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### Petro-structural geology of the Eastern Aspromonte Massif crystalline basement (southern Italy-Calabria): an example of interoperable geo-data management from thin section - to field scale

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## SCIENCE

# Petro-structural geology of the Eastern Aspromonte Massif crystalline basement (southern Italy-Calabria): an example of interoperable geo-data management from thin section – to field scale

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The presented maps provide an example of the synoptic display of multi-scale geological features characterizing the tectono-metamorphic evolution of the crystalline basement terranes in a poly-orogenic-multistadial evolutionary scenario. The petro-structural map of the eastern Aspromonte Massif (southern Calabrian Peloritani Orogen) is characterized by a nappe-like edifice composed by the superimposition of three crystalline basement tectonic units which, sharing the same Alpine-Apennine reworking, underwent a different metamorphic evolution, mostly derived from the Hercynian orogenic cycle. This geological framework is completed by the suture deposition of a Oligocene-Miocene syn-orogenic clastic formation, partly roofed by the back-thrusting of a clay-rich mélangé. In order to understand the potential relationships within the complex dataset deriving from the geological investigations of this crystalline basement area, a geo-database, capable of handling multi-scale information from field-derived structural data (i.e. foliation, lineation, fold- and fault-related structures) to micro-scale derived ones (i.e. thin-section analysis, electron microscope and microprobe investigations, thermodynamic modeling outputs) has been constructed, according to the international standards using the Geo-Scientific Markup Language developed by the Commission for the Management and Application of Geo-science Information. Proposed outputs will show the relationships between field-related geological features, showing collected samples and the subsequent laboratory investigations. These are fundamental to achieving reliable results in geological contexts, such as those for reconstructing the tectono-metamorphic evolution of crystalline basement terrains.

Keywords: GIS geological mapping; structural data; Calabria; GeoSciML; Spline

## 1. Introduction

Geological mapping of crystalline basement areas requires the possibility of handling multi-scale geological data from the outcrop to the thin section-scale and beyond in order to permit the interaction between meso-structural data with micro-analytical investigations. Over the last decade the increased availability of sophisticated analytical techniques that have been routinely performed,

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from the Scanning Electron Microscope (SEM) and Electron Probe Micro Analyzer (EPMA) investigations through to *in-situ* isotopic and geochronological investigations.

This lays the groundwork for the development of a data-management system useful to permit functional data-interaction, even more so when the acquisition and/or the data-processing derive from research groups whose members are increasingly far apart.

In order to establish a more consistent ontology and vocabularies the geo-science community is interested in geological information modeling based on a structured framework of the geological domain, aimed at upgrading geospatial data mapping, especially focused on continuity and compatibility between output generated by different systems, implementing real interoperability between heterogeneous software platforms.

As a result the IUGS (International Union of Geological Sciences) has recently provided considerable resources in order to achieve a global reference model, now published as the GeoSciML (Geoscience Markup Language) (Laxton et al., 2010). This standard application-schema is proposed using the UML (Unified Modeling Language<sup>1</sup>) (Booch, 1996; Llano & Pooley, 2009).

In this context GIS-based Petro-Structural Map of the eastern Aspromonte Massif crystalline basement aims to structure an example of a pluri-geothematic interactive map. This would be an intuitive tool capable of displaying the relationships between field geo-structural data, an articulated system of samples and sub-samples (i.e. portions of the original sample used for different analytical purposes) useful for acquiring: (i) mineral-chemical data; (ii) geochemical data; (iii) isotopic data; (iv) geothermobarometric constraints and so on, through the sampling point location.

This data infrastructure would guarantee high-quality data storage, application of the more common interpolation techniques (e.g. Spline, IDW, Kriging) (Isaaks & Srivastava, 1988), useful to integrate field related data with datasets deriving from several laboratorial analytical sessions. The proposed database infrastructure is primarily based on the last INSPIRE (Infrastructure for Spatial Information in the European Community) guidelines in terms of syntax and logical relations, integrated with the FGDC-GDS (Federal Geographic Data Committee – Geological Data Subcommittee) (<http://www.fgdc.gov>) map symbols. This ensures, as far as possible, the interoperability of geospatial data, useful for developing new platforms of data sharing, which can potentially develop synergies, between individual research groups.

## 2. Methods

In order to manage all the information acquired during the phases of geological field investigation accompanied by laboratory analytical sessions, a new geotadabase called ‘FOS2MAN’ (From Outcrop Scale to MicroANalysis) (Zappalà, 2014), was developed using the GeoSciML model, in order to realize interoperability of geospatial data. The conceptual model of FOS2MAN describes the organization of the entities and their relationships including multiplicity and dependences (Figure 1), looking for full interoperability among the most common geoscience data structures like PetLab (<http://pet.gns.cri.nz/>), MetPetDB (Spear et al., 2009) and Earthchem (Walker et al., 2005). FOS2MAN provides an organized scheme for detailed data acquisition aiming a self-consistent production of all the information potentially deriving, in our case study, from the crystalline basement geological survey of the eastern Aspromonte Massif.

In order to organize evidence the on geological, structural and petrological features, producing a reliable reconstruction of the tectono-metamorphic evolution of this selected Alpine-Apennine sector chain of the southern peri-Mediterranean realm, the specific sequence of the blasto-deformational relationships have been reconstructed, integrating field-related data with petrographic and mineral chemical investigations (mineral abbreviations after Siivola & Schmid, 2007). Particular attention is focused on the reconstruction of the tectono-metamorphic evolution of the two lowermost

