate components have been proposed to derive from the Sardinia-Corsica domain (Atzori et al., 2000; Cirrincione, 1996).

Nappe edifices and crustal domains

Overview

The nappe edifices of Sila and Catena Costiera make entirely up the northern sector of the orogen (Figure 2c). They are separated by the Crati valley, a N-S trending graben ascribed to the Upper Pleistocene (Cello et al., 1982; Tortorici et al., 1995); these edifices consist of three main tectono-stratigraphic complexes (Figure 3 - Ogniben, 1973; Morten and Tortorici, 1993 and references therein) each of them formed by distinct tectono-metamorphic units (Figure 3b - Amodio-Morelli et al., 1976; Piluso et al., 2000; Scandone, 1982).

The basal complex, known as "Apennine Complex", is made of a thick Mesozoic partly metamorphosed carbonate succession (Ietto and Barillaro, 1993; Perrone, 1996; Ietto and Ietto, 1998). Starting from Lower Miocene, the basal complex was involved in the collision between the Iberian and Adriatic domains (Critelli, 1999 and references therein). The intermediate Liguride Complex consists of oceanic-derived units, which have been interpreted as remnants of the Tethys ocean (De Roever, 1972; Beccaluva et al., 1982; Guerrera et al., 1993; Cello et al., 1996; Tortorici et al., 2009), initially involved in subduction and later in Europe verging continent-continent collision events, as structural data suggest (Alvarez et al., 1974; Dietrich, 1988; Cello et al., 1991). Finally, the upper complex, known as Calabride Complex, mostly represents an uninterrupted continental crust section developed during the late Variscan orogeny, with the Longobucco Unit representing its original Mesozoic sedimentary cover, exclusively affected by brittle deformation starting from 23 Ma (Thomson, 1994; Zecchin et al., 2013).

The Serre Massif and the Capo Vaticano Promontory, which are separated by the NE-SW trending Pleistocene graben of the Mesima Valley, represent two portions of the same edifice (Figure 2d) (Ietto and Bernasconi, 2005). This sector of the orogen, especially along the Serre transect, is considered to represent a continuous continental crustal section (e.g., Schenk, 1980; 1990; Caggianelli et al., 2007; Angì et al., 2010) whose metamorphic and magmatic evolution is closely associated to that of the Calabride Complex cropping out in the Sila and Catena Costiera areas. Unlike the northern sector, no elements ascribable either to the Liguride or Apennine Units complex are present at the base of this massif.

The Aspromonte Massif occupies the southern end of Calabria, bordered to the north by the crustal-scale strike-slip fault system known as Palmi Line (Figure 2b-d - Ortolano et al., 2013). It is a south-east verging nappe edifice (Ortolano et al., 2015), where the two uppermost tectonic slices are constituted by two middle-upper crust derived units (the upper Stilo Unit and the lower Aspromonte Unit), both characterised by a multi-stage Variscan metamorphism, locally involving only the deeper one during the latest stages of

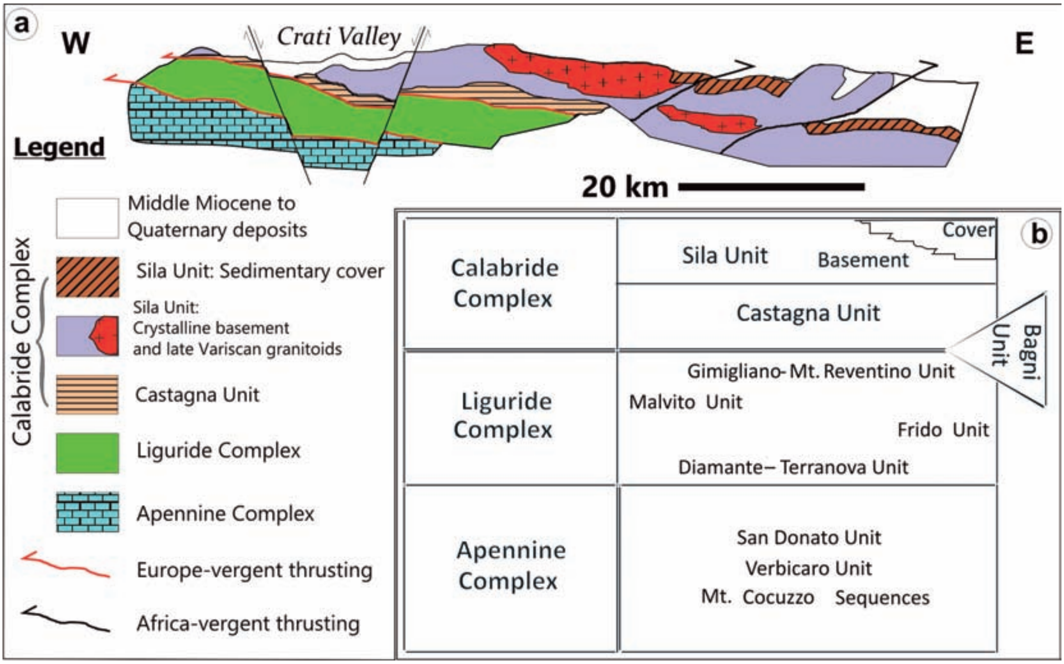


Figure 3. a) E-W geological cross section of the Sila and Catena Costiera Massifs with b) main complexes and related units (modified after Ogniben, 1973).

the Alpine metamorphic cycle (Bonardi et al.,1984a,b; 1992; Graessner and Schenk, 1999; Platt and Compagnoni, 1990; Ortolano et al., 2005; Pezzino et al., 2008). The deepest tectonic unit, separated by the intermediate Aspromonte Unit by a thick mylonitic horizon and composed by medium grade metapelites, exclusively registered a complete Alpine metamorphic cycle (Madonna di Polsi unit; Pezzino et al., 1990; 2008; Ortolano et al., 2005; Cirrincione et al., 2008a; Fazio et al., 2008).

The Peloritani Mountain belt consists of a set of south-verging basement nappes with metamorphic grade increasing upwards and remnants of a Mesozoic-Cenozoic sedimentary sequence (Figure 2d - Atzori and Vezzani, 1974; Lentini and Vezzani, 1975). The belt has been subdivided into two complexes on the basis of their different tectono-metamorphic histories (Atzori et al., 1994; Cirrincione et al., 1999). The Lower Complex, in the southern part of the belt, consists of Cambrian to Carboniferous volcano-sedimentary sequences (Acquafredda et al., 1994; Ferla, 2000; Trombetta et al., 2004; Cirrincione et al., 2005; Somma et al., 2013) affected by Variscan sub-greenschist to greenschist facies metamorphism, covered by Mesozoic-Cenozoic sediments (Cirrincione et al., 1999). The Upper Complex, in the north-eastern part, consists of two tectonic units (Mandanici and Aspromonte units) comprising Variscan greenschist to upper amphibolite facies metamorphic rocks, the latter intruded by late Variscan granitoid plutons, both with a local Alpine greenschist facies metamorphic overprint (Cirrincione and Pezzino, 1991; Atzori et al., 1994; Festa et al., 2004; Punturo et al., 2005; Fiannacca et al., 2008; 2012; Appel et al., 2011; Cirrincione et al., 2012a). Fragmented tectonic slices of a weakly metamorphosed Mesozoic-Cenozoic cover sequence are locally interposed between these two units (Cirrincione and Pezzino, 1991, 1994).

Sila and Catena Costiera Massifs

The basal "Apennine Complex" (Perrone, 1996) or "Panormide Complex" (Figure 3 - Ogniben, 1973) comprises three main units: the San Donato Unit, the Verbicaro Unit and the Mt. Cocuzzo sequence. These Middle Triassic-Miocene thick carbonate successions were interpreted by Grandjacquet (1962) and by Amodio-Morelli et al. (1976) as one whole tectonic "outgrowth" of the African foreland border through the overlying crystalline terrains. They are typical platform deposits up to the Norian, evolving to drowning conditions during the Rhaetian with the deposition of emipelagic sediments (Ietto and Ietto, 1998). Sub-greenschist to greenschist facies metamorphism of the San Donato succession is detected in the metapelite layers interbedded in the carbonatic sequence that, however, retain Mesozoic fossil content, as well as in the metabasites that crop out as dykes in the Anisian-Ladinian metasediments (Dietrich, 1976). The alkaline and transitional alkaline affinity of the basaltic protoliths and the related petrological considerations permit to indicate such products as precursors of oceanisation processes in the central Mediterranean area (Macciotta et al., 1986; Barca et al., 2010).

The intermediate "Liguride Complex" of Sila and Catena Costiera comprises oceanic-derive units, which according to Amodio Morelli et al. (1976) were divided into four different ones: Diamante-Terranova Unit, Malvito Unit, Gimigliano-Mt Reventino Unit and Malvito Unit. Later, Liberi et al. (2006) suggested grouping them all together because of their relatively similar tectono-metamorphic evolution (Figure 3b). The entire ophiolite sequence comprises: mantle-derived serpentinised ultramafic rocks that crop out in the area of Gimigliano-Mt Reventino (Figure 4a) closely associated with massive and foliated metabasites (Figure 4b), sometimes showing well preserved pillow structure as in the area of Malvito (Figure 4c); the fragmentary cover consists of pelagic sediments such as metaradiolarites and Calpionella meta-limestones (Figure 4d - Lanzafame and Zuffa, 1976; Spadea et al., 1976) and of flyschioid sediments represented by metapelites and metarenites of uncertain age and interpreted as proximal terrigenous deposits (Lanzafame et al., 1979). The age of magmatic protoliths is controversial: Colonna and Zanettin Lorenzoni (1972) suggest a Ladinian-Carnian age, whereas Amodio Morelli et al. (1976) indicate a Tithonian-Neocomian age. The geochemical features of the basaltic protoliths clearly attest a T-MORB affinity; serpentinites derive from harzburgitic-lherzolitic rocks (Liberi et al., 2006; Punturo et al., 2004). The mineralogical assemblages of metabasites and metapelites indicate a HP/LT metamorphism (De Roever et al., 1974; Dubois, 1976), with the metamorphic climax at pressure conditions ranging between 0.9 and 1.1 GPa at temperature of 350 °C (Piluso et al., 2000). The differences between the baric peaks in the outcrops that are displaced in the various areas of northern Calabria may be explained with the existence of tectonic slices inside an accretionary wedge (Figure 5, Cirrincione et al., 2002a). Structural analyses carried out suggest an Europe verging accretionary wedge connected to an eastward subduction of the oceanic lithosphere.

The upper "Calabride Complex" (Ogniben, 1973) consists of continental derived units; authors recognise three main tectono-metamorphic units: the basal one, mainly constituted by phyllites, known as Bagni Unit; this is followed by a mylonitic unit, known as Castagna Unit and, at the top of the complex, by the Sila Unit that includes metamorphic rocks

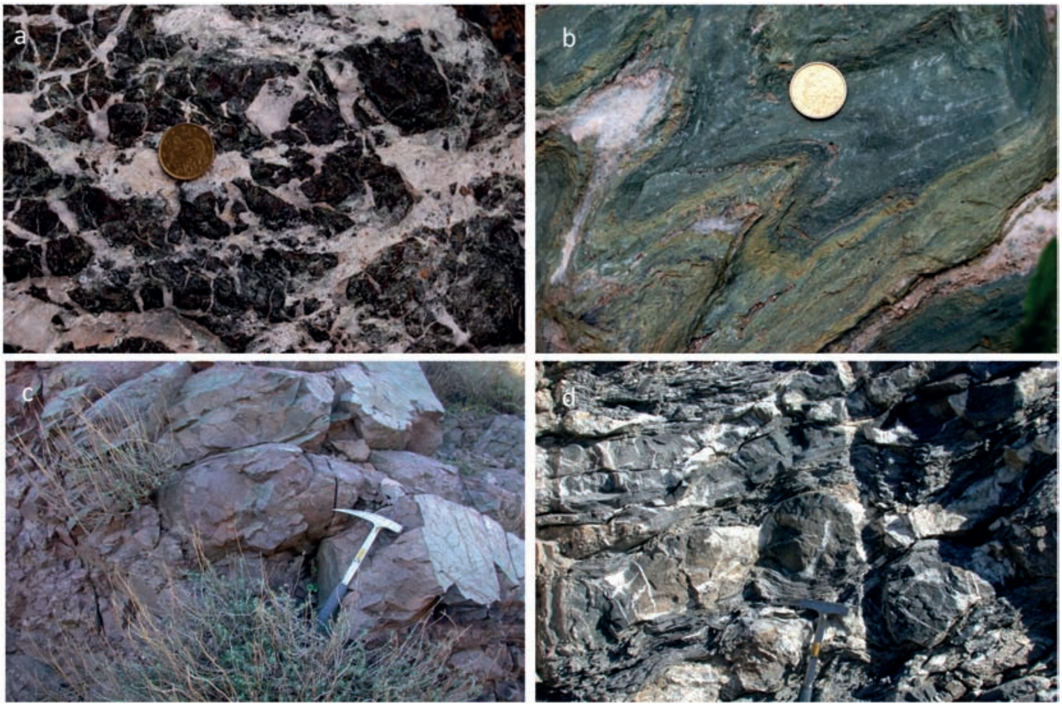


Figure 4. Main rock types of the Liguride complex: a) serpentinite from Mount Reventino area (southern Sila); b) metabasiti from Gimigliano area (south-eastern Sila; c) relics of pillow structures in metabasalts near Malvito village (northern Sila); d) metalimestone representing the cover of oceanic crust illustrated in (c).

equilibrated under metamorphic conditions ranging from granulite (Polia Copanello Unit of Amodio Morelli et al., 1976) to sub-greenschist facies, late Variscan granitoids (Graessner and Schenk, 2001) and their relative sedimentary cover (Longobucco Unit, Perri et al., 2008; Critelli, 1999; Zuffa et al., 1980 - Figure 6a).

In the past, the occurrence of a phyllitic unit at the base of the complex inspired a model accounting as an overthrow of the metamorphic complex. This was similar to the mainstream models of the first half of the XX century that used to interpret reverse metamorphic sequences as a result of huge folds, rooted in the adjacent oceanic basins (Figure 7).

However, serious doubts rise about the belonging of the Bagni phyllitic unit to the Calabride Complex: indeed phyllites with a Mesozoic cover in stratigraphic contact are observable only in a small area near to Guardia Piemontese (NW Calabria; Amodio Morelli et al., 1976); nevertheless, based on new field observations (Cirrincione, personal communication), these rocks are to be considered as the metamorphic basement of carbonate sequences ascribable to the Apennine Complex.

