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Tectonics

# Structural setting and tectonic evolution of the Apennine Units of northern Calabria

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**Abstract**

A new structural–stratigraphic synthesis of the Apennine units of northern Calabria is presented. The Meso-Cenozoic successions are grouped into two tectonic units, named Pollino–Ciagola Unit (PCU) and Lungro–Verbicaro Unit (LVU), comprising terrains formerly attributed to five different tectonic units. Fe–Mg carpholite and blue amphibole record HP–LT metamorphism in the LVU, followed by progressive decompression leading to final greenschist facies re-equilibration during dominantly extensional deformation. Final tectonic emplacement of the LVU over the PCU post-dated the metamorphism of the LVU and was accompanied by intense ductile deformation along zones of strain localisation in footwall rocks. All of the units were later affected by folding and minor thrusting during subsequent Apennine tectonics. ***To cite this article: A. Iannace et al., C. R. Geoscience 337 (2005).***


**Résumé**

**Mise en place structurale et évolution tectonique des Unités apenniniques en Calabre septentrionale.** Une nouvelle synthèse structurale et stratigraphique des Unités apenniniques de Calabre septentrionale est ici présentée. Les successions méso-cénozoïques sont regroupées en deux unités tectoniques, désignées sous le nom de Pollino–Ciagola (PCU) et Lungro–Verbicaro (LVU), comprenant des formations antérieurement attribuées à cinq unités tectoniques différentes. La carpholite Fe–Mg et l'amphibole bleue témoignent d'un métamorphisme HP–LT dans la LVU, suivi par une décompression, conduisant à un rééquilibrage final en faciès schistes verts, pendant la déformation à dominante extensionnelle. L'emplacement tectonique final de la LVU sur la PCU post-date le métamorphisme de la LVU et a été accompagné d'une déformation ductile intense le long de zones de tension dans les roches du compartiment chevauché. Toutes ces unités ont été ultérieurement plissées et légèrement charriées lors de la tectonique apenninique. ***Pour citer cet article : A. Iannace et al., C. R. Geoscience 337 (2005).***


*Keywords:* Calabria; Southern Apennines; HP–LT metamorphism; Fe–Mg Carpholite; Regional geology

*Mots-clés :* Calabre ; Apennin méridional ; Métamorphisme HP–BT ; Carpholite Fe–Mg ; Géologie régionale

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## 1. Introduction

The aim of the present paper is to provide a new synthesis of the regional geology of the Tyrrhenian side of northern Calabria between Maratea and Cetraro. This is a key area in the western Mediterranean alpine chains in that it represents the connection between the sedimentary and non-metamorphic carbonate and pelitic successions of the external Apennine domains with the ophiolitic units of the Calabrian Arc, affected by HP–LT to greenschist facies Alpine metamorphism.

The geology of the study area has been investigated mainly in the 1960s by French and Italian teams within the framework of several projects of geological mapping [6,7,14,21,22]. These studies provided a great amount of data, pointing out the extreme complexity of the regional geology. Subsequently, a different stratigraphic-structural setting was proposed [1,3], which, as pointed out by some of us in several recent papers [23–25], did not provide substantial original data and left open several crucial points concerning the stratigraphy and the deformation characteristics of the successions. Nevertheless, this latter structural-stratigraphic scheme has been generally accepted, with minor modifications, in most of the papers concerned with the geodynamics of the area [2,4,11,18,29,43]. Even a recent contribution by Rossetti et al. [38], proposing a new geodynamic interpretation, is mainly based on structural and petrologic data, without any detailed evaluation of the stratigraphic architecture.

Because of the great interest of the region, it was thus urgent to carry out a reappraisal of the stratigraphic and structural framework and to put some order in the quite confusing stratigraphic nomenclature produced by the numerous published papers. In this study, after a critical evaluation of the previous literature, we propose a new stratigraphic setting for the area, based on a thorough field re-examination of the geology of the region [17,25,26,44,45]. The latter, integrated within the results of structural and petrologic studies, still in progress, allows us to work out a new, detailed palaeogeographic and geodynamic reconstruction. In particular, strong evidence for HP–LT metamorphism in the Apulian continental palaeomargin is provided here for the southern Apennines.

## 2. Previous studies

The historical and fundamental works by Cortese [15] and Quitzow [36] pointed out for the first time the occurrence in the area of a complex mix of carbonates, phyllites, metabasalts, and marbles. Grandjacquet [21,22] and Compagnoni and Damiani [14] were the first authors who mapped and described in modern times the area. The stratigraphic units they described have been later on rearranged in different structural frameworks, as we have shown diagrammatically in Fig. 1. The main stratigraphic units occurring in the area are the following:

- Middle Triassic phyllites with carbonate intercalations of the Lungro area;
- Ladinian-Carnian metalimestones in the Cozzo del Pellegrino massif;
- Norian–Rhaetian dark dolomites widespread across the whole region;
- a Rhaetian to Palaeogene slope to basin carbonate and cherty succession;
- a Norian to Miocene carbonate platform succession in the Pollino Massif area;
- laminated, recrystallised limestones in the Campotenese and Monte Ciagola area (*calcaires plaquettés*);
- low-grade metapelites of the Lao River valley.