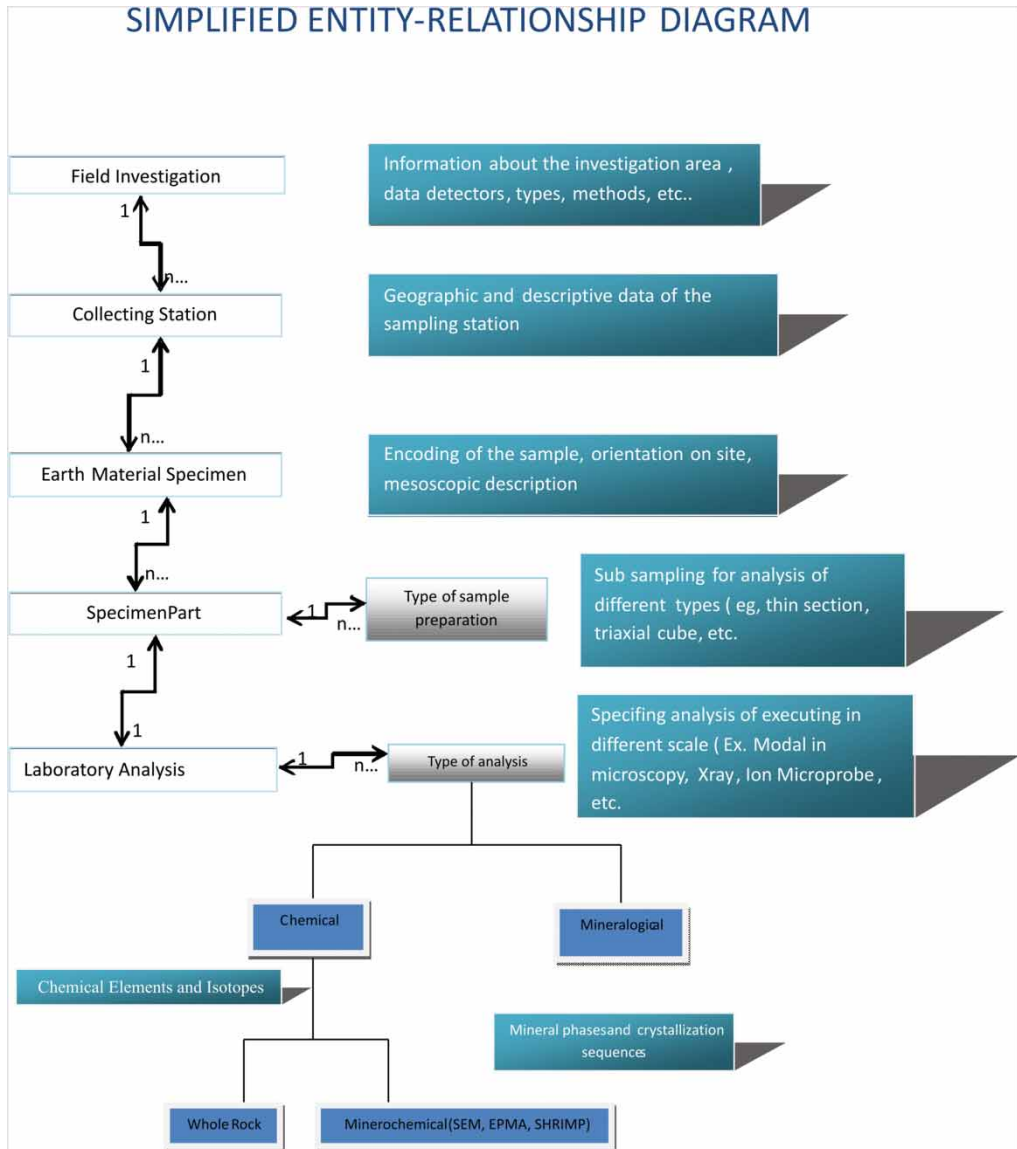


Figure 1. FOS2MAN – Simplified diagram of the Entity-Relationship model (after Ortolano & Zappala, 2012 modified). Acronym meaning: SEM: Scanning Electron Microscope; EPMA: Electron Probe Micro Analyzer; SHRIMP: Sensitive High Resolution Ion Micro Probe

crystalline basement units, which underwent polyorogenic – multistadial evolution (Cirincione et al., 2008a).

The sequence of foliations, lineations and fold related structures, as well as identified deformational events (potentially) accompanied by metamorphic ones, followed the customary time-related concept, where the eldest recognizable planar structural fabric without any evidence of sedimentary origin is indicated with the letter 'S' followed by the subscript 1,2,3; the linear ones by the letter 'L' followed by the same subscript sequence, as well as for the sequence of the folding axis 'b' and for the deformational 'D' or metamorphic event 'M', subscripted by the

same progressive numeric sequence. To avoid confusion between structural sequences specifically observed within a single tectono-metamorphic unit, the specific structural symbol (i.e. S, L or b) were preceded by the apex of a unit's acronym.

Finally, reported paragenetic equilibria follow the same time-related concept for those minerals clearly linked with a specific metamorphic event. The mineral chemical compositions of these equilibria have been used to constrain the PT evolution of the two lowermost outcropping crystalline basement units already calculated in [Cirrincione et al. \(2008a\)](#), by means of thermodynamic modeling via PT pseudosection calculation ([Connolly & Petriani, 2002](#)).

The above description has resulted in a clear data structure for managing the multiscale features of the available geological data. A detailed hierarchical criterion, useful for managing the general and particular aspects of the field and laboratorial geological investigations, have been followed, including any typical elements of the metamorphic domain, sampling data storage, handle sampling description and characterization, analytical chemistry from bulk analysis to microstructural and mineral-chemical observation.

In this view, during the production of FOS2MAN our attention has been particularly focused on addressing parental relationships existing between the sampling site, as the single outcrop framed within a 'geological unit', the earth material sampled from the site or the sample collection, the reduction in subsample and the part to be analyzed, with each one treated with a specific method or analytical process ([Figure 2](#)).

The graphical representation of the structural-geological data refers to a model proposed by the FGDC-GDS (<http://www.fgdc.gov>). Such a decision was taken that, whilst the INSPIRE model is representative for European geosciences data sharing, it is less refined and sometimes lacking in several aspects (e.g. specific structural-geological symbolization such as faults, foliations, lineations, cleavages, folds and joints symbols). Geo-structural symbolization in INSPIRE is relatively poor at representing the various aspects of geo-structural investigations, beginning from mesoscale derived information and, even more so for those related to the domain of microanalysis.

More specifically geological features, such as those used to describe the entity 'fault', can be less or more specified with information derived from the feature. For example, the entity fault can be generally specified as: generic, vertical, sub-vertical, or high-angle; or unknown or unspecified orientation or sense of slip. The above generic characterization can be then be detailed as an entity 'fault' among ten types of faults, such as 'Low-angle fault', 'Reverse fault', Rotational or scissor fault, etc. In each case there are other rules to specify the identity, the certainty or location accuracy. By means of the combination of the above mentioned attributes, it is then possible to choose a specific symbol that represents a synthesis of all of them, identifying each single specific case.

For 'Foliations', it's possible to use generic foliation terms or, better, define any kind of primary foliation or secondary one, specifying where it is 'vertical metamorphic' or 'tectonic foliation' and if it appears showing strike or less. Using a specific symbol, the author can detail directly a mylonitic foliation or a horizontal eutaxitic one, providing the user a wide range of information, already clearly defined from the simple observation of the used symbols, coded according to international standards.

For 'Lineations' there are a lot of different ways to detail their origin and other geo-structural meanings such as stretching-, intersection- or mineral-lineation, just to mention a few.

Furthermore, as data within the database can potentially be acquired from different sources, it is noted to the left of each item. This work aims to highlight the uncertainty of the data through graphical representation ([Balestro et al., 2010, 2013](#)).

Following the above mentioned concepts, two different outputs have been developed.

The first one ([Map 1](#)) provides a classic geological map 1:25,000 scale, supplemented with a detailed geological setting and four geological cross-sections. This first map has as a topographic