In other areas of Southern Sila and Catena Costiera, phyllites are closely associated to Calpionella limestones and to serpentinites (Piluso et al., 2000). This evidence indicates that these phyllites may derive from the metamorphism of the siliciclastic deposits of an ophiolite cover and may be therefore considered belonging to the Liguride Complex (Figure 6b -

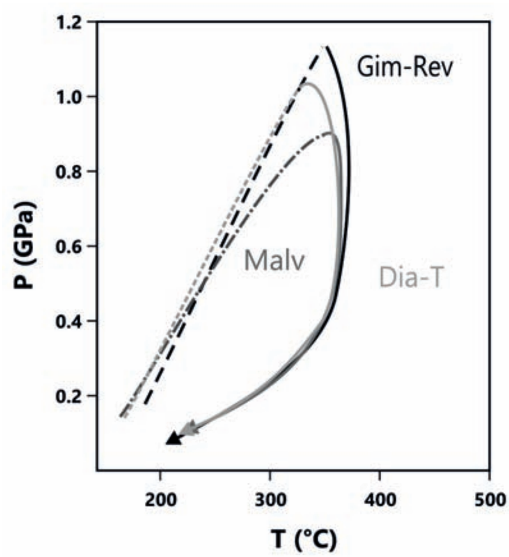


Figure 5. P-T paths of the different units of the Liguride complex (Malv = Malvito Unit; Gim-Rev = Gimigliano, Mt Reventino Unit; Dia-T = Diamante Terranova Unit).

Cirrincione et al., 2002 b).

The interpretation of the overlying Castagna Unit is controversial as well: this is formed by medium to high grade mylonitic gneisses cropping out in a discontinuous way at the western edge of the Catena Costiera, as well as at the southern edge of the Sila Massif (Figure 2c). It has been considered to be placed at the base of the granulitic-migmatitic gneiss of the Sila Unit (De Vuono et al., 2004). Detailed structural investigations at 1:10,000 scale performed along two geological NW-SE trending transects of the Sila Piccola Massif (De Vuono, 2005; Sacco, 2012), suggested as the shearing event involved various lithotypes at different crustal levels. These mylonites could be therefore considered as the product of a shearing event, which affected the granulitic-migmatitic gneiss, basic granulite, augen gneiss and granitoid rocks of deep and intermediate crust (De Vuono, 2005; Micheletti et al. 2011 - Figure 6b; 8a).

Undeformed leucocratic aplite-pegmatitic dykes linked to the final stages of late-Variscan magmatic activity in the Sila Massif crosscut the

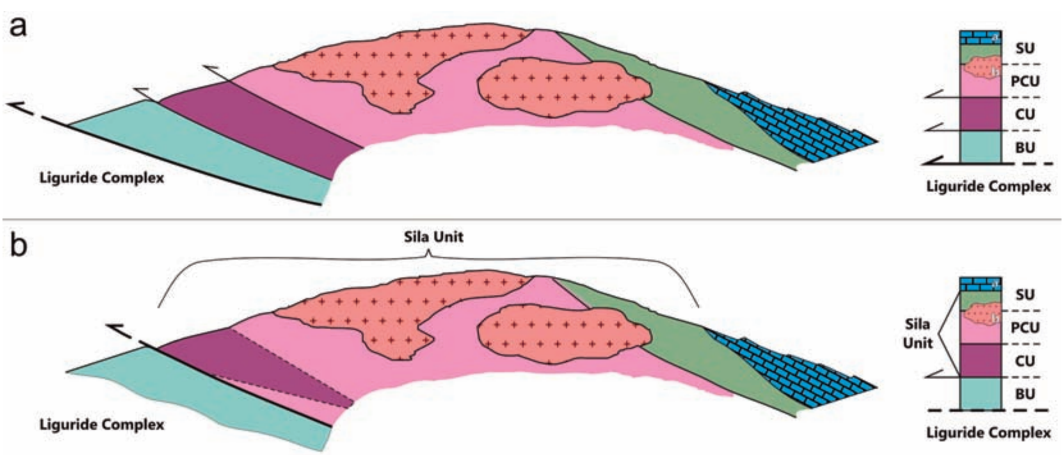


Figure 6. a) Old and b) new interpretation of the northern sector of the CPO (please see text for more details); (BU = Bagni Unit; CU = Castagna Unit; PCU = Polia Copanello Unit; SU = Stilo Unit).

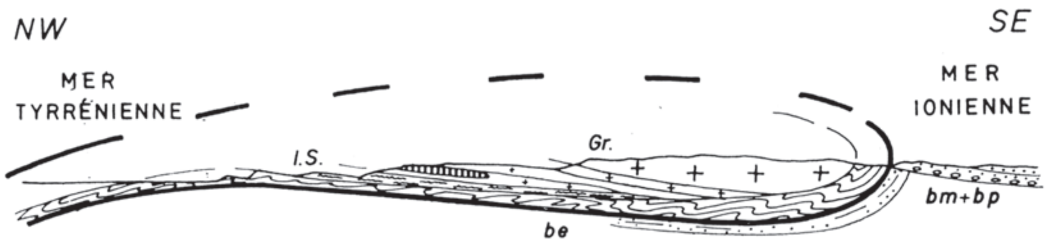


Figure 7. Tectonic structure of northern Calabria according to Limanowski (1913).

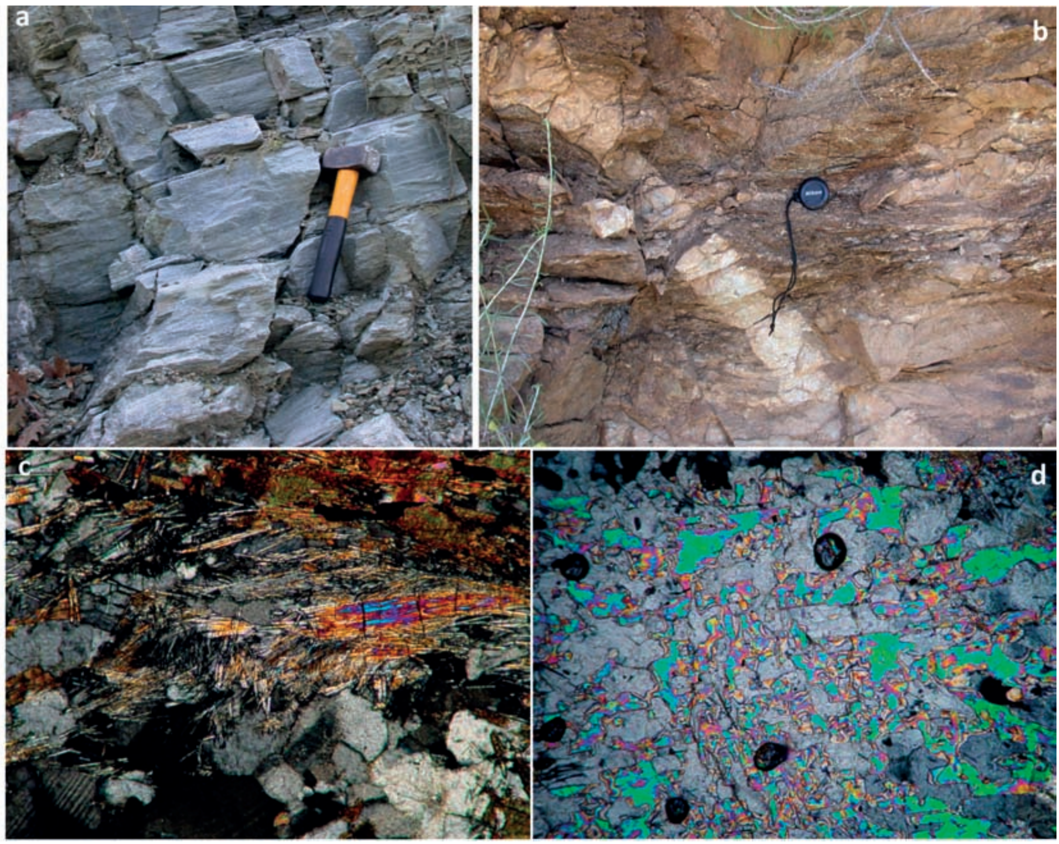


Figure 8. a) Mylonitic marbles of the Castagna Unit; b) aplitic dyke crosscutting mylonitic gneisses of the Castagna Unit; c-d) Photomicrographs of migmatitic gneisses from Sila Unit (Mt. Botte Donato) recording dehydration muscovite-out conditions. Field of view is 8 mm wide in c) and 5 mm wide in d) (crossed polars): c) sillimanite and plagioclase; d) white mica and K-feldspar .

mylonitic foliation, constraining the shearing event to late-Variscan tectonic activity (Figure 8b). In this scenario, the “Castagna Unit” can be interpreted as a late to post-Variscan extensional shear zone, locally re-activated during the building of the Alpine orogen (De Vuono et al., 2007), as supported by geochronological data (56 Ma; Borsi and Dubois, 1968).

The Sila Unit, at the top of the Calabride Complex, includes high grade gneisses intruded by late Variscan granitoids and by greenschist to amphibolite facies metamorphic rocks with Mesozoic cover. Two tectonic models are confronted: the first one suggested by Amodio Morelli et al. (1976) and by Lorenzoni and Zanettin Lorenzoni (1979; 1983) is complicated and assumes the existence of three different “Alpine crustal slices” of a nappe-pile edifice (Units of Polia Copanello, Mt Gariglione and Longobucco, respectively). The second model is simpler and was formerly proposed by Dubois (1970; 1976) and later remarked by Messina et al. (1991): it considers that the contacts at the two sides of the plutonic rocks are primary and not of tectonic origin. All of metamorphic and magmatic rocks may be considered as a whole Alpine unit, named “Sila Unit”. Graessner and Schenk (2001), support the continuity of “Sila Nappe” with petrological data, indicating it as a quite complete section of continental crust. The portion of exposed lower crust is represented by migmatitic metapelites, whose metamorphic peak conditions are of P = 0.6 GPa and T = 770 °C at the base and of P = 0.4 GPa and T = 740 °C at the top (Graessner and Schenk, 2001).

The lower crust cropping out in Catena Costiera represents deeper conditions than its analogous in Sila; metamorphic peak conditions are around 0.9-1.0 GPa at 800 °C (Piluso and Morten, 2004) and constituting lithotypes are migmatites and para-granulites, spinel-harzburgites and pyroxenites; small volumes of gabbros with tholeiitic affinity intrude at the contact between the lower crustal rocks and the mantle slices within a thinned continental crust. The P-T conditions of these small gabbroic bodies are of 0.6 GPa and 800 °C, suggesting they set out after the metamorphic peak, during a decompression stage (Figure 9). The fact that the intrusion took place within a thinned crust (about 18 km) during the exhumation stage, preserved gabbros from re-equilibration under granulite facies conditions. U-Pb LA-ICP MS zircon dating suggest a middle Permian or middle Triassic emplacement age that would be therefore associated with the continental rifting stage preceding Pangea fragmentation (Liberi et al., 2011). Such Permian-Triassic gabbros, marking the post-Variscan continental lithosphere thinning, can be considered as analogous of those ones exposed in both the Austroalpine and Sudalpine domains of the Alps (Rebay and Spalla, 2001 and reference therein). In stratigraphic continuity over the lower crust there is the complex of intrusive magmatic rocks forming the Sila Batholith (De Vivo et al., 1991 - Figure 9). This is a NW-SE elongated small batholith (ca 600 km^2), made of undeformed (45%) and foliated (15%) tonalites and granodiorites, two-mica granites (25%) and of small gabbro-diorite bodies (5%); minor volumes of porphyritic granites and aplite-pegmatite dykes also occur. The magmatic affinity is calc-alkaline with geochemical features suggesting a post-collisional geodynamic setting. Petrological investigations carried out by various Authors (Ayuso et al., 1994; Caggianelli et al., 1994) indicate that a simple fractionation model cannot explain the compositional variety neither among the different groups, nor within each group. Similarly to what supposed for other European batholiths, authors agree in considering that the Sila plutonic complex has a predominant crustal component with a variable contribution of magmas of mantle origin. Liotta et al. (2008) suggest magma emplacement along a shear zone and, by taking into account micro-

Figure 9. Geological sketch map of the Sila Massif (northern Calabria) with the main subdivisions of the Sila Unit rock types.

and meso- structure, define the succession of the magmatic pulses: porphyritic granites with large K-feldspars would be the first intruded magmas followed by tonalites, granodiorites and granites. The emplacement of gabbros and diorites is subsequent to the shearing event; the magmatic cycle is completed by aplites and pegmatites. By considering that U-Pb dating constrains the emplacement of foliated plutonic rocks to ~ 304-300 Ma (Graessner et al., 2000) and that undeformed dykes cutting the wall rock mylonitic foliation have been dated at ~ 280 Ma (Liotta et al., 2008), shearing was likely active during this time span. Moreover, the batholith construction also occurred in the same time span of ~ 20 Ma maximum. Rare andesite-dacite dykes close the late to post-Variscan magmatic activity (Romano et al., 2012).

The upper crust section comprises two units known in the literature as Bocchigliero Unit (sub-greenschist to greenschist facies) and Mandatoriccio Unit (greenschist to amphibolite facies; Bouillin et al., 1987; Acquafredda et al., 1988). They consist of metapelites together with either acidic and basic metavolcanites originated from sedimentary or volcanoclastic sequences. The history of polyphase metamorphism for this upper crust portion is very similar to that one proposed for other European complexes: the early metamorphic event dates ~ 330 Ma at middle pressure conditions (Acquafredda et al., 1991) and is followed by a late low pressure event dating ~ 299 Ma (Langone et al., 2010). In this scenario, the time of the thermal peak of the upper crust coincides with that one of the granulitic peak of the lower crust and with the emplacement of the granitoids.

Serre Massif

The Serre Massif occupies the central position of the Calabria-Peloritani Orogen. It is bounded on the north by the Catanzaro Line and extends southward to the Piana di Gioia Tauro, where the Palmi-Line separates it from the Aspromonte Massif. The Serre Massif mainly consists of a crystalline basement made up of Variscan metamorphic and plutonic rocks; a relatively well preserved Mesozoic sedimentary cover devoid of any Alpine metamorphism is present along the south-eastern side of the Massif along the Ionian coast (Figure 10a). The massif has been segmented into a number of dislocated sectors as an effect of the intense Alpine and Neogene tectonic reworking affecting the whole CPO; the main body, in the central part of the massif, runs with continuity from the line joining the towns of Curinga and Copanello to the north, to the town of Cittanova to the south. Another sector, important for its extension, occupies all of the Capo Vaticano Promontory and is separated from the main body by the Mesima graben (Figure 10a).