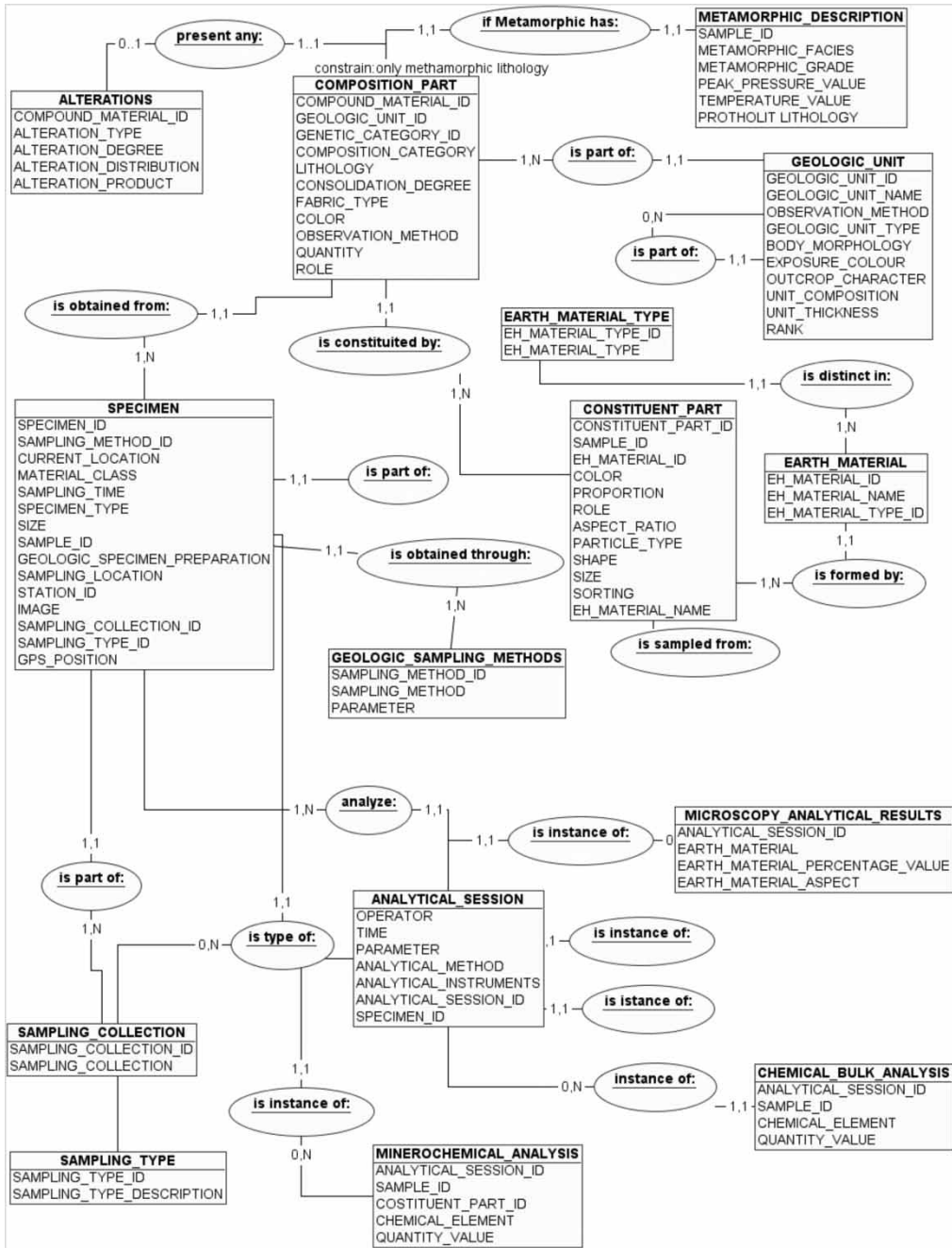


Figure 2. FOS2MAN – Conceptual model of the Entity-Relationship (after Ortolano & Zappala, 2012 modified)

base map, part of sheets 602 (first and second quadrant) and 603 (third and fourth quadrant) of the 1:25,000 scale topographic map of the military Italian geographic institute (IGM – Istituto Geografico Militare), projected according to WGS 84 / UTM zone 33N. The grid is in meters from the equator and latitude and longitude (from the Greenwich meridian), respectively.

The second cartographic output highlights the main structural features as well as the whole-rock- and mineral-chemistry of representative samples for the two lowermost crystalline basement units, depicted as a simplified geological map at 1:25,000 scale, using contour lines as a topographic base. Structural data were used to interpolate the average attitude and inclination of the mylonitic foliations as well as of the stretching lineations from about 500 structural stations, accompanied by stereoplots. Whole-rock and mineral-chemical data were used instead as input to derive the PT constraints calculated via thermodynamic modeling after [Cirrincione et al. \(2008a\)](#).

### 3. Geological setting

The study area is located in the eastern part of the Aspromonte Massif, a nappe-like structure consisting of three stacked crystalline basement units located in the southern part of the Calabrian Peloritani Orogen (CPO) ([Figure 3](#)) ([Map 1](#)). This is a relic fragment of the original southern European Variscides presently involved within the thin-skinned Apennine thrust system, developed during the later stages of the Alpine orogenic cycle.

In this scenario, the crystalline basement units which constitute the backbone of the CPO are the result of a poly-orogenic multi-stage history ([Barbera et al., 2011](#); [Cella et al., 2004](#); [Cirrincione et al., 2008a](#)) which has led to the formation of the present-day composite terrane ([Cirrincione et al., 2010](#)), composed of Variscan, or possibly older, sub-terrane (e.g. [Critelli, 1999](#); [Cirrincione et al., 2005](#); [Critelli et al., 2011, 2013](#); [De Gregorio et al., 2003](#); [Ferla, 2000](#); [Fiannacca et al., 2013](#); [Micheletti et al., 2007](#); [Pezzino et al., 2008](#); [Perri et al., 2011](#); [Perri et al., 2013](#); [Williams et al., 2012](#)). The present-day lateral juxtaposition of these differently evolved sub-terrane were essentially due to the activation of an early deep seated strike-slip tectonics ([Ortolano et al., 2013](#)), which accompanied the following Alpine-Apennine large-scale stacking activity, leading to the joining of originally separated crystalline basement domains. This work has the aim of expanding evidence of the specific structural and petrological features of the crystalline basement units outcropping in the eastern sector of the Aspromonte Massif for an area of about 135 Km<sup>2</sup> ([Figure 3c](#)) ([Map 1](#)).

In particular, focus is on the uppermost unit of the thrust edifice of the Aspromonte Massif represented by the Stilo Unit (SU) ([Crisci et al., 1982](#); [Fazio et al., 2012](#); [Graefner & Schenk, 1999](#)). In the mapped area, it outcrops as sporadic klippen and consists of very low-grade Hercynian metapelites ([Figure 4a](#)). The SU lies in brittle tectonic contact over the Aspromonte-Peloritani Unit (APU), which is made up of amphibolite facies Paeleozoic rocks with late to post-Hercynian peraluminous intrusive bodies, locally overprinted by Alpine age metamorphism, developed along a deep-seated shearing zone at about 25–30 Ma ([Bonardi et al., 1987](#); [Bonardi et al., 2008](#); [Cirrincione et al., 2009](#); [Cirrincione et al., 2010](#)) ([Figure 4b](#)). This event, characterized by the evolution of a thick mylonitic horizon ([Ortolano, Cirrincione, & Pezzino, 2005](#)), thrust the APU onto the lowermost outcropping metapelite unit, which marks the beginning of the joint structural and metamorphic history of these two units. Before this event, the APU preserved clear relics of a metamorphic history, characterized by a prograde low pressure gradient evolution, peaking at low pressure (LP) high temperature (HT) conditions, ascribable to the later stages of the Hercynian orogenic cycle ([Cirrincione et al., 2008a](#)). By contrast, the lowermost unit, surfacing along several underlying low- to medium-grade tectonic windows: (a) the Cardeto window ([Fazio et al., 2008](#)); (b) the Madonna di Polsi window ([Pezzino et al., 1990](#)); (c) the Samo-Africo window ([Messina et al., 1992](#)), seems to be characterized by a complete Alpine reworking ([Heymes et al., 2010](#)) or to be exclusively affected by complete Alpine metamorphic cycle peaking at relatively HP conditions ([Cirrincione et al., 2008a](#); [Ortolano et al., 2005](#); [Pezzino et al., 2008](#)), in view of the