Early studies considered the Serre Massif formed as the result of the juxtaposition of several tectonic slices characterised by distinct tectono-metamorphic evolution that came into contact before the intrusion of the late Variscan granitoids (Colonna et al., 1973; Amodio Morelli et al., 1976; Borsi et al., 1976; Atzori et al., 1977; Del Moro et al., 1986). On the contrary, most authors now regard it as a nearly complete continental crustal section that showed a single tectonic evolution during most of the Variscan orogenic cycle (Schenk, 1980; 1984; Bonardi et al., 1984a; Thomson, 1994; Caggianelli et al., 2000a,b; 2007; Festa et al., 2003; 2012; Angì et al., 2010).The magmatic and metamorphic rocks forming the different levels of the original cross section of Variscan continental crust were exhumed during the Variscan orogeny to middle-upper crustal levels, where they cooled down more or less isobarically during the Mesozoic and were finally uplifted to the surface during the Cenozoic (Schenk, 1980). In this crustal section it is possible to distinguish three segments that crop out from the north-west to the south-east and are broadly representative of the lower, middle and upper crust, respectively: a) the lower crust portion, 7-8 km thick, which occupies the north-western sector of the massif and is composed by a basal granulitic complex, overlain by a migmatitic metapelite complex; b) the middle crust portion, 12 -13 km thick, in the central part of the massif, consisting of the late Variscan Serre Batholith; c) and, finally, the upper crust portion, in the southern part, made up of amphibolite to greenschist facies metapelites with interbedded metabasites (Figure 10b).

The lower crustal granulite complex (~ 2-3 km overall thickness) is composed of mafic granulites (Figure 11a), including basal metagabbros, with interleaved felsic granulites and rare fine grained metapelites (Figure 11b); the metagabbros are interpreted as basic magmatic rocks metamorphosed under granulitic conditions at 790 ± 30 °C and 800 MPa (Schenk, 1980) or,

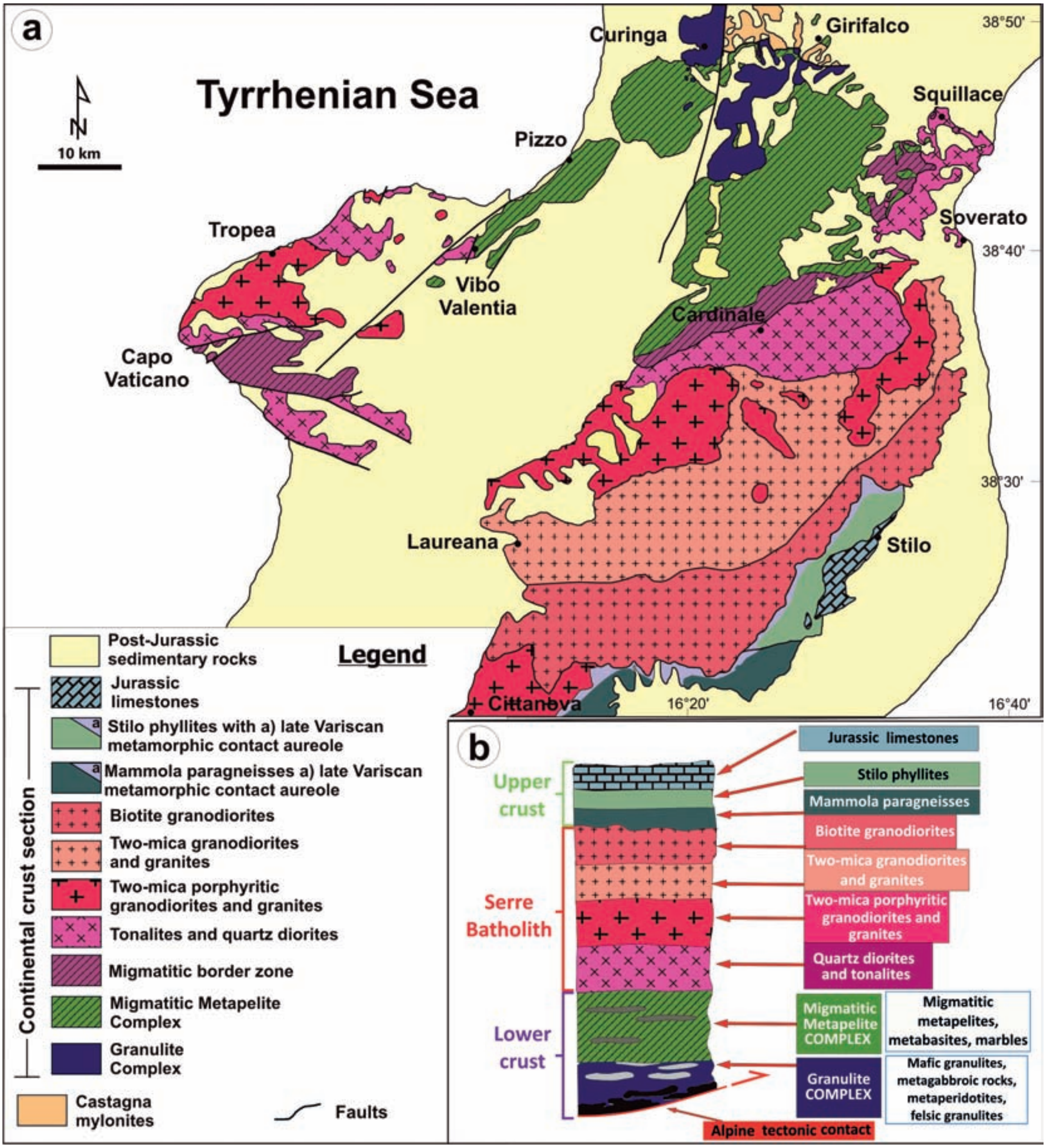


Figure 10. Geological sketch map of the Serre Massif and Capo Vaticano Promontory (after Fiannacca et al., and reference therein) with relative schematic lithological column for the Serre crustal section (modified after Festa et al., 2004).

according to Acquafredda et al. (2008), at 1 GPa and 900 °C (Figure 12). The overlying migmatitic metapelite complex (~ 5-6 km thick) comprises dominant migmatitic paragneisses (Figure10a) and lesser felsic granulites, with intercalated metabasites and rare marbles (Schenk, 1984;

Figure 11. a-b) Granulite complex rock types: mafic and felsic granulite, respectively; c) migmatitic gneisses of the migmatitic metapelite complex (Vibo Valentia Marina); d) Field occurrence of peritectic garnet in metapelites from the migmatite border zone (Capo Vaticano area) with d') close-up picture highlighting that garnet is always surrounded by leucosome patches; e) porphyritic two-mica granodiorites from Capo Vaticano promontory (Parghelia; Cirrincione et al., 2013b) with e') an enlargement highlighting the presence of ~ 6 cm-sized K-feldspar megacrysts ; f) enclave in biotite granodiorite from southern Serre Massif.

Acquafredda et al., 2006). P-T paths obtained by Acquafredda et al. (2006) for the migmatitic paragneisses at the top of the lower crustal section indicate peak P-T values of ~ 0.8 GPa at 700 °C, related to crustal thickening, followed by a multi-stage decompressional path (Figure 12). According to Caggianelli et al. (1991) the Serre lower crustal section was a pile of meta-arenites, or arenite-pelite mixtures, metapelites, metalimestones, and metavolcanic rocks intruded by the layered gabbros at about 553 Ma (Schenk 1980; Micheletti et al., 2008; Fornelli et al., 2011). This intrusion age has been recently questioned by Cirrincione et al. (2013 a), who have obtained preliminary SHRIMP U-Pb zircon data suggesting a possible mid-Ordovician or, even, late Carboniferous magmatic age of the metagabbro. In this regard work is still in progress, aimed also to verify if this basic magmatism could be correlated with that one typifying other Italian areas, such as the well known Ivrea-Verbano Zone (e.g., Peressini et al., 2007), but also the Catena Costiera, in the northern CPO (Liberi et al., 2011), where a late- to post-Variscan age is clearly documented.

The intermediate portion of the crust is entirely composed by the intrusive rocks of the Serre Batholith (Rottura et al., 1990; 1991) that, alike the Sila Batholith, has a relatively modest extension of about 1200 km^2, also including the granitoids from the Capo Vaticano Promontory. The batholith varies in composition from quartz diorite to leucogranite, with rare quartz-gabbro; biotite tonalites and weakly to strongly peraluminous granodiorites are the main rock

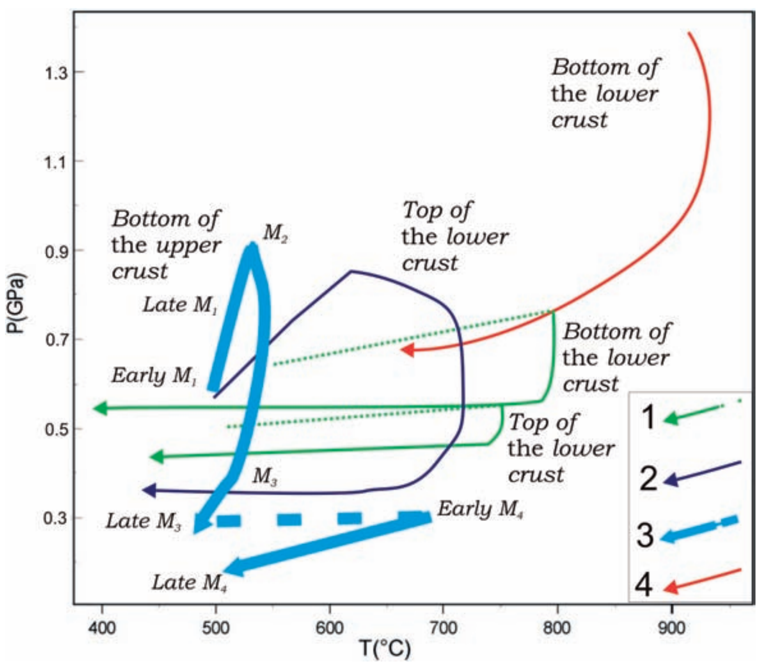


Figure 12 - Summary of P-T paths obtained for different portions of Serre Massif crustal section: 1) top and bottom portions of the lower crust (after Schenk, 1989); 2) top of the lower crust (after Acquafredda et al., 2006); 3) bottom of the upper crust (after Angì et al., 2010); 4) bottom of the lower crust (after Acquafredda et al., 2008).

types. Quartz diorites and tonalites occur close or at the contact with the lower crust portion while the more felsic rock types occur at shallower crustal levels. Similarly to the Sila Batholith, most authors agree that the emplacement of the plutonic rocks took place along ductile shear zones in an extensional regime (e.g., Rottura et al., 1990; Caggianelli et al., 2007; Angì et al., 2010), at depths ranging from ~ 23 to ~ 6 km (Caggianelli et al., 1997). In particular, the strongly foliated granitoids intruded earlier at somewhat deeper structural level, whereas the weakly foliated to unfoliated ones intruded later, in higher crustal domains (Rottura et al., 1990; Caggianelli et al., 2007; Angì et al., 2010). Preliminary AMS data, integrated with field and microstructural information on the different granitoid rocks reveal a magnetic fabric, indicating syntectonic crystallization, also for the apparently unfoliated granitoids, with no evidence for inferring an extensional regime (Fazio et al., 2014). The contacts between the batholith and the metamorphic host rocks are considered primary: the bottom contact is marked by a thick migmatite border zone characterised by the presence of quartz diorites containing xenoliths of the migmatitic paragneiss host rocks and peritectic garnet-bearing silica-rich melt deriving by partial melting of the same metapelites (Clarke and Rottura, 1994 - Figure 11 c,d,d'), while the top one by a well developed contact aureole (Figure 10a).

The granitoid rocks making up the Serre Batholith (Rottura et al., 1990; 1991; Fiannacca et al., 2015) can be grouped into two main suites: a) a dominant metaluminous to weakly peraluminous suite, representing more than 70% of the exposed granitoids, which includes quartz diorites, tonalites and biotite granodiorites (Figure 11e) and b) a strongly peraluminous association, consisting of two-mica ± Al-silicates granodiorites and granites, which also include strongly porphyritic types typified by K-feldspar megacrysts up to 10 cm in size (Figure 11 f,f'). The geochemical features of the granitoids are consistent with an origin of the batholith from the assembling of several batches of magmas derived by dehydration melting of different crustal sources of likely magmatic arc derivation, such as magnesian igneous rocks and sediments derived from their rapid dismantling (Fiannacca et al., 2015).

The upper crustal section, cropping out in the south-eastern Serre Massif, is characterised by the juxtaposition of two units separated by a low-angle tectonic detachment, which divides a lower metamorphic grade hanging wall complex (Stilo-Pazzano complex) from a higher metamorphic grade footwall metamorphic complex (Mammola paragneiss complex), both overprinted by contact metamorphism induced by the intrusion of the late Variscan granitoids (Figure 10a - Bonardi et al., 1987; Rottura et al., 1990; Angì et al., 2010; Cirrincione et al., 2012b; Festa et al., 2013). The uppermost Stilo-Pazzano complex (SPC), includes lower greenschist facies metapelites and minor metalimestones, quartzite and metavolcanic levels, unconformably covered by a composite Mesozoic sedimentary succession (Festa et al., 2003). The lowermost Mammola paragneiss complex (MPC), is formed by amphibolite facies paragneisses, leucocratic gneisses and amphibolites locally affected by a sub-vertical mylonitic foliation (Figure 13 a,b) microscopically characterised by clear recovery effects as indicated by the recrystallised pressure shadows of the s-type porphyroclasts, as well as by widespread relics of re-crystallized ribbon-like quartz (Figure 13 c,e). The metamorphic rocks from both complexes are locally intruded by late to post-Variscan felsic to mafic dykes (Figure 13d - Romano et al., 2011). P-T paths obtained by Angì et al. (2010) for the upper crustal paragneisses indicate a crustal thickening evolution analogue to that of the lower crustal metapelites, up to peak P-T conditions of 0.9 GPa at 530 °C, and a subsequent fast exhumation