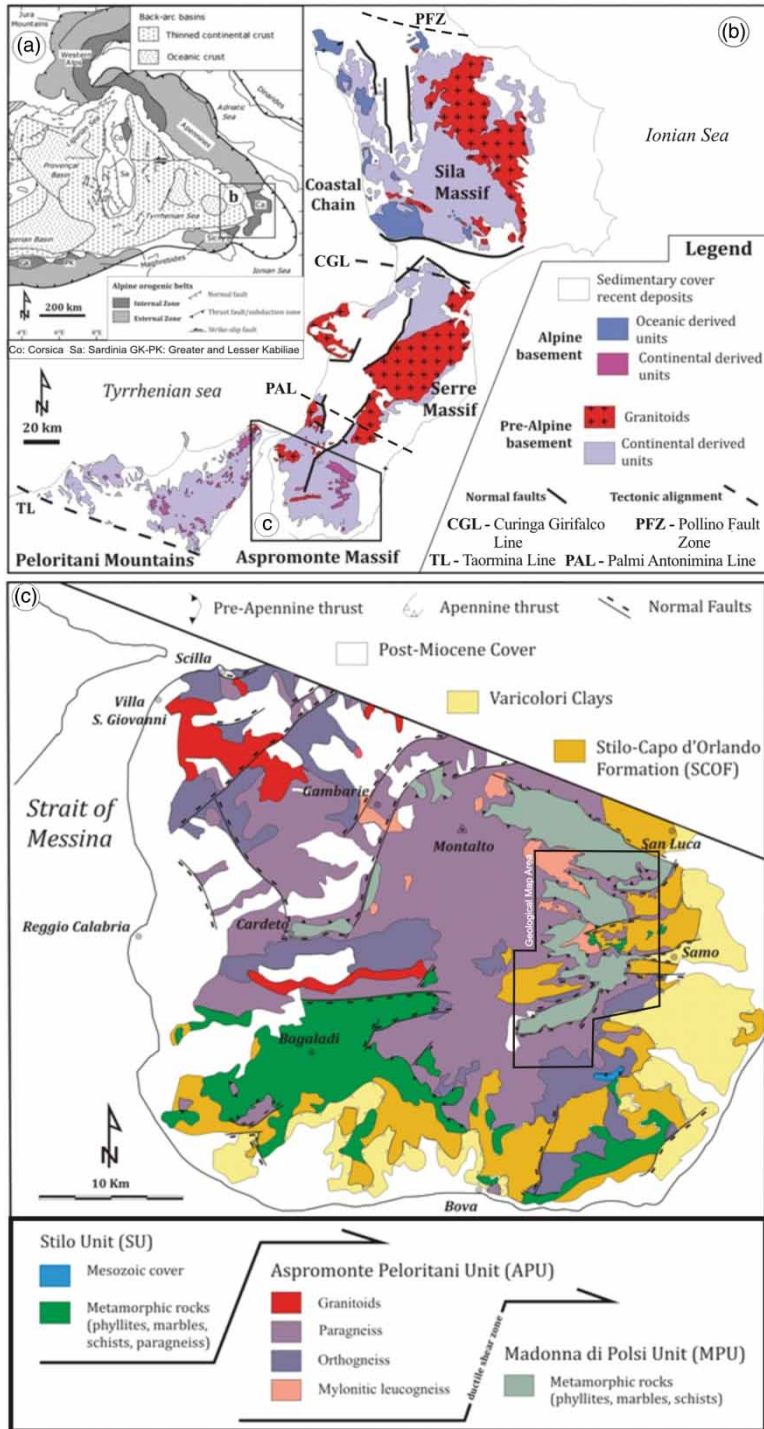


Figure 3. Synthesis of geological setting (a) Areal distribution of Alpine belt in the central Mediterranean realm; (b) Geological sketch map of Calabrian Peloritani Orogen (CPO) (modified after Angi et al. 2010; Cirrincione et al., 2011). (c) Geological sketch map of the Aspromonte Massif (after Pezzino et al., 1990, 2008; Ortolano et al., 2005; Fazio et al., 2008).



Figure 4. General mesoscopic features of the outcropping units (a) Klippen of phyllite of the Stilo Unit partially covered, in basal unconformity, by arenaceous levels of the Stilo-Capo D’Orlando Formation (SCOF); (a’) particular of the SU phyllite with widespread presence of quartz-rich isoclinal hinge depicting the  $SU S_1$  surface; (b) mylonitic leucocratic gneiss of the Aspromonte Peloritani Unit with kinematic indicator consistent with a top to NE sense of shear in the present-day geographic coordinates; (c) SCC’ mylonitic fabric in garnet-muscovite schist of the Madonna di Polsi Unit consistent with a top to NE sense of shear; (d) Particular of the stratigraphic basal alternance of the SCOF sequence passing from relatively thin levels of phyllite-rich clasts to relatively thick arenaceous levels.

subtle identification of clear metamorphic relics ascribable to the previously detected orogenic events (Figure 4c). According to this last view, this unit, named the Madonna di Polsi Unit (MPU) by Pezzino et al. (2008), can be framed within the southern CPO geodynamic scenario as a prevalent metapelite sequence, differently affected by an early Alpine evolution along an HP geothermal gradient (Cirrincione et al., 2008b). As a consequence of this proposed model, the comparison between Aspromonte Massif and Peloritani Mountains nappe-like edifices (Cirrincione et al., 1999; Cirrincione et al., 2012) was facilitated, contributing to our understanding of the location of this orogenic sector in the wider geodynamic puzzle of the western Mediterranean realm (e.g. Critelli et al., 2008; Perrone et al., 2006; Perri et al., 2011, 2013; Zaghloul et al., 2010).

The study area is also characterized by the wide presence of the syn- to late-tectonic deposition of the silicic-clatic terrigenous sequence named the Stilo-Capo D'Orlando Formation (SCOF) (Cavazza et al., 1997), locally suturing the contact between the APU and SU (Figure 4d). The tectono-stratigraphic evolution of this sequence of the CPO southern sector terminates in this area with the back-thrusting (Ogniben, 1960; Tripodi et al., 2013) or re-sedimentation (Cavazza & Barone 2010; Critelli et al., 2013), of a clay-rich *mélange* (i.e. the Varicolori Clays).

#### 4. Structural and stratigraphic features

Structural investigations, synthetically summarized in Figure 5, highlights that the Stilo Unit (Figure 5a) underwent a mono-orogenic metamorphic cycle of Variscan age, characterized by a first stage of isoclinal folding deformation ( $^{\text{SU}}\text{D}_1$ ) with formation of a pervasive axial plane schistosity ( $^{\text{SU}}\text{S}_1$ ) (Figure 4a') clearly followed by a sub-millimeter sized micro-crenulation, leading to the formation of a pervasive axial culmination lineation ( $^{\text{SU}}\text{b}_2$ ) (Figure 5a). In the mapped area the SU is sandwiched between the overlying suturing of the SCOF, locally highlighted by the presence of rich-phyllite cataclastic *mélanges*, probably linked with a tectonic replacement of the original stratigraphic basal discordance (Figure 4d), and the underlying APU. Also in this case this last tectonic contact is marked by a cataclastic horizon with no evidence of any relic of more deep-seated deformational structures.

By contrast, the contact between the two lowermost tectonic units (i.e. APU and MPU), although also characterized by the presence of a relatively thick cataclastic horizon, shows clear evidence of a share weak to strong pervasive mylonitic foliation (Ortolano et al., 2005). This deformational stage permits only rarely the preservation of the pre-mylonitic structures, presently observable at the micro-scale such as in the APU rock-types. It is rarely detected at the outcrop scale in the MPU rocks where, the first recognizable deformational event ( $^{\text{MPU}}\text{D}_1$ ), characterized by the formation of an isoclinal fold axial plane foliation ( $^{\text{MPU}}\text{S}_1$ ), is demonstrated by quartz-rich fold hinge relics within phyllite layers (Figure 6). Occasionally a new subsequent surface ( $^{\text{MPU}}\text{S}_2$ ) is also recorded, as a result of a millimeter wave-lengthened folding event ( $^{\text{MPU}}\text{D}_2$ ) leading to the formation of a crenulation cleavage rarely evolving to a real schistosity (Figure 5c).

The subsequent deformational stage led to the formation of the share pervasive mylonitic foliation,  $^{\text{APU}}\text{S}_3$ , and  $^{\text{MPU}}\text{S}_3$ , for APU and MPU rocks, respectively, which also developed to a pervasive stretching lineation averagely trending SW-NE, with kinematic indicators consistent with a top to NE sense of shear in the present-day geographic coordinates (Figures 4b and 4c and 5b and 5c). Mylonitic foliation evolves to an isoclinal folding deformation (Figures 5b and 5c and 7a), suggesting that the two units underwent a similar deep-seated event, before being exhumed along a joint brittle tectonic contact preceded by the formation of asymmetric folds, producing prevalent centimeter to decameter up to hectometer sized SSE-SE verging tectonic structures, accompanied by secondary conjugate NNW-NW verging ones (Figures 5a–c and


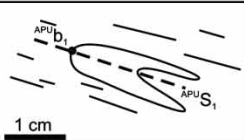
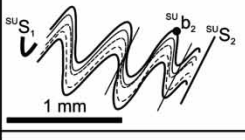
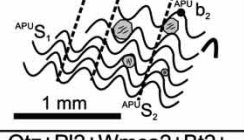

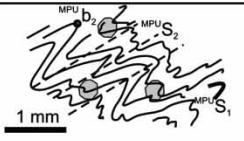
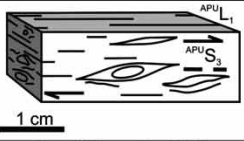
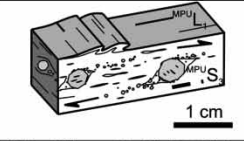
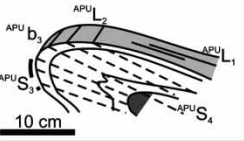
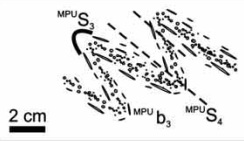
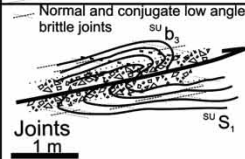
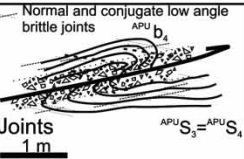
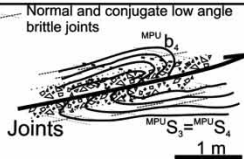
OROGENIC STAGES	BLASTO-DEFORMATION SEQUENCE	UNIT		
		(a) STILO UNIT	(b) ASPROMONTE PELORITANI UNIT	(c) MADONNA DI POLSI UNIT
Early Hercynian	D <sub>1E</sub>			
	M <sub>1E</sub>	Qtz+Ilm+Wmca1+Bt1+Pl1	Qtz+Pl1+Wmca1+Bt1 ±Grt1±Sil±Kfs	
Late Hercynian	D <sub>2E</sub>			
	M <sub>2E</sub>	Qtz+Chl1+Wmca2+Bt2	Qtz+Pl2+Wmca2+Bt2±Grt2±Chl1±And1	
Early Alpine	D <sub>1A</sub>			
	M <sub>1A</sub>			Qtz+Pl1+Wmca1±Chl1 ±Grt1±Ep1±Ilm1±Amph1
	D <sub>2A</sub>			
	M <sub>2A</sub>			Qtz+Chl2±Wmca2 ±Grt2±Ilm2
Late Alpine	D <sub>3A</sub>			
	M <sub>3A</sub>		Qtz+Wmca3+Chl2 ±Bt3±Grt3±Pl3±Czo1±Tur	Qtz+Wmca3+Chl3±Grt3 ±Pl3±Czo±Tur±Amph2
	D <sub>4A</sub>			
	M <sub>4A</sub>		Qtz+Wmca4+Pl4±Czo2	Qtz+Chl4±Pl4±Wmca4
Apennine	D <sub>5A</sub>			

Figure 5. Sequence of the blasto-deformation events of the metamorphic basement units of the studied area: (a) Stilo Unit; (b) Aspromonte Peloritani Unit; (c) Madonna di Polsi Unit (see text for the meaning of the acronyms)



Figure 6. Relic of isoclinal hinge within mylonitic layers in amphibole schist of the Madonna di Polsi Unit (Aposcipo river).

7b–d) (Map 2). The activity of these two last deformational events have produced the folding of the original mylonitic layers, contributing to produce an anomalous thickening of the original mylonitic zone as well as repetition of the original contact, already locally preserved in some places (Map 1). This compressional tectonic activity is often accompanied by the activation of brittle strike-slip tectonics probably as re-activated relics of the early Alpine deep-seated strike-slip tectonics presently rarely preserved within the CPO (Ortolano et al., 2013). This last tectonics led to the formation of fault system mainly oriented NW-SE and characterized both by right- or left-sided kinematism. In the mapped area, these structures are well preserved by the presence of part of the Bovalino-Bagnara strike-slip fault (Del Ben et al., 2008), observable along the Buonamico river (Maps 1 and 2).

The top of the nappe-like structure of the crystalline basement resulted in covering by the suturing activity of the Oligocene-Miocene SCOF, characterized by a conglomerate horizon gradually passing to thick arenaceous levels (Figure 4d), evolving in turn to widely distributed pelite ones. Finally, in the eastern sector of the mapped areas, it is possible to recognize, relatively thinned levels of Varicolori clays, interpreted as the result of the back thrusting activity of the clays of the original Sicilide basin (Ogniben, 1960; Tripodi et al., 2013).

The following detected tectonic activity terminates with the activation of a normal faulting system that marks the switch from a compressional to an extensional regime (Cirrincone et al., 2008b). This last deformational system is delineated by the presence of widespread high-angled joint systems, spanning from decimeter-sized fracture cleavage to kilometer size Horst and Graben structures (Figure 7e), all of these averagely oriented WNW-ESE and WSW-ENE, following the formation of the main seismogenic structural systems (Map 2) (Morelli et al., 2011, ITHACA Project).