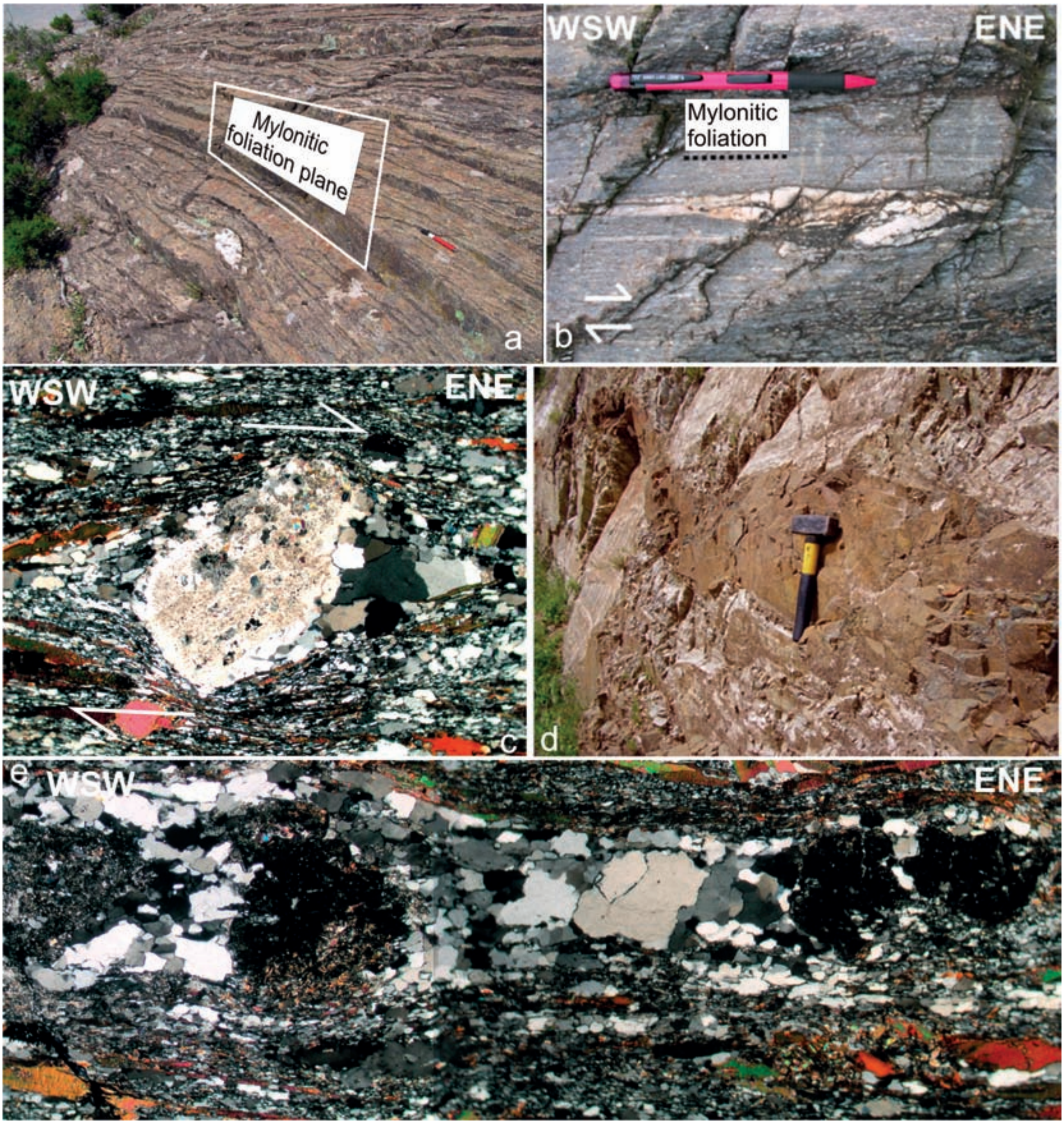


Figure 13. Lithotypes from the upper crustal levels of the Serre Massif: a) Field evidence of the locally developed late-Variscan subvertical mylonitic foliation; b) Asymmetric intrafoliar fold within late-Variscan mylonitic foliation highlighting a top to ENE sense of shear in the present-day geographic coordinates; c) s-type plagioclase porphyroclast indicating a top to ENE sense of shear characterized by pressure shadows with re-crystallized quartz (crossed polarizers 3.5 mm * 2.5 mm); d) Post-Variscan mafic dyke cutting the mylonitic foliation of the phyllite host rocks in the southern Serre Massif; e) Relic re-crystallized ribbon-like quartz level in mylonitic micaschist with garnet porphyroclasts (crossed polarizers 11 mm * 2.5 mm).

along a dominantly extensional shear zone which also favoured the emplacement of the granitoids, in turn responsible for late- to post-tectonic contact metamorphism in the upper crustal rocks (Figure 12). At its southern termination, the Serre Massif is in contact with a strongly peraluminous granite pluton, known as "Cittanova granite" (Hieke Merlin and Lorenzoni, 1972; Atzori et al., 1977; Crisci et al., 1979; D'Amico et al., 1982; Rottura et al., 1990; Graessner et al., 2000). In agreement with Bonardi et al. (1984 a,b) and Messina et al. (1988) this magmatic body, commonly considered as a single pluton, is instead likely composed by a northern portion belonging to the Serre Massif, where the granitoids are intruded in the greenschist facies rocks of the Stilo-Pazzano complex, and by a southern portion pertaining to the adjacent Aspromonte Massif, consisting of the granitoids emplaced within the migmatites of the Aspromonte Unit. The geological boundary between the Serre and Aspromonte Massifs here represented by the Cortaglia river strike-slip fault (Critelli et al., in press) is considered as the natural prosecution of the strike-slip mylonitic Palmi Shear Zone (Ortolano et al., 2013), delineating together the Palmi line (Figure 14).

Aspromonte Massif

The Aspromonte Massif occupies the southernmost edge of the Italian peninsula (Figure 2d, 15a) (Cirrincione et al., 2013c). It is separated from the Serre Massif by a complex strike-slip system, operating since the early Eocene up to the Tortonian, as testified by the mylonitic deep-seated shearing activity of the Palmi Shear Zone (Ortolano et al., 2013 - Figure 16). This is characterised in the present-day geographic coordinate by an average WNW-ESE attitude which can be followed in outcrop for about 1200 m inland before disappearing below a Tortonian siliciclastic formation (Tripodi et al., 2013 - Figure 16). Field evidence (Figure 17a) accompanied by Rb-Sr biotite ages (Prosser et al., 2003) suggest mylonitic shearing activity at about 56-51 Ma. Structural analysis of mylonitic rocks, consisting of an alternance of mylonitic-skarns and mylonitic-migmatitic paragneisses (Figure 17 b,c), highlighted that the average attitude of the sub-vertical foliation as well as the stretching lineation range from W-E, to NW-SE with a transport direction top-to-E, SE in the present-day geographic coordinates (Ortolano et al., 2013).

Contrasting interpretations about the geological framework of the Aspromonte Massif can be summarized in two hypotheses. The first hypothesis, proposed by Bonardi et al. (1984 a,b; 1992), Graessner and Schenk (1999) and Messina et al. (1990; 1992) considers the Aspromonte Massif composed of three tectonic slices as follows: the Variscan low greenschist- to amphibolite-facies Stilo Unit at the top; the Variscan amphibolite-facies Aspromonte Unit in intermediate geometrical position, partly to totally re-equilibrated during the Alpine orogenesis (e.g., area of the sanctuary of Madonna di Polsi; Bonardi et al., 1984a; Platt and Compagnoni, 1990); the lowest greenschist-facies metapelite tectonic slice, characterised by Variscan metamorphism with an Alpine overprint; this last slice crops out into two tectonic windows near to the villages of Cardeto and Africo (Figure 15a). The sequence cropping out in the Cardeto area was considered the northern termination of the Mandanici Unit that outcrops in Sicily in the same structural position (Bonardi et al., 1980b; Graessner and Schenk, 1999). Conversely, according to Pezzino et al. (1990; 1992; 2008); Ortolano et al. (2005); Fazio et al. (2008; 2010; 2015a), and Cirrincione et al. (2008b, 2009), the geological framework of the Aspromonte Massif is the result of the stacking of: a) the Stilo Unit, as it was defined by previous Authors; b) the intermediate Aspromonte Unit, mostly corresponding to the Aspromonte Unit of the previous Authors, which also crops out in

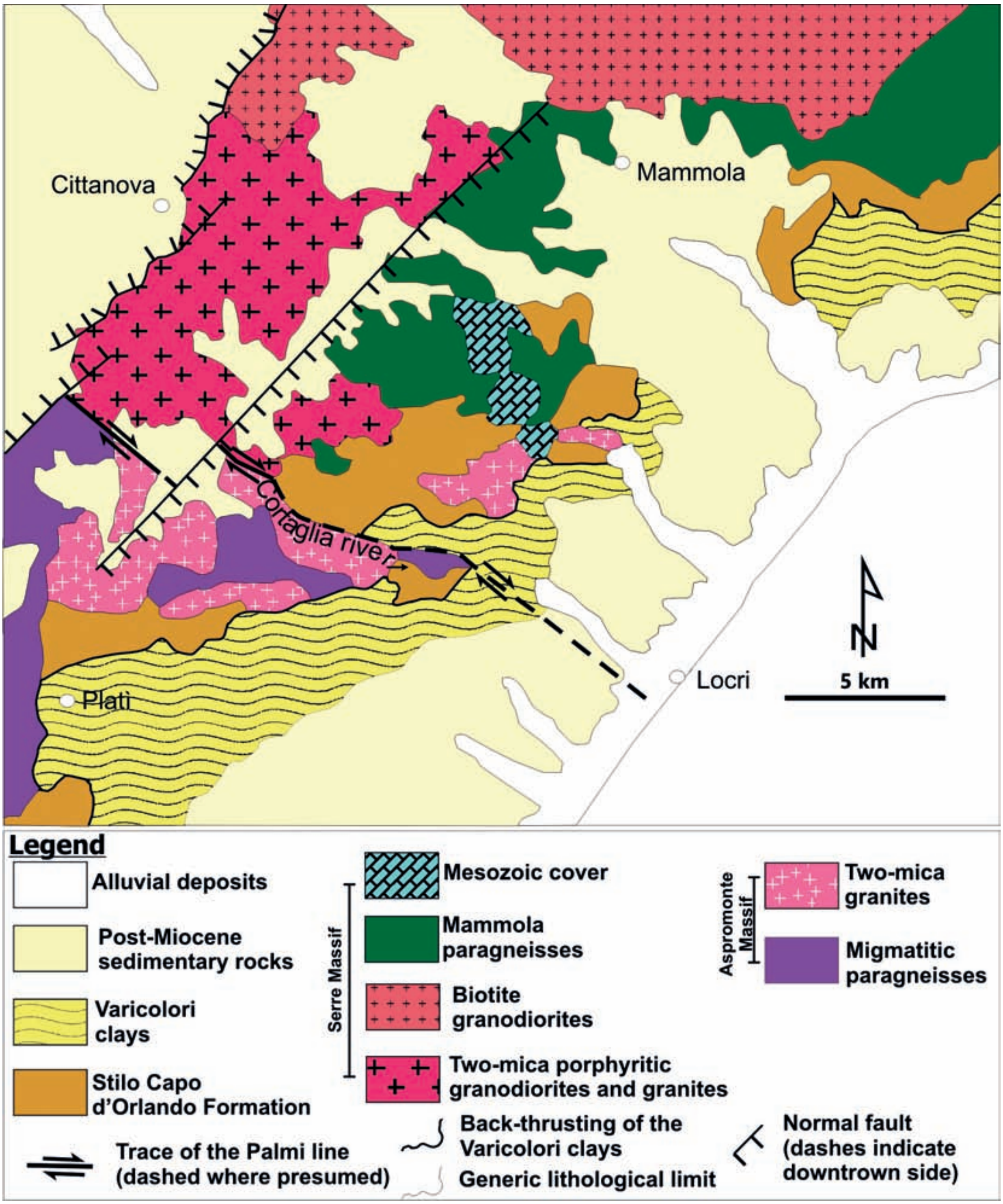


Figure 14. Geological sketch map of the boundary between Serre and Aspromonte Massifs along the Cortaglia River.

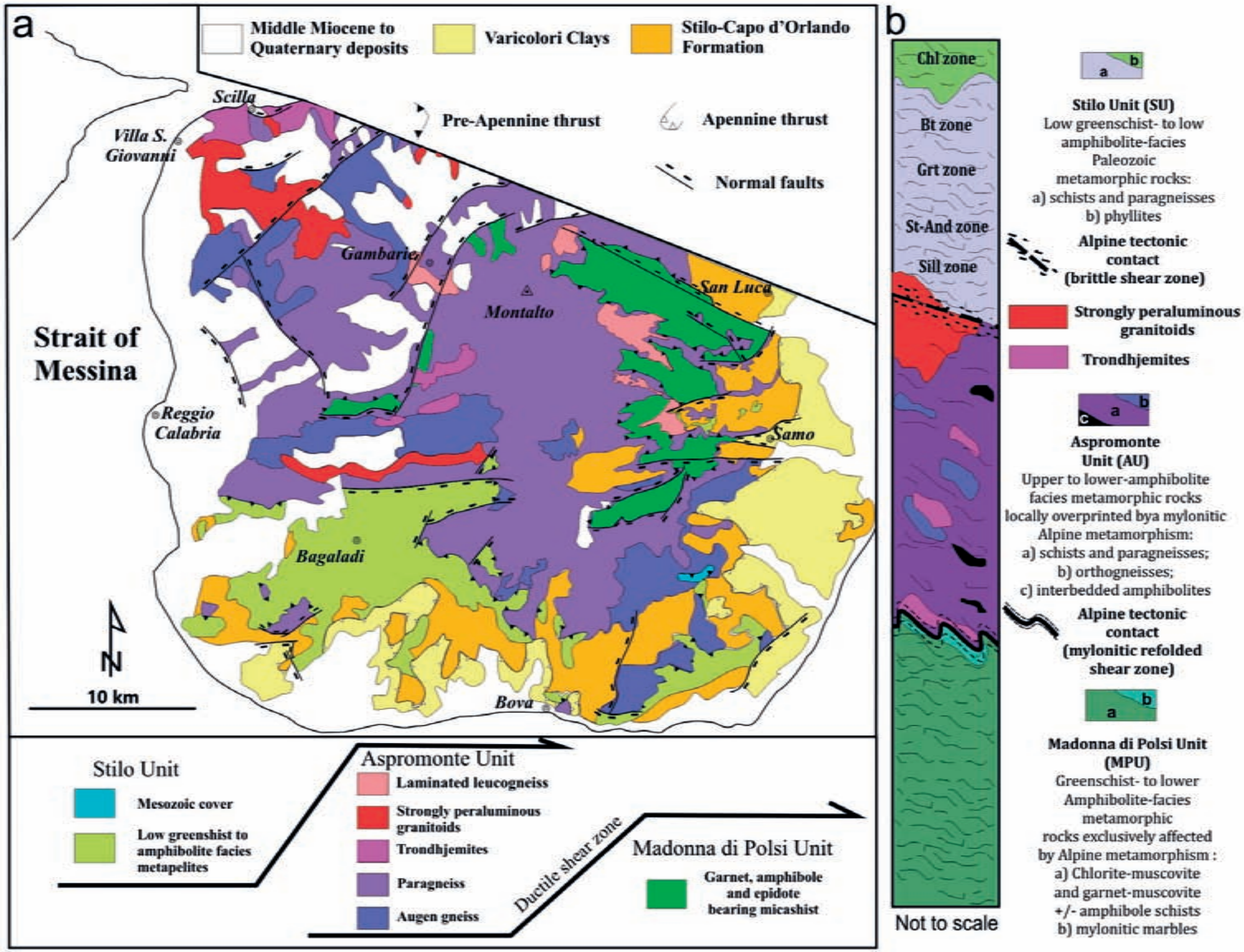


Figure 15. a) Geological sketch map of the Aspromonte Massif nappe-like edifice with b) relative tectono-stratigraphic column (after Ortolano et al., 2015 modified).

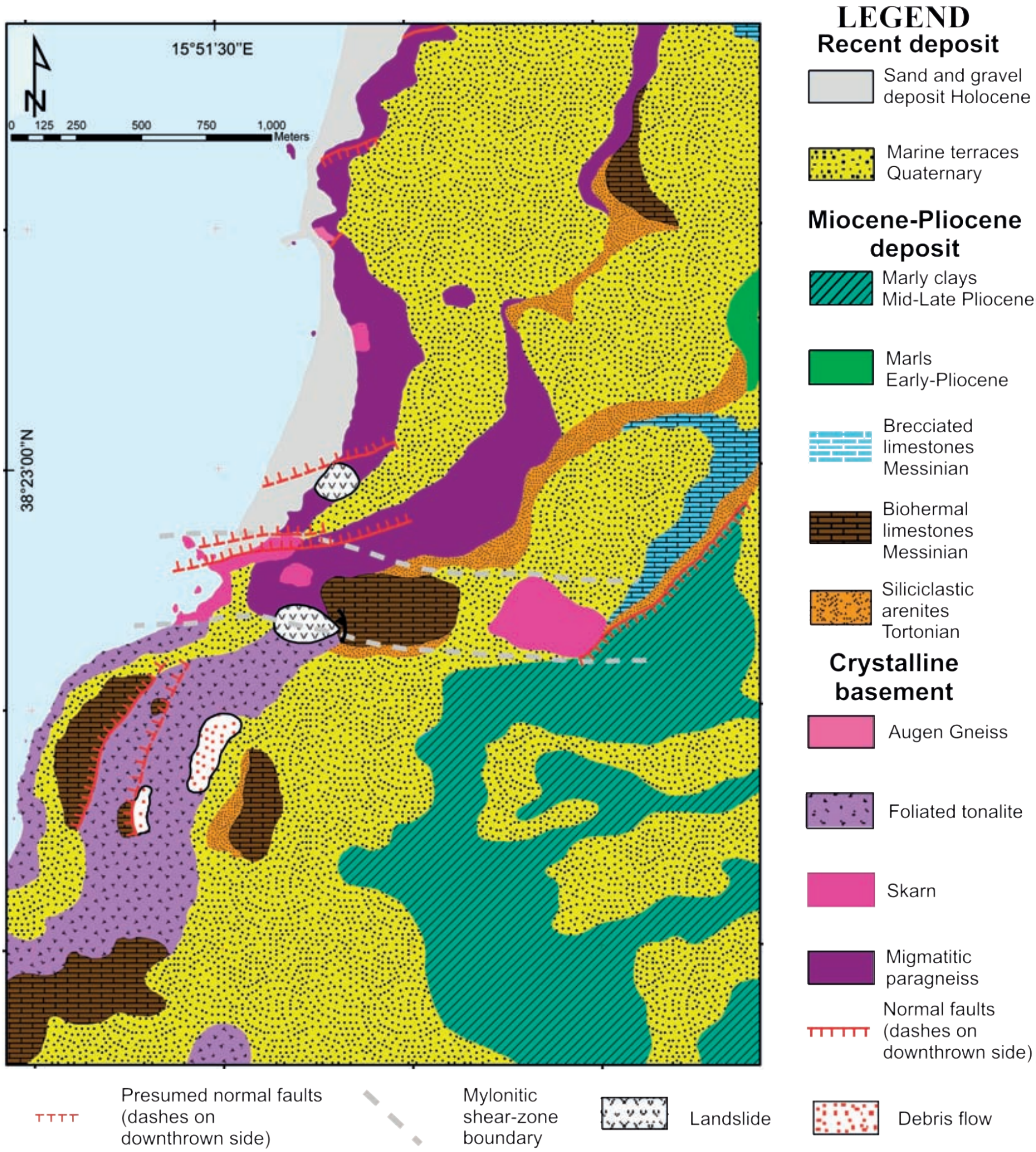


Figure 16. Geological sketch map of the Palmi area with location of the mylonitic Palmi Shear Zone (after Ortolano et al., 2013 modified).

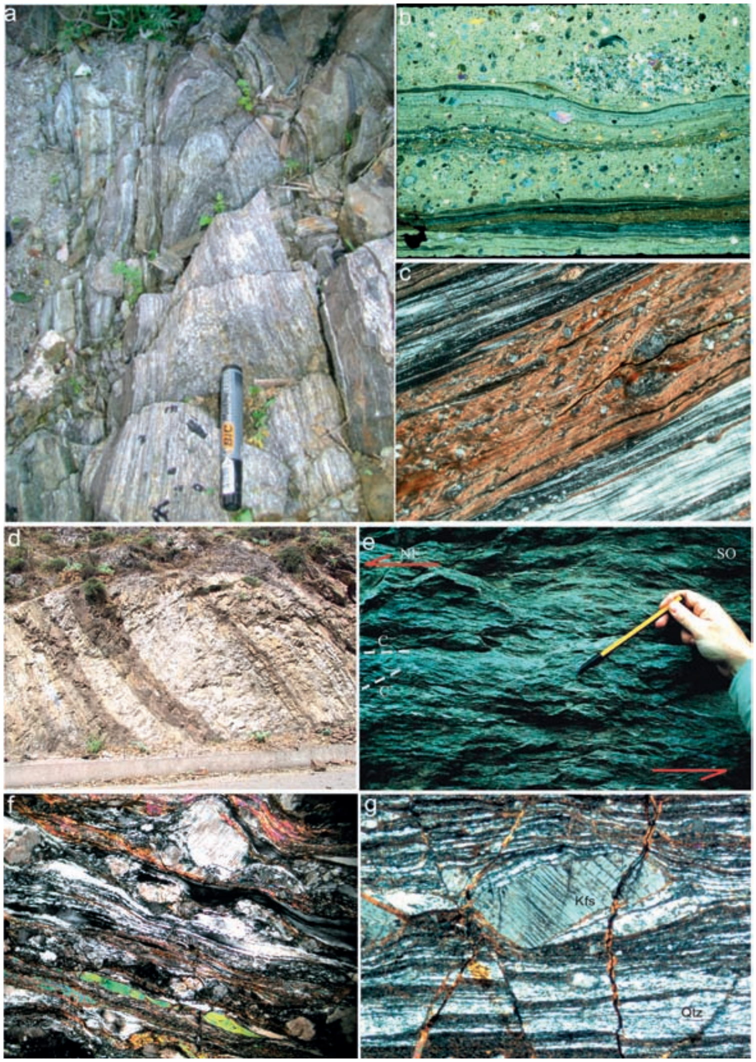


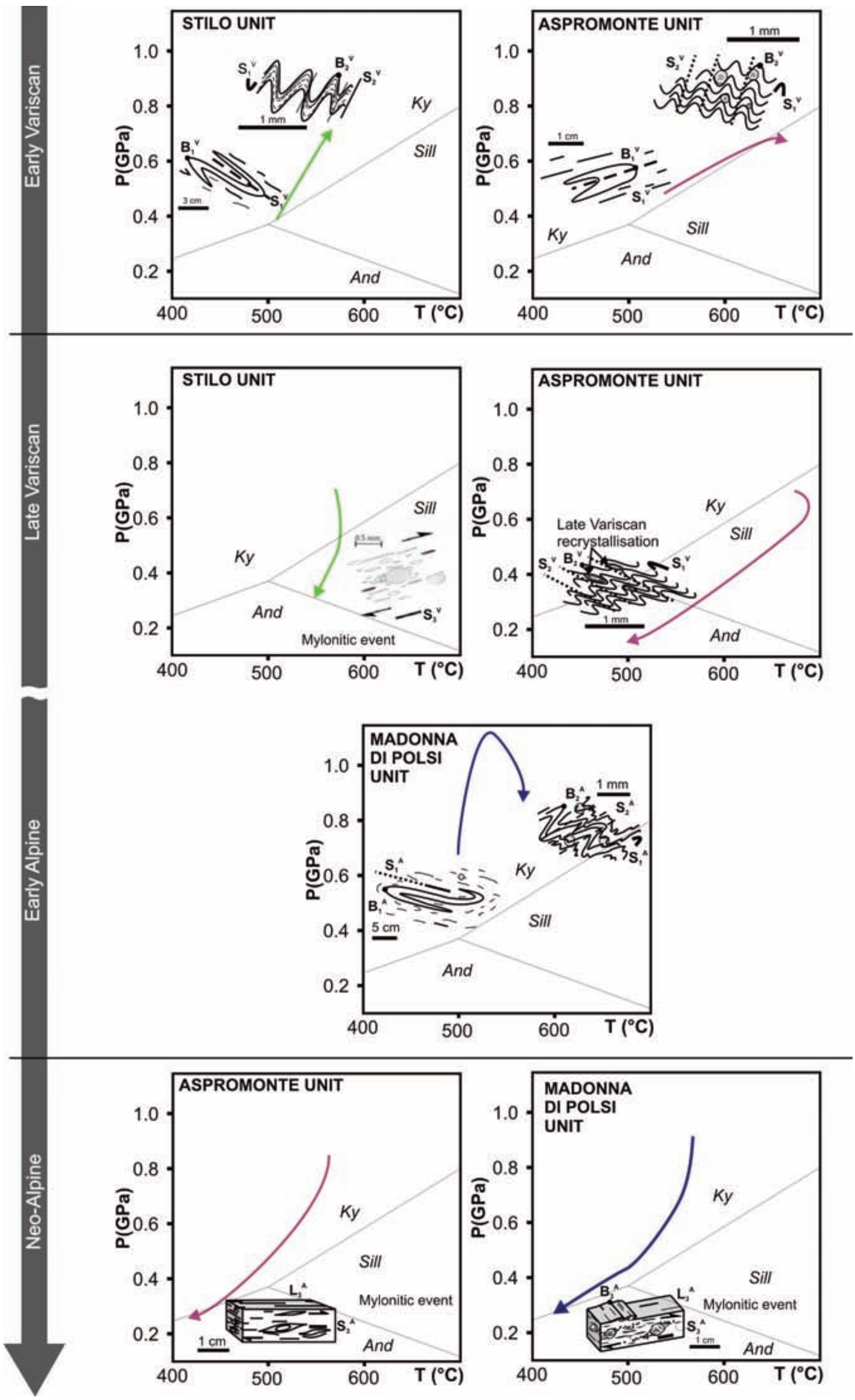
Figure 17. a) Sheath fold in mylonitic tonalite of the Palmi Shear Zone (after Ortolano et al., 2013); b) High resolution thin section scan (crossed polarizers 3.5 cm * 2.5 cm) of the mylonitic skarns developed along the Palmi Shear Zone; c) Microphotograph (crossed polarizers 3.5 mm * 2.5 mm) of mylonitic migmatitic paragneiss highlighting the alternance between the ribbon-liked leucosome levels and the melanosome, at present characterized by the development of SC-type structures and sigma-type feldspar porphyroclasts; d) Alternance between mylonitic laminated leucogneisses and mylonitic paragneisses of the Aspromonte Unit, highlighting the folding of the original mylonitic foliation; e) S-C-C' type structure in mylonitic micaschist of the Madonna di Polsi Unit indicating a top to NE sense of shear in the present-day geographic coordinates; f) Microphotograph (crossed polarizers 2.8 mm * 2 mm) of a mylonitic paragneiss of the AU, the main assemblage is given by K-feldspar, plagioclase, white mica and quartz; g) Microphotograph (crossed polarizers 1.8 mm * 1 mm) of a mylonitic leucogneiss overprinted by brittle micro-normal faults showing a K-feldspar porphyroclast enveloped by a quartz micaceous matrix (Fazio et al., 2015b).

the Peloritani Mountains; c) an underlying metamorphic sequence, exclusively affected by an entire Alpine orogenic cycle (Ortolano et al., 2005), not completely recorded in the rocks of the overhanging unit (Figure 15b). This sequence crops out in the three tectonic windows, which were named after the localities where they surface (i.e. Cardeto and Africo villages as well as the area of Madonna di Polsi). Compared to the interpretations of the first group of authors, the sequence corresponds to the Variscan metapelite sequences cropping out in the Africo and Cardeto tectonic windows, together with the re-equilibrated Alpine zone of the Aspromonte Unit (Bonardi et al., 1984a; Platt and Compagnoni, 1990).