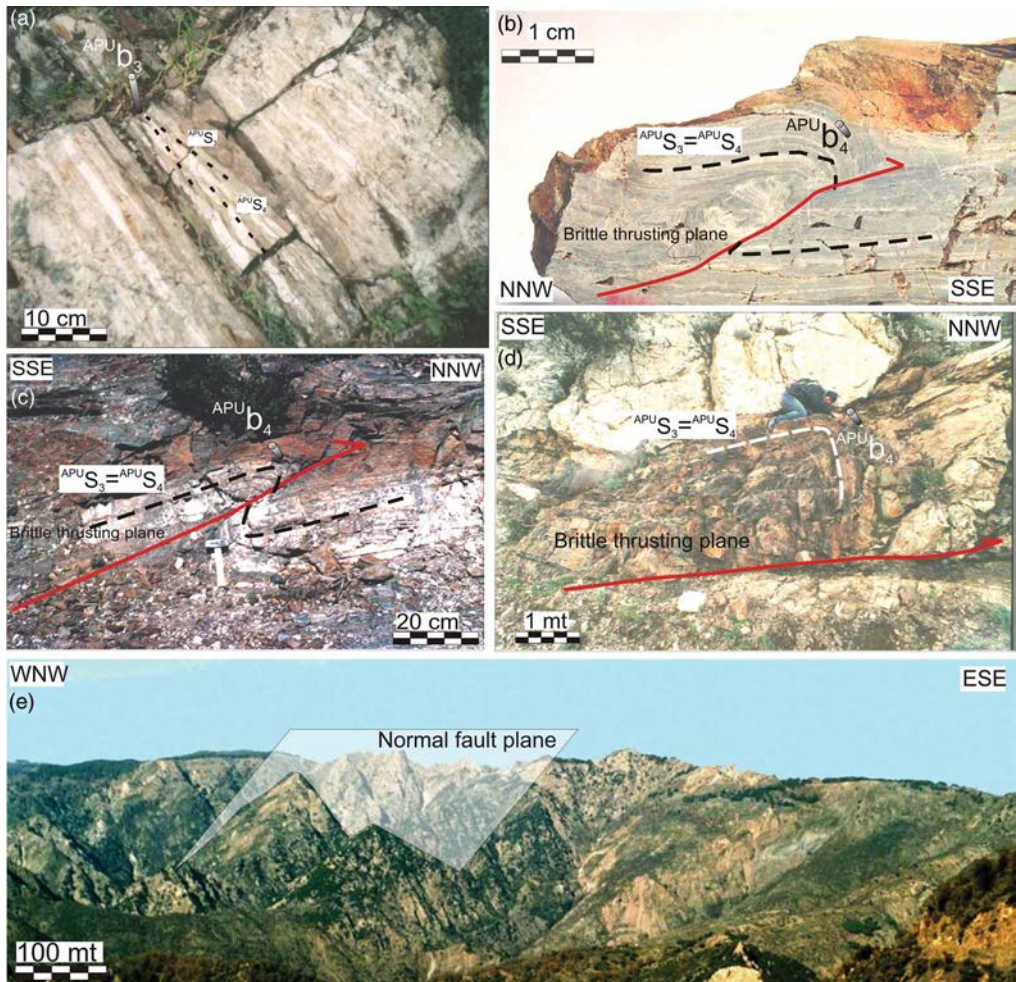


Figure 7. (a) Post-mylonitic isoclinal folding in laminated leucocratic gneiss (APU); (b), (c), (d) Fractal distribution of thrusting activity from centimeter to meter sized ramp and flat structures; (e) Triangular facets delineating normal fault planes along the southern slope of Monte Perre (Map 1).

## 5. Microstructural and Petrological Features

Microstructural and petrological analyses permitted integration of field investigations allowing reconstruction of the sequence of the blasto-deformational relationships of the outcropping crystalline basement units (Figure 5), allowing us to constrain the evolution of the single unit in the frame of the present-day joint geological scenario.

### 5.1. Madonna di Polsi unit

The MPU rock-types outcropping in the study area are mainly constituted from south to the north by chlorite-muscovite schists ( $Qtz + Wmca + Chl + Pl \pm Ep \pm Ttn$ ), muscovite-epidote schists ( $Qtz + Wmca + Ep + Pl \pm Bt \pm Chl \pm Grt$ ), muscovite-amphibole schists ( $Qtz + Wmca + Amph + Pl \pm Bt \pm Chl \pm Ep \pm Grt \pm Ttn \pm Rt$ ) and muscovite-garnet schists ( $Qtz + Wmca + Pl + Grt \pm Bt \pm Chl \pm Ep \pm Ttn \pm Rt$ ), subordinately accompanied by calc-schist ( $Cc + Qtz + Wmca + Flog + Ab \pm Ttn \pm Ep \pm opaques$ ).

The evolution from the  $^{MPU}D_1$  to  $^{MPU}D_2$  deformational event is linked to the prograde metamorphic trajectory ( $^{MPU}M_1$ – $^{MPU}M_2$ ) characterized by a PT path ranging from 0.95 to 1.35 GPa for T from 400° to 560 °C, constrained by means of thermodynamic modeling of selected garnet-muscovite bearing schist, which allowed the better rocks to constrain the PT history of the unit in view of the presence of well preserved compositionally zoned pre-mylonitic garnet porphyroclast (XSp<sub>s</sub>0.23-0.05, XGr<sub>s</sub>0.38-0.07, XAlm<sub>s</sub>0.74-0.43, XPyr<sub>s</sub>0.15-0.02) (Map 2) (Cirincione et al., 2008a). This is indeed characterized by a complex system of inclusion trails highlighted by the alignment of ilmenite, epidote, chlorite and white mica with a moderate to high-phengite content (i.e. 3.04 to 3.35 Si a.p.f.u. – atom per formula unit) (Figure 8a) (Map 2). The subsequent shear event ( $^{MPU}D_3$ ) produced a pervasive mylonitic foliation  $^{MPU}S_3$  and a stretching lineation  $^{MPU}L_1$  (Maps 1 and 2) locally accompanied by the formation of syn-tectonic intrafolial asymmetrical folds, S-C and S-C-C' fabrics as well as oblique foliation depicted by the alignment of quartz re-crystallized micrograins within pseudomorphosed ribbon-like quartz levels (Figure 8b–d). Syn-mylonitic metamorphism ( $^{MPU}M_3$ ), constrained by means of the widespread distributed syn-kinematic paragenetic equilibria (i.e. Qtz + Wmca<sub>3</sub> + Chl<sub>3</sub> ± Grt<sub>3</sub> ± Pl<sub>3</sub> ± Czo ± Tur ± Amph<sub>2</sub>), well demonstrated within the pressure shadows of the pre-kinematic garnet/feldspar porphyroclasts (Figure 8d), retrogradely ranging from 560 to 480°C and from 0.95 to

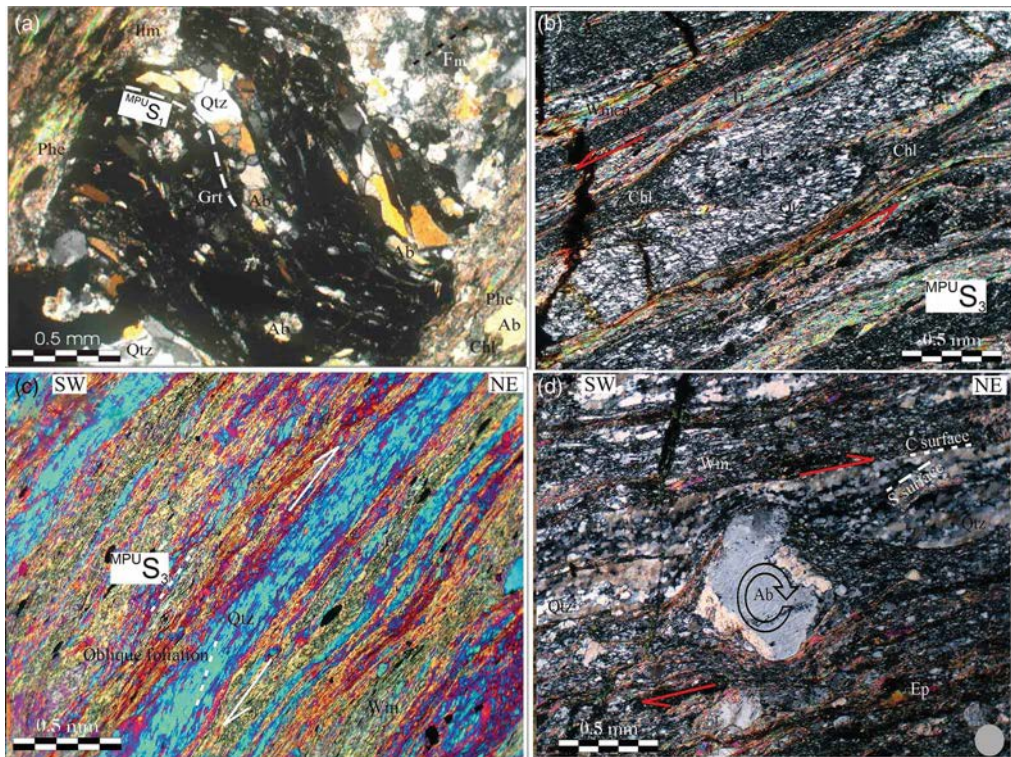


Figure 8. Petrographical features of the Madonna di Polsi Unit (a) Inclusion trails within garnet porphyroclast of the MPU (nicols +); (b) Intrafoliar folds within mylonitic levels (MPU) (nicols +); (c) Oblique foliation given by the preferential elongation of new forming quartz grains within pseudomorphosed ribbon-like quartz level (MPU) (nicols + with quartz wedge); (d) Mylonitic micaschist with  $\sigma$ -type plagioclase porphyroclast and SC structure consistent with a top to NE sense of shear (MPU) (nicols +).

0.50 GPa (Map 2). A fourth deformational stage ( ${}^{\text{MPU}}\text{D}_4$ ) caused asymmetrical to isoclinal folding of the  ${}^{\text{MPU}}\text{S}_3$  mylonitic foliation, rarely producing a new foliation surface ( ${}^{\text{MPU}}\text{S}_4$ ).

## 5.2. *Aspromonte Peloritani unit*

The main rock-types which constitute the APU are mainly represented by paragneiss and micaschist ( $\text{Qtz} + \text{Pl} + \text{Bt} + \text{Wmca} \pm \text{Sill} + \text{Kfs} \pm \text{Grt} \pm \text{And}$ ) and by augen gneiss ( $\text{Qz} + \text{Pl} + \text{Kfs} + \text{Bt} \pm \text{Ms}$ ), weakly to strongly mylonitic leucogneiss ( $\text{Qtz} + \text{Pl} + \text{Wmca} \pm \text{Kfs} \pm \text{Bt}$ ), amphibolites and amphibole gneiss ( $\text{Amph} + \text{Pl} + \text{Qtz} + \text{Bt} \pm \text{Ttn} \pm \text{Ep}$ ). A rare, unmappable, intrusion of weakly peraluminous trondhjemites ( $\text{Qtz} + \text{Pl} + \text{Bt} \pm \text{Kfs} \pm \text{Wmca} \pm \text{Sill}$ ) and strongly peraluminous leuco-granodiorites and granites ( $\text{Qtz} + \text{Pl} + \text{Kfs} + \text{Wmca} + \text{Bt} \pm \text{Sill} \pm \text{And} \pm \text{Crd}$ ) of late-Hercynian age, also occur (Fiannacca et al., 2005; Fiannacca et al., 2008; Rottura et al., 1990).

The first relic deformational event ( ${}^{\text{APU}}\text{D}_1$ ), linked to an early isoclinal folding, produced the oldest identifiable metamorphic surface ( ${}^{\text{APU}}\text{S}_1$ ), dated to 330 Ma (Bonardi et al., 1987), (Figures 5b and 9a). This stage is characterized by relic mineralogical assemblages consisting of quartz, andesine ( $\text{Pl}_1$ ), almandine garnet (with relatively low grossular and high spessartine contents) ( $\text{Grt}_1$ ), sillimanite, biotite ( $\text{Bt}_1$ ), muscovite s.s ( $\text{Wmca}_1 \pm \text{K-feldspar}$ ). The microcrenulation of  ${}^{\text{APU}}\text{S}_1$  represents the subsequent deformation phase ( ${}^{\text{APU}}\text{D}_2$ ), locally producing a  ${}^{\text{APU}}\text{S}_2$  schistosity (Figures 5b and 9b), given by the aligned growth of  $\text{Qtz} + \text{Pl}_2 + \text{Wmca}_2 \pm \text{Bt}_2 \pm \text{Grt}_2 \pm \text{Chl}_1 \pm \text{And}_1$ .

The following recognized mylonitic shearing stage ( ${}^{\text{APU}}\text{D}_3$ ), developed along a deep-seated compressional shear zone (Ortolano et al., 2005), coincide with the same mylonitic event (e.g.  ${}^{\text{MPU}}\text{D}_3$ ) observed for the MPU (Figure 5b and 5c). This last deformational stage gave rise to a pervasive overprint, which locally replaced the pre-existing foliations, producing a weak to strong grain size reduction (Cirrincione et al., 2009, 2010) (Figures 4b and 9c and 9d). During this last stage a new mineralogical assemblage characterized by quartz, albite ( $\text{Pl}_3$ ), low phengite white mica ( $\text{Wmca}_3$ ), clinozoisite, ilmenite, chlorite, tourmaline ( $\text{Tur}_1$ ) and biotite ( $\text{Bt}_3$ ), occurs, where the iso-oriented mica layers depict the weakly to strongly pervasive mylonitic foliation ( ${}^{\text{APU}}\text{S}_3$ ) and, on the foliation surface, the quartz ribbon-like layers delineate the stretching lineation ( ${}^{\text{APU}}\text{L}_1$ ). A post-mylonitic deformational stage ( ${}^{\text{APU}}\text{D}_4$ ) produces an isoclinal folding of the previous fabric with the formation of a new axial plane foliation ( ${}^{\text{APU}}\text{S}_4$ ) parallel with the previously detected mylonitic one along which re-crystallize plagioclase ( $\text{Pl}_4$ ), white mica ( $\text{Wmca}_4$ ) and clinozoisite (Figures 5b, 7a and 9e and 9f).

The PT range of the relic Variscan tectono-metamorphic evolution, constrained by means of the observed paragenetic sequence of the first sample, varies from  $0.56 \pm 0.05$  GPa at  $570^\circ \pm 10^\circ\text{C}$  to peak at conditions of 0.63 GPa for a temperature of  $710^\circ\text{C}$  (Map 2) (Cirrincione et al., 2008a). These conditions are in agreement with the occurrence of relic sillimanite in equilibrium with biotite inclusions within plagioclase cores. The following recognized paragenetic equilibria (i.e.  $\text{Qtz} + \text{Pl}_2 + \text{Wmca}_3 \pm \text{Bt}_2 \pm \text{Grt}_2 \pm \text{Chl}_1 \pm \text{And}_1$ ) permitted depiction of an evolution consistent with a retrograde Variscan-type metamorphism, characterized by P of 0.25 GPa at T of  $540^\circ\text{C}$  (Cirrincione et al., 2008a; Ortolano et al., 2005), probably linked to a late Variscan widespread episode of hydration under decreasing temperatures caused by the massive emplacement of metaluminous to strongly peraluminous late-Variscan granitoids at about 300 Ma (Appel et al., 2011; Fiannacca et al., 2008; Rottura et al., 1990).

Finally, a subsequent late Alpine shearing event has been recognized, highlighted by a clear detectable retrograde mineral paragenesis ( $\text{Qtz} + \text{Bt}_3 + \text{Wmca}_3 + \text{Chl}_2 + \pm \text{Grt}_3 \pm \text{Pl}_3 \pm \text{Tur}$ ) which allows the PT conditions for the mylonitic overprint to be constrained at a pressure of  $0.38 \pm 0.14$  GPa for a temperature of  $475^\circ \pm 25^\circ\text{C}$  (Map 2).