The above interpretations suggest, for the southern sector of the Calabria Peloritani Orogen, two different tectonic frameworks which can be synthesized as follows: a) it represents a stacked structure of several basement rocks linked to the Variscan cycle, locally reworked (in part to totally) in an extensive Alpine shearing phase during late Oligocene - early Miocene orogenic exhumation (Platt and Compagnoni, 1990; Heymes et al., 2008; 2010); or b) it is the result of a complete Alpine orogenic cycle, involving either Variscan basement rocks and Mesozoic sedimentary sequences (Ortolano et al., 2005; Fazio et al., 2008). In this context, Pezzino et al. (2008) propose for southern Calabria a new simplified geological model based on new structural, petrological and thermobarometric data, where the lowest succession is unified into the sole Madonna di Polsi Unit (MPU). The resulting geological scheme, according to Pezzino et al. (1990; 2008), Ortolano et al. (2005), Cirrincione et al. (2008a,b), and Fazio et al. (2008), envisages, in the Aspromonte area, the presence of three polyphase metamorphic units: the uppermost Stilo Unit (SU) at the top, the intermediate Aspromonte Unit (AU), and the basal Madonna di Polsi Unit. The uppermost Stilo unit is made up of low greenschist- to low amphibolite-facies Palaeozoic metamorphic rocks (Crisci et al., 1982; Bonardi et al., 1984; Graessner and Schenk, 1999). Late Variscan magmatic bodies intruded into the metapelites produced a contact aureole (biotite, muscovite and andalusite blastesis). The SU lies along a brittle tectonic contact over the Aspromonte-Peloritani Unit, which is made up of amphibolite-facies Palaeozoic rocks locally intruded by late Variscan strongly peraluminous intrusive bodies (ca. 303-300 Ma; Graessner et al., 2000; Fiannacca et al., 2008), both locally overprinted by an Alpine mylonitic metamorphism which developed at about 25-30 Ma (Figure 17d) (Bonardi et al., 1987). A thick mylonitic horizon marks the tectonic contact between the AU and underlying low- to middle- grade metamorphic rocks of Madonna di Polsi Unit (Figure 17e). A siliciclastic succession, Late Oligocene to upper Miocene in age, known as "Stilo-Capo d'Orlando Formation" covers, with angular unconformity, the nappe edifice, sealing at times previously formed tectonic contacts. The back-thrusting of the Varicolori clays marks the final stage of the syn-sedimentary tectonic activity (Cavazza et al., 1997). According to the structural investigations by Fazio et al., (2015a) and Ortolano et al., (2015) the uppermost basement units of the nappe edifice (i.e. the Stilo Unit) underwent a mono-orogenic Variscan metamorphic cycle, characterised by an isoclinal folding deformation, with formation of a pervasive axial plane schistosity, followed by a microcrenulation associated with prograde PT conditions ranging in pressure from ~0.35 to ~ 0.7 GPa for a temperature spanning from ~ 480 to ~ 550 °C. (Figure 18 - Fazio et al., 2012). Pressure of 0.7 GPa and temperature of 570 °C values were obtained for the peak metamorphic conditions reached in this area, successively followed by a retrograde evolution caused by the development of a deep-seated shearing activity locally producing a pervasive mylonitic foliation, which is often obliterated by the static effects ascribable to the emplacement of the late-Variscan granitoids (Figure 18). On the basis of the available geological data, the exhumation of the SU can be solely attributed to the effects of a thin-skinned tectonics, coeval with the development of the south-eastward thrusting activity testified by tectonic contacts exclusively marked by cataclastic horizons, with no evidence of post-Variscan mylonitic activity. By contrast, the contact between the two lowermost tectonic basement units (i.e. AU and MPU), although similarly characterised by the presence of a thick cataclastic horizon, also shows a clear evidence of a weak to strong pervasive mylonitic structure, well preserved in the rocks of both units (Pezzino et al., 1990; Ortolano et al., 2005). The pervasiveness of the mylonitic deformational stage mostly prevented the preservation of the pre-mylonitic structures, which are indeed only rarely observable at the micro-scale in the AU, as survived inclusion trails assemblages in Variscan garnet (Cirrincione et al., 2008b), or rarely detected at the outcrop scale in the MPU rocks as relic isoclinal folds within late Alpine mylonitic foliation. According to Cirrincione et al. (2008b) the pre-mylonitic prograde PT paths of these two units indicate two different evolutions: a) the MPU prograde path is characterised by a HP-LT trajectory ranging from 0.95 to 1.25 GPa at temperature ranging from 400 to 600 °C (Figure 18), related to crustal thickening which, according to Puglisi and Pezzino (1994) and Cirrincione et al. (2008a), occurred during an early Alpine deformational episode: b) a Barrovian-type prograde path is instead characteristic of the AU rock-types, with temperature estimates ranging from 650 to 675 °C at relatively low pressure conditions of 0.4-0.5 GPa (Ortolano et al., 2005, Cirrincione et al., 2008a) ascribable to an early Variscan tectono-metamorphic evolution, followed by a final widespread episode of hydration under decreasing temperatures (480 °C), probably caused by the massive emplacement of the late-Variscan granitoids at about 300 Ma (Figure 18 - Rottura et al., 1990; Graessner et al, 2000; Fiannacca et al., 2008). The subsequent deformational stage led to the formation of pervasive mylonitic foliation (Figure 17 d,f) in both the AU and MPU rocks, as well as to the development of a pervasive stretching lineation averagely trending SW-NE, with kinematic indicators consistent with top to NE sense of shear in the present-day geographic coordinates (Pezzino et al., 2008). Mylonitic foliation evolved in both units to an isoclinal folding deformation, putting into evidence as the two units have undergone the same deep-seated shearing event. MPU and AU rocks were then involved in the formation of centimeter to decameter up to hectometer sized SSE-SE asymmetric folds before being finally exhumed along a joint brittle tectonic contact. This compressional tectonic activity was often accompanied by the activation of a brittle strike-slip tectonics which locally re-activated relics of the early Alpine deep-seated strike-slip tectonics, which are only rarely preserved (e.g., Palmi Shear Zone; Ortolano et al., 2013). The reconstructed tectonic activity terminates with the activation of a normal fault system that marks the switch from a compressional to an extensional regime (Cirrincione et al., 2008b; Fazio et al., 2015b). This last deformational system is delineated by the presence of widespread high-angled joint systems, spanning from microscopically sized joint system network (Figure 17g - Fazio et al., 2015b), passing from decimeter-sized fracture cleavage to arrive to kilometer-sized horst and graben structures averagely oriented WNW-ESE and WSW-ENE, linked to the main present-day seismogenic structural systems (Catalano et al., 2008; Morelli et al., 2011).

Peloritani Mountain Belt

The Peloritani Mountain Belt, in NE Sicily, represents the southernmost sector of the



Early Variscan
Late Variscan
Early Alpine
Neo-Alpine
STILO UNIT
ASPROMONTE UNIT
MADONNA DI POLSI UNIT
P(GPa)
T (°C)
Ky
Sill
And
Late Variscan recrystallisation
Mylonitic event
1 mm
1 cm
3 cm
5 cm

Calabria-Peloritani Orogen (Figure 2). It is bounded on the south by the Taormina Line, whose meaning is still widely debated: originally interpreted as a dextral strike-slip fault (Bonardi et al., 1976; Amodio Morelli et al., 1976), it is now likely considered to represent a thrust front displaced as a consequence of the anti-clockwise rotation of the entire orogen (Ghisetti et al., 1982; 1991). The belt is a south-verging nappe edifice, formed by a set of tectonic units made of a pre-Alpine basement, with local Alpine overprints and Mesozoic covers (Figure 19a). It may be subdivided into two complexes with different tectono-metamorphic evolution (Cirrincione et al., 1999; Atzori et al., 2001). The Lower complex, located in the south-eastern sector of the mountain belt, consists of sub-greenschist facies Variscan Palaeozoic sequences with unmetamorphosed Mesozoic covers. The Upper complex, in the north-eastern sector, is made of low to medium-high grade Variscan basement with interbedded slices of fragmental Mesozoic covers, locally affected by a metamorphic Alpine overprint that produced belts of cataclastic to mylonitic rocks and, locally, pseudotachylites (Figure 19b; Cirrincione et al., 2012a). The Stilo-Capo d'Orlando formation seals the contacts between the tectonic units, postdating the main nappe emplacement. The Lower complex consists of three tectonic units (St. Andrea Unit, Taormina Unit and St. Marco d'Alunzio Unit) sharing the same sub-greenschist facies basement (Lentini and Vezzani, 1975; Pezzino, 1982; Acquafredda et al., 1994; Ferla et al., 2000; Trombetta et al., 2004; Cirrincione et al., 2005; Somma et al., 2013). They are mostly composed of metapelites and metapsammites with interbedded metabasites of volcanic and volcanoclastic derivation and with subordinate metacarbonates. Metamorphic conditions are estimated below the chlorite isograd ($T \leq 350$ °C, $P \geq 0.2$ GPa; Atzori, 1970; Atzori and Ferla, 1992). The Upper complex comprises two units: the Mandanici Unit and the overlying Aspromonte Unit. The tectonic contact between the two units, marked by a thick cataclastic horizon with widespread remnants of mylonitic relics zones, suggests that the juxtaposition of the two units took place in a ductile environment (Messina et al., 1990; Atzori et al., 1994). The Mandanici Unit (Ogniben, 1970; Atzori and Vezzani, 1974) consists of greenschist to lower amphibolite facies rocks; prevailing lithotypes are phyllites and phyllitic quartzites (Figure 20a) with interbedded levels of metabasites and subordinate marbles and calc-schists. Evidence of a clockwise P-T evolution, with peak estimates of 0.9 GPa and ~ 530 °C is considered consistent with a Variscan crustal thickening stage at middle-lower crustal conditions, followed by a retrograde trajectory (constrained at 0.30-0.60 GPa and 420-460 °C) associated to exhumation (Fiannacca et al., 2012). A Mesozoic sedimentary succession, known as "Alì sequence" (Atzori, 1968) and characterised by a weak Alpine metamorphism (Figure 20b), occurs either at the bottom of the unit and as tectonic slices within the Variscan basement, mainly in proximity of the tectonic contact with the overlying unit (Ferla and Azzaro, 1976; Cirrincione and Pezzino, 1991; 1994; Cirrincione et al., 2012a). The anchimetamorphic rocks of the Alì sequence exhibit a succession of

Figure 18. PT path trends of the crystalline basement units of the Aspromonte Massif nappe edifice subdivided into prograde and retrograde trajectories along the temporal scale of the Variscan and Alpine orogenic stages (PT constraints from Cirrincione et al., 2008 and Fazio et al., 2012). S = foliation; L = lineation; B = fold axis; numbers in pedicle represent the sequence of the deformational events, while apex A or V is for Alpine or Variscan, respectively.

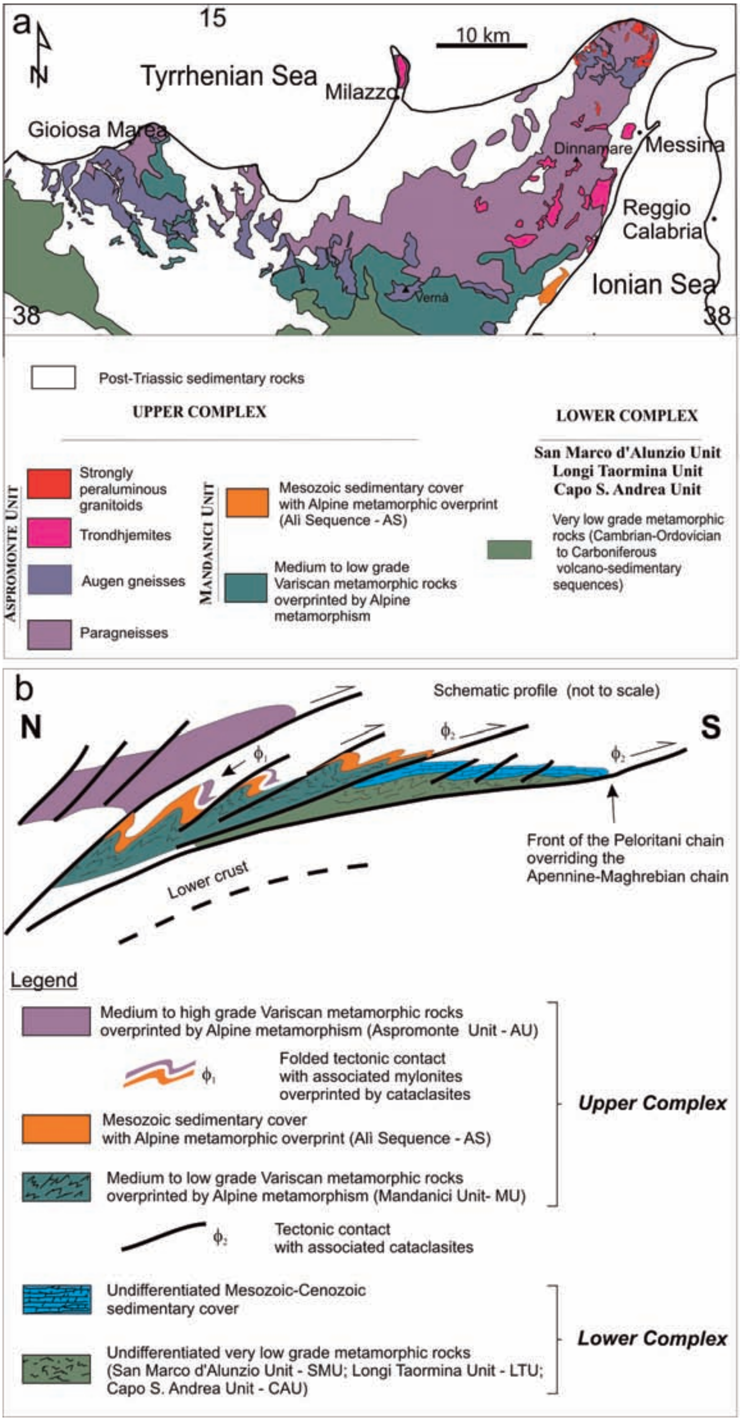


Figure 19. a) Geological sketch map of the Peloritani Mountain Belt with relative b) tectonic scheme of the nappe edifice (modified after Cirrincione et al., 2012a).

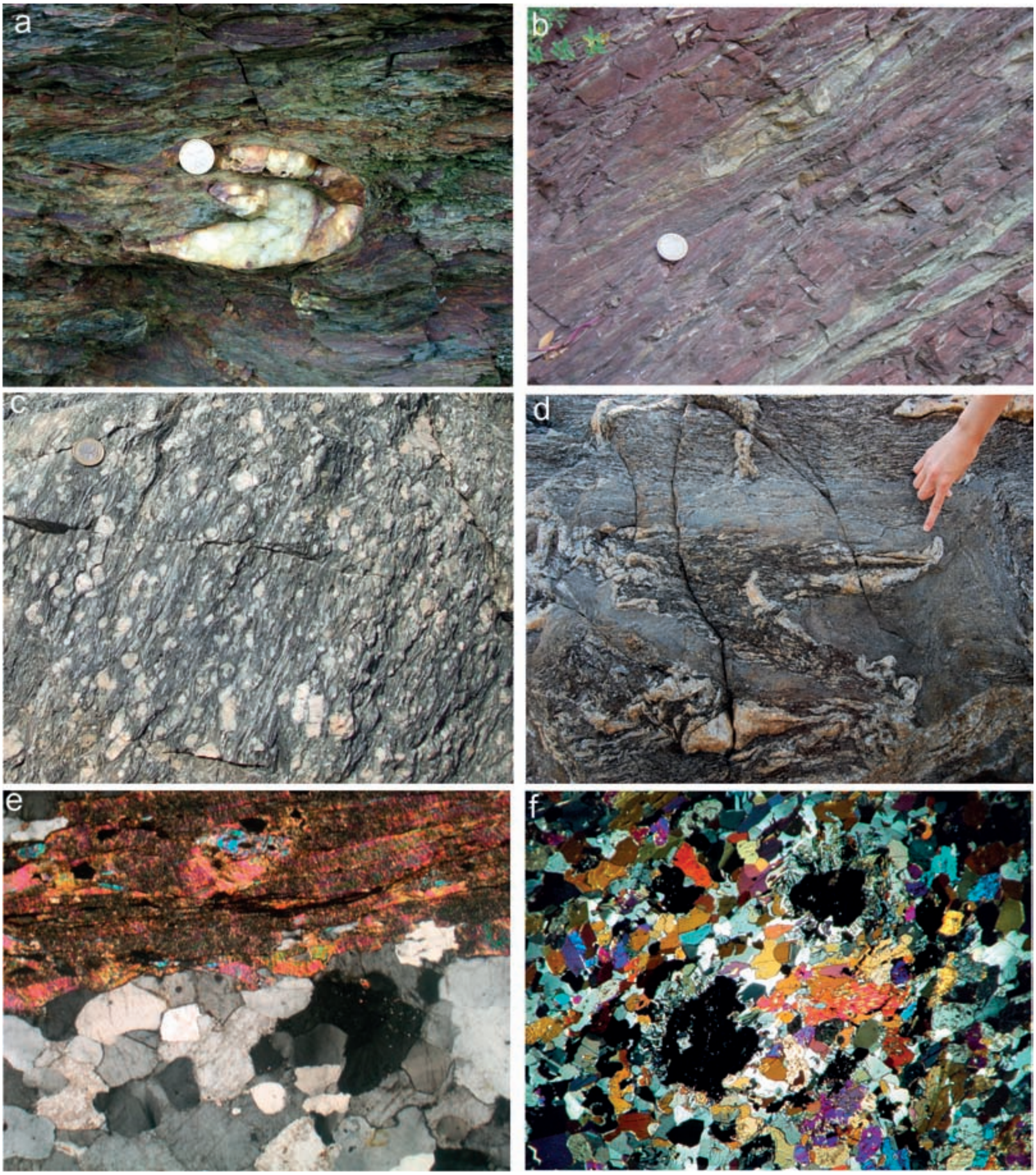


Figure 20. a) Third-type interference figure produced by Alpine isoclinal refolding of Variscan isoclinal fold in phyllites from the Mandanici Unit; b) Metaradiolarites of the Alì sequence; c) Mylonitic augen gneisses from the Aspromonte Unit in the western Peloritani; d) Folded leucosomes in migmatitic paragneisses of the Aspromonte Unit (Capo Rasocolmo); e) Plagioclase-hornblende coronitic symplectites replacing garnet porphyroblasts in amphibolite of the Aspromonte Unit. Field of view 10 mm wide. f) Sillimanite-free, biotitic melanosome and associated trondhjemite leucosome from a metatexite migmatite of the Aspromonte Unit documenting water-fluxed melting of the original paragneiss (after Fiannacca et al., 2005b). Field of view 6 mm wide.