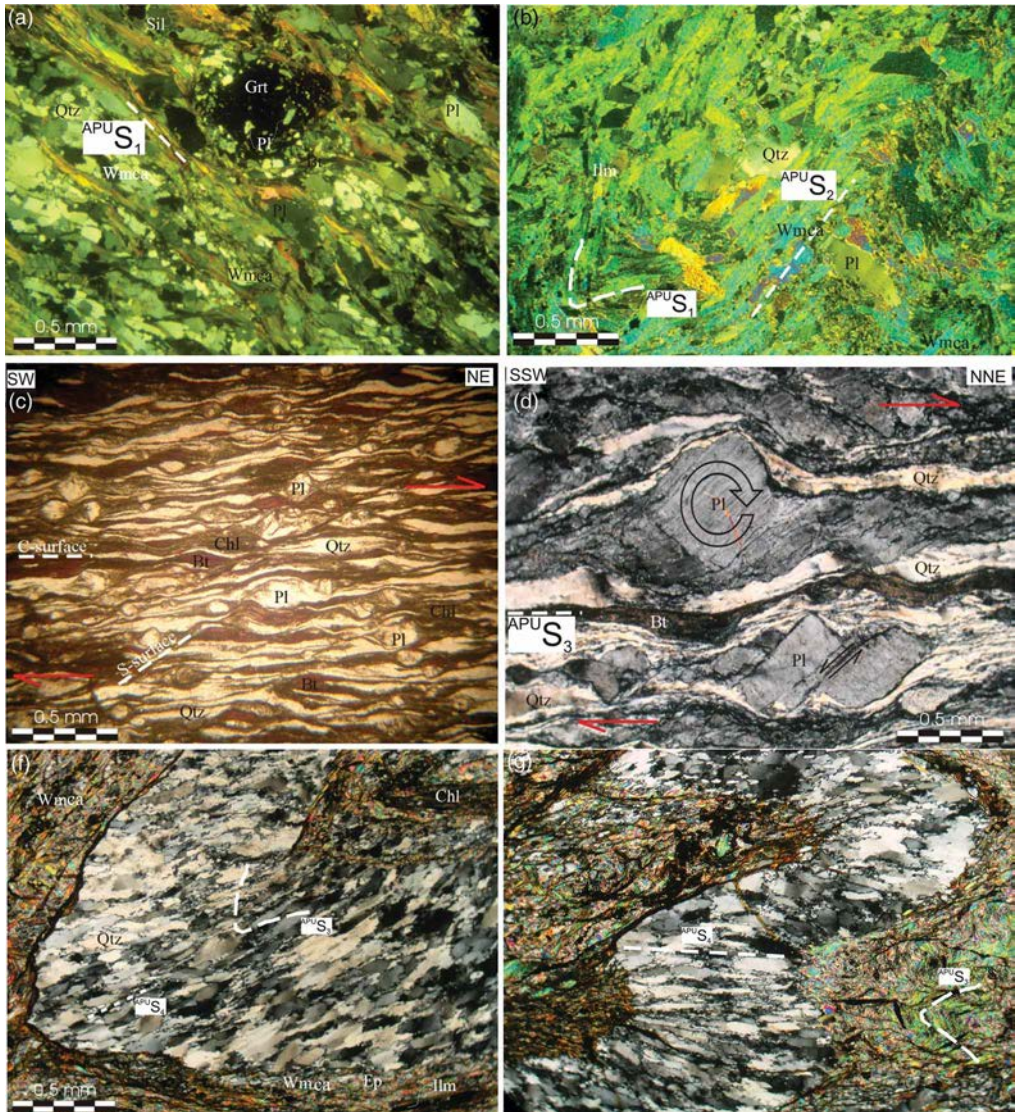


Figure 9. Petrographical features of the Aspromonte-Peloritani Unit (a) axial planar schistosity ( $^{APU}S_1$ ) highlighted by  $Qtz + Pl_1 + Bt_1 + Wmca_1 + Grt_1 + Sill$  assemblage (nicols +); (b) Incipient crenulation schistosity ( $^{APU}S_2$ ) developing in lepidoblastic levels of the sillimanite bearing paragneiss (APU) (nicols +); (c) Mylonitic paragneiss of the APU with SC structure consistent with a top to NE sense of shear (nicols +); (d) Mylonitic leucogneiss of the APU with  $\delta$ -type and antithetic book-shelf-sliding structure consistent with a top to NNE sense of shear (nicols +); (e), (f) Post-mylonitic isoclinals folding with formation of new axial plane foliation ( $^{APU}S_4$ ) (nicols +).

### 5.3. Stilo unit

The main recognized deformational events recognized in the rock-types of the Stilo Unit can be entirely ascribable to the Variscan orogeny (Crisci et al., 1982; Fazio et al., 2012) where, the sedimentary surface, appears at mesoscopic scale as isoclinally folded quartz layers, leading to the formation of a new axial plane foliation ( $^{SU}S_1$ ) accompanied by a widespread recognizable

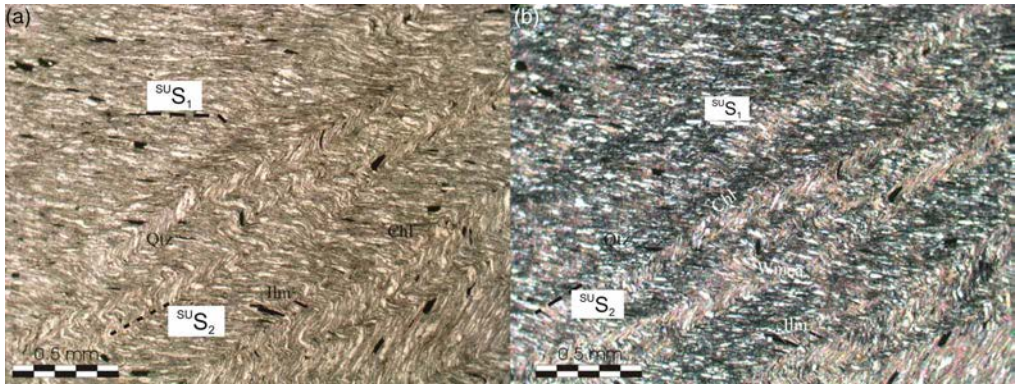


Figure 10. Petrographical features of the Stilo Unit (a) (nicols +), (b) (nicols =) Incipient crenulation schistosity ( $^{SU}S_2$ ) due to the micro-folding of the ( $^{SU}S_1$ ) surface.

fold axis ( $^{SU}b_1$ ) (Figure 4a'). The syn- $^{SU}S_1$  assemblage (Qtz+Ilm+Wmca<sub>1</sub>+Bt<sub>1</sub>+Pl<sub>1</sub>) is partly replaced by minerals such as chlorite (Chl<sub>1</sub>), white mica (Wmca<sub>2</sub>) and biotite (Bt<sub>2</sub>) locally growing along a weakly to strongly pervasive crenulation cleavage foliation ( $^{SU}S_2$ ) (Figures 5a and 10a and 10b), which creates an associated microfold hinge lineation ( $^{SU}b_2$ ).

## 6. Conclusion

Result from the presented GIS-based infrastructure was the construction of two different outputs, which present a variety of aspects for each structural and petrological feature characterizing the mapping activity in crystalline basement areas. All the potential multi-scale information has been included, ranging from an inspection site up to the different outputs of laboratory analyses, as well as the related metadata acquisition criteria. This will allow the potential to include many more items of information from the sampling activity, including those referring to the laboratory analytical stages.

The first output is a classic geological map at 1:25,000 scale using, as topographic basemap, the current 1:25,000 scale map of the Italian Military Geographic Institute, together with four original geological cross-sections.

The second output is the result of the interpolation of structural data derived from ~500 structural stations, mainly located in the two lowermost metamorphic units (i.e. the Madonna di Polsi and Aspromonte Peloritani units). This derives the present-day trend of the late Oligocene-early Miocene mylonitic structural features, related to the early Alpine evolutionary stage of this original southern European block. The structural outline is accompanied by the petrological features of ~200 analyzed samples with the aim of highlighting the whole-rock- and mineral-chemistry of selected representative samples accompanied by the PT constraints derived from the thermodynamic modeling of further samples. This is useful for completing the reconstruction of the tectono-metamorphic evolution of the two lowermost crystalline basement units of the area, as representative of pre- to late- Alpine History of this original southern European block.

## Software

The geological maps were compiled using ESRI ArcGis 10.2 version and refined using Corel Draw 12. Stereonet plots were produced using Stereonet (Allmendinger, 2011)

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## Note

1. It is a diagrammatic graph-based semi-formal language for specifying, visualizing, constructing, and documenting the artifacts of an information system, allows to model any domain of application also in multi-disciplinary contexts.

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