deformational phases perfectly matching the Alpine ones in the phyllites of the Mandanici Unit; this led Cirrincione and Pezzino (1994) to interpret this sedimentary sequence as a remnant of the original cover of the Mandanici Unit. Both the Mandanici Unit and the Alì sequence were involved in the Alpine orogenic cycle (Cirrincione and Pezzino, 1991; Pezzino et al., 2008; Cirrincione et al., 2012a) documented by Neo-Alpine sub-greenschist to greenschist metamorphic assemblages dated at 26 ± 1 Ma (white mica Rb-Sr ages; Atzori et al., 1994). The Aspromonte Unit represents the highest tectonic unit of the Peloritani nappe edifice. Similarly to the adjacent Aspromonte Massif, it consists of amphibolite facies metamorphic rocks, mainly represented by paragneisses, migmatitic paragneisses and augen gneisses (Figure 20c), with minor marbles and amphibolites, diffusively intruded by late Variscan granitoid plutons (D'Amico, 1979; Paglionico and Rottura, 1979; D'Amico et al., 1982; Rottura et al., 1993; Fiannacca et al., 2005a; 2008). Unlike the batholiths of the Sila and Serre Massifs, the late Variscan granitoids of the Aspromonte Unit only occur as isolated plutons of a few km^2 in size and of trondhjemitic and leucogranodioritic-leucogranitic composition, typically intruded in migmatitic paragneisses (Figure 20 d,e). In particular, the weakly peraluminous trondhjemites, that are exclusive of the Aspromonte Unit, represent the earliest identified occurrence of Late Variscan granitoid magmatism in the CPO (314 ± 4 Ma; Fiannacca et al., 2008), predating the emplacement of the widespread strongly peraluminous leucogranodiorite plutons by more than 10 Ma. Approximate P-T estimates in the range of ~ 0.5 GPa at ~ 550-680 °C have been obtained for the Aspromonte Unit in the Peloritani Mountains by Ioppolo and Puglisi (1988) and Rotolo and De Fazio (2001), with P-T peak conditions similar to those ones estimated for rocks of the same unit in the central Aspromonte Massif (0.4-0.5 GPa at 650-675 °C; Ortolano et al., 2005). Festa et al. (2004) reported the possible occurrence of pre/Eo-Variscan mafic granulites within the migmatites of the northern Peloritani, with assemblages suggesting slightly higher temperature and pressure values up to 0.8-1.0 GPa. This possibility is reinforced by the occurrence of decompression microstructures, such as plagioclase+hornblende coronitic symplectites replacing, partly to totally, former garnet porphyroblasts in rare amphibolite samples from north-eastern Peloritani (Fiannacca, personal communication - Figure 20f); furthermore, pressure up to 0.8 GPa at ~ 600 °C were recently obtained by Ortolano et al. (2014) by pseudosection computation of garnet micaschists from Santa Lucia del Mela area. Although the Peloritani Mountains are a segment of the southern Alpine orogenic belt and an Alpine subgreenschist- to greenschist-facies metamorphic overprint is indeed locally recorded in the rocks of the Upper complex (Atzori et al., 1994; Pezzino et al., 2008; Cirrincione et al., 2012a), the Peloritani basement is considered to represent, on the whole, a portion of middle-upper late Variscan crust. The dominant metamorphism recorded in the belt is of late Carboniferous-early Permian age (Atzori et al., 1990; 1994; De Gregorio et al., 2003; Appel et al., 2011) and some authors, such as Atzori et al. (1984) and Ioppolo and Puglisi (1988) proposed an entirely Variscan origin for the medium- to high-grade basement of the Peloritani Mountains. Other authors suggested instead that most of the northern Peloritani Mountains were part of a pre-Variscan basement (e.g. Ferla, 1978; 2000; Bouillin et al., 1987; Acquafredda et al., 1994) or resulting from the amalgamation of various pre-Variscan and Variscan terranes during the last stages of the Variscan orogeny (De Gregorio et al., 2003). Recent SHRIMP U-Pb zircon dating of paragneisses and augen gneisses from different areas of the north-eastern Peloritani (Williams et al., 2012; Fiannacca et al., 2013) has demonstrated that at least large portions of the Aspromonte Unit formed during the latest stages of the Cadomian Orogeny (~ 550 Ma), in the NE African part of the peri-Gondwana realm. Furthermore, by also considering the distribution of analogue augen gneiss bodies throughout the whole CPO (Fornelli et al., 2007; Micheletti et al., 2007) it appears evident the presence of a large late Precambrian-early Cambrian granitoid province related to the final assembly of Gondwana and produced through rapid recycling of late Precambrian crust (less than ~10 Ma from crust erosion to granitoid emplacement; Fiannacca et al. 2013). As far as the Mandanici Unit is concerned, Dubois and Truillet (1971) suggested that it was the sedimentary cover of a pre-Variscan basement metamorphosed during the Variscan orogeny, whereas Ferla (2000) proposed a pre-Variscan origin of the whole Upper complex basement, with only the basement units of the Lower complex representing the original Palaeozoic sedimentary cover of the old basement. Reconstructions by Williams et al. (2012) support a basement-cover relationship between the Upper and Lower complexes, but no relevant geochronological data are still available for the rocks of the Mandanici Unit to provide undisputable evidence in this regard. The tight compositional and structural analogies between the Peloritani Mountain Belt and the Aspromonte Massif are long known and have been discussed by a number of authors (Ogniben, 1960; Amodio Morelli et al., 1976; Bonardi et al., 1976). The largest debate is centered on the possible correlations between the tectonic units underlying the Aspromonte Unit. As already mentioned, the lowest tectonic units in the Aspromonte Massif have been considered as the northern continuation of the Mandanici Unit (e.g., Bonardi et al., 1980b; Graessner and Schenk, 1999; Messina and Somma, 2002), sharing the same structural position. On the contrary, the more recent tectonic model by Pezzino et al. (2008) considers the metamorphic sequences exclusively affected by Alpine metamorphism of the Madonna di Polsi Unit, cropping out in tectonic windows beneath the Aspromonte Unit, as the northern continuation of the Mesozoic Alì Sequence. All of these variously metamorphosed sedimentary successions would correspond to a portion of a thinned active continental margin that, following subduction, was extruded along the suture of a collision zone along a late Oligocene-early Miocene retrograde shear zone in a compressional regime (Pezzino et al., 1990 - Figure 21).

Geodynamic debate

As previously written, the evolution and geodynamic significance of the Calabrian-Peloritani Orogen is still the subject of numerous and contrasting interpretations due to its vaguely defined position within the palaeogeography of Central Mediterranean. Indeed, this segment of Alpine chain is interpreted as: a) a fragment of the original Neo-Tethys European palaeo-margin (Ogniben, 1970; Bouillin et al., 1986); b) a fragment of the Austroalpine domain of the Africa plate, emplaced onto the Apennine domains during Neogene times (Haccard et al., 1972; Alvarez, 1976; Bonardi et al., 1976); and c) the basement and relative cover of a micro-continent located between the Europe and Africa plates and involved in their collision (Critelli, 1999; Beccaluva et al., 2011). Whatever be the different views, Authors are inclined considering the Calabrian Peloritani Orogen as a whole geologic body, interpreted as a remnant of the Variscan chain reworked during the Alpine-Apennine orogeny.

The comparison between the crustal sections exposed in the crystalline massifs of Sila-Catena Costiera, Serre, Aspromonte and Peloritani Mountains that are briefly outlined in Figure 22, permits to highlight the

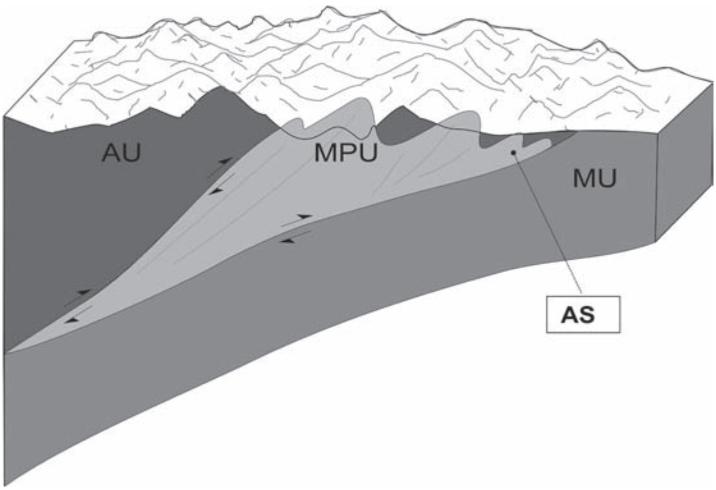


Figure 21. Schematic cross section showing the main tectonic slices composing the Alpine edifice of the Peloritani Mountain Belt and Aspromonte Massif (modified after Pezzino et al., 2008; AU = Aspromonte Unit; MPU = Madonna di Polsi Unit; AS = Alì sedimentary sequence; MU = Mandanici Unit).

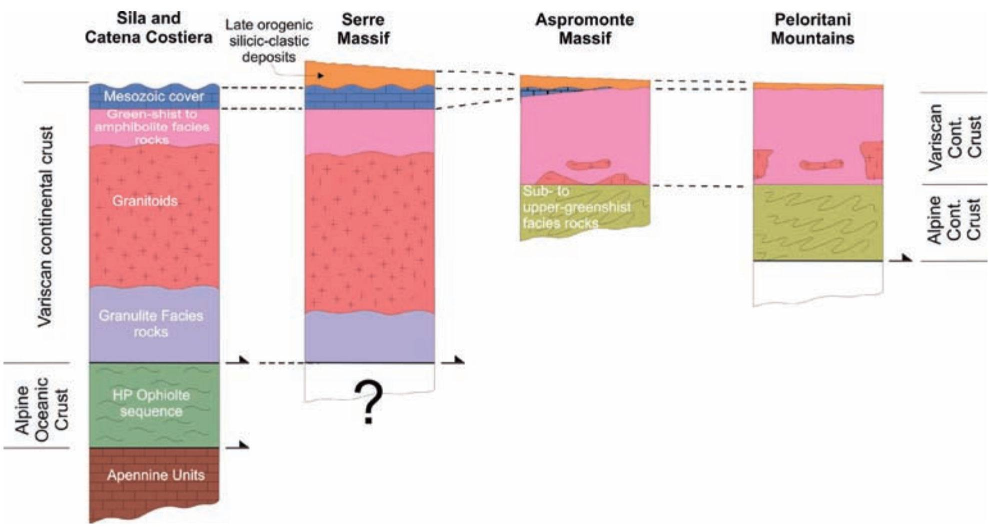


Figure 22. Comparison among schematic tectono-stratigraphic columns of the Sila and Catena Costiera, Serre Massif, Aspromonte Massif and Peloritani Mountain Belt.

correlation of the main Variscan and Alpine geological events, contributing thus to develop new perspectives which may be the basis for geodynamic models.

Late Variscan scenario

The outstanding occurrence of two nearly complete sections of continental crust that are well exposed in the Sila and Serre Massifs, permits their tectono-metamorphic history to be compared as well as to highlight their similarities and differences. Within the orogenic metamorphic belt, the portions of deep crust are usually characterised by HT/LP metamorphic events and, according to England and Thompson (1984), the high geothermal gradient required to produce this kind of metamorphism is > 60 °C/km. In the opinion of same authors, these conditions may be obtained after either underplating of mantle-derived basic magmas or intrusion of large volumes of granitoids in the middle crust (De Yoreo et al., 1989). The granulitic peak reached within these crustal regions, together with the long period of rock staying under such high temperature conditions usually obliterates the prograde segment of the P-T-paths, erasing therefore evidence of episodes linked to continental collision, otherwise recorded by the baric peaks. The deep crust then becomes an exclusive chronicler of the post-peak history, without saving memory of previous events. The comparison between the two sectors of deep crust occurring in both Sila and Serre Massifs shows a quite similar late Variscan evolution (Figure 23a). The scenario depicted after the comparison is the following: a) metamorphic peak at ~ 300 Ma; b) isothermal exhumation at intermediate crustal levels; c) isobaric cooling at intermediate crustal conditions at ca. 10-15 km for the Sila segment and a little bit shallower (12-18 km) for the Serre segment; finally, an ultimate exhumation stage begun during the Oligo-Miocene, has been interpreted by Thomson (1994) as due to a post-orogenic extension probably due to unroofing process related to a massive erosion event. Differently from the deep crust, the upper crust underwent metamorphism under amphibolite to greenschist conditions preserving the record of its prograde history and therefore, may provide important information for reconstructing the evolution of the entire chain sector, marking the transition from the collisional stage up to the final contact metamorphism event. Moreover, important analogies rise from the comparison between the evolution events of the two upper crust sectors (Figure 23b). The history of polyphase metamorphism of Sila upper crust depicts a sequence of episodes characterised by early-medium P metamorphic event dating ~ 330 Ma according to Acquafredda et al. (1994). It follows a thermal peak coinciding with the age of the granulitic peak of the lower crust and with the granitoids emplacement. On the contrary, meaningful differences rise from the comparison between the middle crust sectors occupied by each batholith. In both cases most authors agree in considering the granitoids emplacement to have occurred along a shear zone (e.g., Liotta et al., 2008; Caggianelli et al., 2007), because of the occurrence of a marked foliation within the oldest magmatic products. However, in the Serre Batholith the foliated rocks are mostly the more mafic ones, represented by quartz-diorites, tonalites and rare cumulitic gabbros (e.g., Rottura et al., 1990), whereas in the Sila batholith the least evolved terms (gabbros, norites and diorites; Caggianelli et al., 1994) represent unfoliated late products of the batholith construction, ascribed by Liotta et al. (2008) to post-shearing events. According to the latter authors, the mantle involvement during the late stages of the Sila batholith construction undoubtedly testifies an extensional geodynamic context; conversely, this evidence lacks in the Serre batholith. This difference in lithotypes distribution within the two batholiths could thus outline a significantly different late-Variscan scenario in which the two respective crustal sections, characterised by a joint and almost overlapping Variscan evolution, were involved in the last stages of Pangea assembly. As supported by most authors, the genesis of the supercontinent concluded around 300 Ma ago with the amalgamation of Gondwana, Gondwana-derived micro-continents, Laurussia and with the definitive

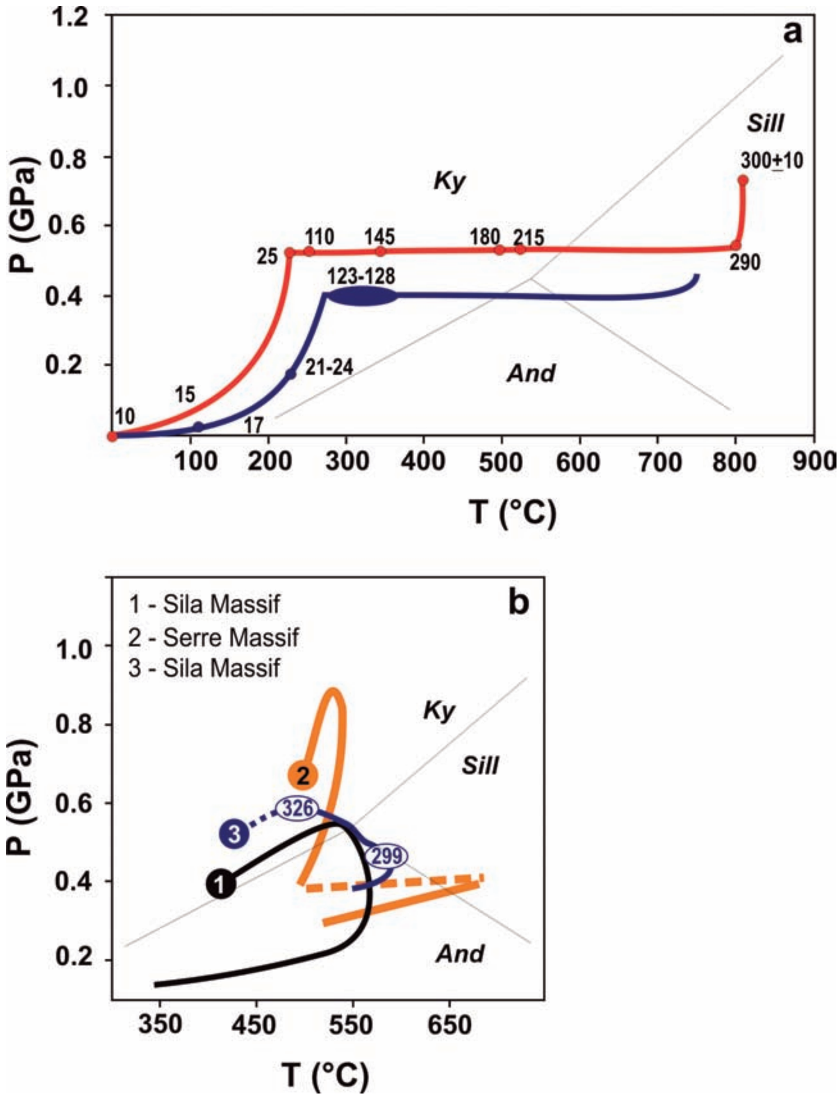


Figure 23. a) Comparison between P-T-paths of the lower crust in Sila (blue line) and Serre Massifs (red line) (after Caggianelli et al., 2007; Graessner et al., 2000; Graessner and Schenk, 2001); b) Comparison between the P-T- paths of the upper crust of Sila (curves 1 and 3; after Borghi et al., 1992; Langone et al. 2010) and Serre Massifs (curve 2 after Angì et al., 2010).

closure of the oceanic basins placed between (Franke, 2000; Matte, 2001; Stampfli and Borel, 2002; Stampfli and Kozur, 2006; von Raumer et al., 2003). This event likely occurred in a context of a complex pattern of coeval strike-slip shear zones active up to 300 Ma (Padovano et al., 2014, and reference therein). A branch of this complex network of tectonic lines known as East Variscan Shear Zone (EVSZ) (Corsini and Rolland, 2009; Elter and Padovano, 2010; Padovano et al., 2012; 2014) and characterised by a complessive dextral strike-slip, runs from the external massifs of the Alps to the Variscan Massifs of Corsica and Sardinia, also involving the Calabria-Peloritani Orogen (Liotta et al., 2008; Angì et al., 2010). In spite of the similar geological features, produced by an analogous metamorphic evolution, the presence of coeval transpressional and/or transtensional macro-domains may be the reason of some of the different features observed in the Sila and Serre batholiths, such as the occurrence of post-tectonic gabbros only in the Sila one. In the same context, the presence of late Variscan anatectic magmatism in the Aspromonte Massif and in the Peloritani Mountain Belt, responsible for the production of small silica-rich intrusive bodies and not able to form composite batholiths, could be explained by their peripheral position with respect to the EVSZ.

Alpine scenario

The architecture of the various tectono-stratigraphic complexes that constitute the massifs of the Calabrian-Peloritani Orogen described in the previous sections, together with their geological setting, would exclude that CPO behaved as a whole geological body during the Alpine orogeny. On the contrary, the orogen features would be the result of juxtaposition of crustal blocks initially belonging to different continental palaeomargins. The Liguride complex, comprised between the Apennine complex and the Calabride complex and constituted of slices of oceanic lithosphere belonging to the neo-Tethys realm that crop out discontinuously in the western and in the southern part of northern CPO, exhibits a succession of deformation stages indicative of a subduction towards the present-day eastward direction (Lanzafame and Zuffa, 1976; Piluso et al., 2000). These data provide useful information for constraining the pre-Cretaceous position of the continental basement of the Northern CPO. Structural investigation carried out on ophiolite units indicates a deformation history developed during two stages: 1) subduction and exhumation processes associated with Alpine orogenesis; 2) overprint of brittle deformation related to Apennine orogenesis and to the opening of the Tyrrhenian Sea, which affected the whole orogen from early Miocene onwards (Cirrincione et al., 2002a,b; Liberi et al., 2006). The ductile deformation structures related to Alpine tectonics led to the detection and kinematic characterisation of the Alpine accretionary wedge: Cello et al. (1991; 1996) recognised a subduction-related deformation history with a northwest-vergency in the Diamante area; Carrara and Zuffa (1976) provided structural data for the northern Catena Costiera, indicating a top to the west tectonic transport; in the southern border of the Sila and Catena Costiera, Dubois (1976) and Piluso et al. (2000) distinguished the same groups of Alpine structural deformations characterised by the same south-westward vergency. All the structural data related to Alpine deformation events consequently confirm an Europe-verging accretionary wedge connected to an eastward subduction of oceanic lithosphere (Figure 24 - West Calabrian accretionary wedge). Structures related to the same deformation stages are also present within the mylonitic rocks of the Calabride complex (Castagna Unit; De Vuono, 2005). Locally, in the southwestern margin of the Sila Massif, fragments of the Calabride complex showing a HP metamorphic overprint (Colonna and Piccarreta, 1976) may represent the involvement of small volumes of continental crustal rocks in the Alpine accretionary wedge. The above observations suggest that the Calabride complex, which overthrusted the ophiolite accretionary wedge after the neo-Tethys closure, should be located in the eastern margin of the oceanic basin, and therefore be either part

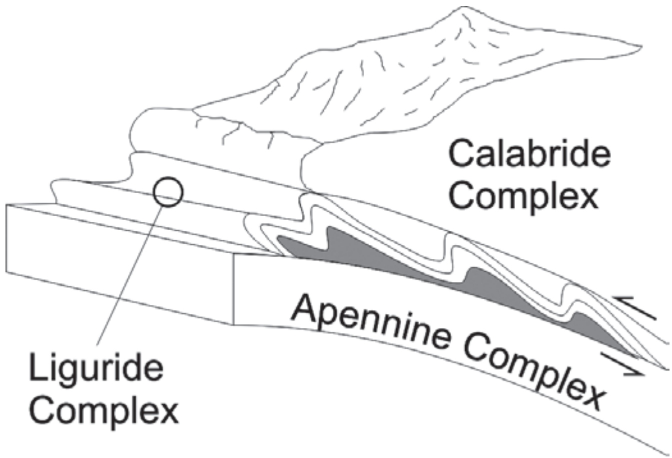


Figure 24. Schematic representation of the Euro-vergency of the Liguride complex in the northern Calabria.

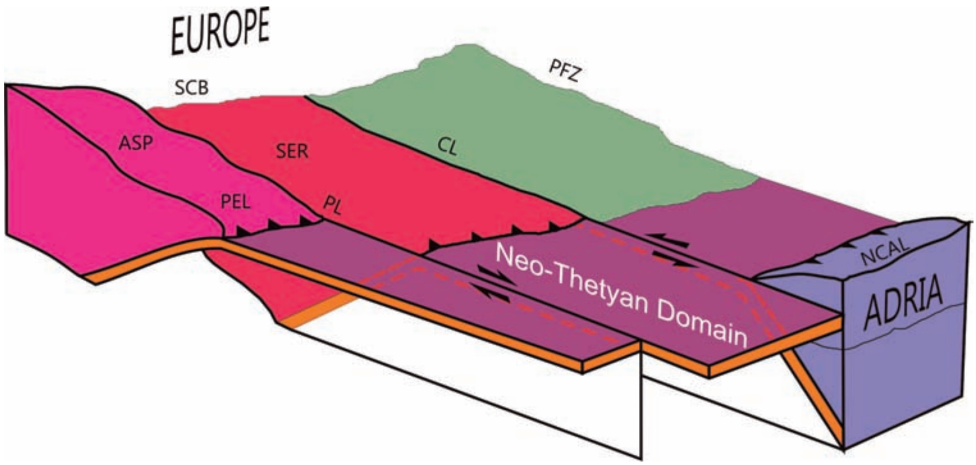


Figure 25. 3D block diagram of the pre-collisional Cretaceous palaeo-geodynamic scenario of the CPO within the central Mediterranean area (NCAL: Northern Calabria; ASP: Aspromonte; PEL: Peloritani; SER: Serre; SCB: Sardinia Corsica Block; PL: Palmi Line; CL: Catanzaro Line; PFZ: Pollino Fault Zone).

of the African palaeomargin, or of a continental microplate once situated between the African and the European plates. As already pointed out in the previous sections, the opposite situation is observed in the Aspromonte Massif and in the Peloritani Mountain Belt, where structures linked to crustal thickening and exhumation indicate only an African vergency, thus implying the existence of an accretion wedge placed to the west of the continental basement (Pezzino et al., 2008; Cella et al., 2004; Cirrincione et al., 2012a). The above considerations envisage a pre-collision scenario schematically set out in Figure 25, where northern CPO (including the

Sila and Catena Costiera Massifs) and southern CPO represented by the Serre and Aspromonte Massifs and by the Peloritani Mountain Belt, were located on opposite continental margins separated by the neo-Tethys basin; as a result, the northern and southern sector are ascribed to the African and Iberian plate, respectively. In this context, the Catanzaro Line, formerly identified for explaining the lack of Alpine metamorphism in southern CPO (Tortorici, 1982), is given now greater significance. Indeed, this important sinixtral strike slip line pulls together the former margins of the two continents and therefore represents a mark of the collisional suture. The hypothesis of an Alpine composite orogen, originated after the amalgamation of the two fragments of Iberian and African continental crust, is supported by the occurrence of late to post orogenic deposits (Stilo-Capo D'Orlando Formation) which exclusively crop out in the southern sector of the orogen and whose clastic component is considered to derive from the Sardinia-Corsica domain (Mazzoleni, 1991; Cirrincione, 1992; Atzori et al., 2000).

Concluding remarks

The purpose of the present paper was that of introducing the reader to the geology of the Calabria-Peloritani Orogen (CPO), outlining the state of the art of its geological and petrological knowledge and focusing to unsolved questions.

Both the strongholds and the hiata of its geodynamic evolution since the final stages of the Variscan orogenesis were presented and discussed; besides new challenging interpretations were here provided.

A basic unresolved issue is still that revolving around the possible geodynamic meaning of the subdivision of the CPO in a northern and a southern sector and the first key to address this issue is in the comparison of the crustal sections exposed in the Sila and Serre Massifs. These crustal sections were set up during the Variscan orogenic cycle and shared the same tectono-metamorphic evolution up to the final stages of batholith's construction, which were instead marked by significant differences. In fact, the final products are represented by large volumes of granodiorites and granites in the Serre Batholith and by gabbroic and dioritic rocks in the Sila Batholith, attesting for a relatively significant mantle involvement in the latter. This would suggest, in turn, a different location of the Sila and Serre Massifs with respect to the transpressional/transtensional domains developed along the last stages of the East Variscan Shear Zone activity, with northern Calabria affected by transtensional kinematics, as already suggested by Festa et al. (2008) and Padovano et al. (2012), but with the southern Calabria located in a transpressional domain, where the Serre Massif likely occupied a inner part while the Aspromonte Massif and the Peloritani Mountains, only characterised by small volumes of silica-rich granitoids, represented the most peripheral sector.

The areas of crustal weakness distributed across this continental-scale shear zone system did likely represent preferential breakup lines in the subsequent Permo-Triassic Pangea rifting and Tethys basin opening, with strong evidence suggesting, as far as the CPO is concerned, that the northern and southern sectors of the orogen were located into different continental margins (Figure 25).

The above interpretation, also largely rising from the observation of the present collisional setting, depicts a pre-collisional scenario where the Sila and Catena Costiera Massifs would represent a fragment of the Adria palaeomargin, overlapped onto the oceanic domain that is nowadays represented by the Liguride Units, which are exposed with European vergency along the northern and southern sectors of the orogen. Differently, the Serre and Aspromonte Massifs together with the Peloritani chain would represent the relic of an Africa verging accretionary wedge that was resulting from the deformation of the European continental margin, where the front is represented by the nappe-like edifices of the Aspromonte Massif and the Peloritani Mountains, while the Serre represents a fragment of a more inner chain domain (i.e. less shortened), today laterally juxtaposed due to the strike-slip tectonic activity of the Palmi line.

In this new framework, the Catanzaro Line gets the rank of segment of a sinixtral strike-slip line of continental-scale importance; at the same time, the Calabria-Peloritani Orogen can be envisaged as a crustal raft passively transported as a single piece across the Tyrrhenian Sea but, in fact, enshrining a relic of the collisional suture between the Europe and Adria continental blocks.

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