Grandjacquet [21,22] and Compagnoni and Damiani [14] considered these units as derived from a carbonate platform domain and an adjoining slope and pelagic basin (Fig. 1). Later on, Bousquet and Grandjacquet [8] and Bousquet [7] interpreted the Middle–Upper Triassic phyllites and carbonates as the base of the platform carbonate succession. However, as already pointed out in a recent study [24], this relationship has no actual field evidence, whereas the stratigraphic transition to the slope to basin succession has been confirmed [24,25].

Amodio Morelli et al. [1], in the most cited synthesis of the area, claimed that it was necessary to separate the non-metamorphic successions of the Pollino Massif from the metamorphic ones, the latter including the Triassic phyllites and carbonates of the Lungro area and the *calcaires plaquettés*. Hence they introduced the metamorphic San Donato Unit, which has been quoted in most of the subsequent literature, but has never been properly mapped. Moreover, its distinction contrasted with the gradual transition between the *calcaires plaquettés* and the undeformed platform carbonated reported and mapped by previous workers [7,14]. In fact, Iannace and Vitale [23] have recently demonstrated that part of the rock units considered as metamorphic actually consist of highly deformed carbonates and marls involved in zones of localised strain contained within the unmetamorphosed limestones. Furthermore, in Amodio Morelli et al. [1] the low-grade metapelites of the Lao River valley, con-

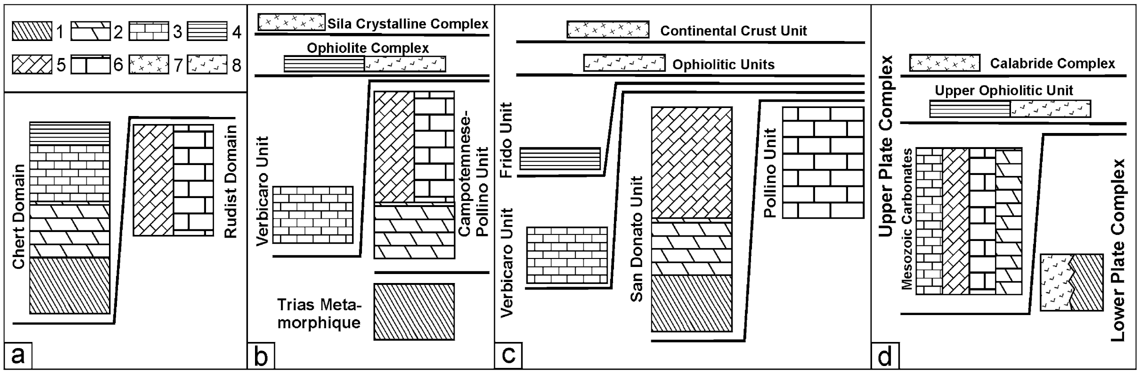


Fig. 1. Synoptic scheme showing structural interpretations of the successions exposed in the studied area according to: (**a**) Compagnoni and Damiani [14] and Grandjacquet [22], (**b**) Bousquet and Grandjacquet [8], (**c**) Amodio Morelli et al. [1], (**d**) Rossetti et al. [38]. **1**: Middle Triassic phyllites; **2**: Ladinian Carnian meta-limestones; **3**: Norian to Palaeogene slope-to-basin carbonate and cherty succession; **4**: low-grade metapelites of the Lao River valley; **5**: laminated, recrystallised limestones of Campotenese and Monte Ciagola (*calcaires plaquettés*); **6**: Norian to Miocene carbonate platform of Monte Pollino; **7**: crystalline continental basement rocks; **8**: ophiolitic rocks. Bold lines represent major tectonic contacts.

Fig. 1. Schéma montrant les interprétations structurales des successions affleurant dans la zone étudiée selon (**a**) Compagnoni et Damiani [14] et Grandjacquet [22], (**b**) Bousquet et Grandjacquet [8], (**c**) Amodio Morelli et al. [1], (**d**) Rossetti et al. [38]. **1** : Métapélites du Trias moyen ; **2** : métacalcaires du Ladinien–Carnien ; **3** : succession carbonatée et siliceuse de pente et bassin du Norien–Paléogène ; **4** : métapélites de la vallée du Lao ; **5** : calcaires laminés et recristallisés de Campotenese et Monte Ciagola ; **6** : carbonates de plate-forme du Monte Pollino ; **7** : roches cristallines de socle ; **8** : roches ophiolitiques. Les lignes noires représentent les contacts tectoniques.

sidered as a Miocene flysch in previous studies [14], were attributed to the Cretaceous ophiolitic Frido unit. Finally, all of these units were tectonically overlain by slices of crystalline and ophiolitic rocks of the Calabrian Arc (Sila [5], Diamante-Terranova and Malvito [1] Units).

Rossetti et al. [38] basically accept the terminology of Amodio Morelli et al. [1], however distinguishing two main tectonic units resulting from nappe stacking followed by extensional deformation. The upper plate includes all carbonate and cherty successions, overlain by – or embedded as tectonic slices within – the metapelites of the Frido Unit. The lower plate, showing an HP–LT metamorphic signature, contains the Triassic phyllites and the ophiolitic Diamante–Terranova unit. This reconstruction, based on petrological data and inferred structural relationships, contrasts with the well-documented stratigraphic continuity between the Anisian–Carnian phyllites and the Ladinian–Carnian carbonates at Lungro [9,24,27]. Moreover, the reconstruction proposed by the authors [38] involves the occurrence of Diamante–Terranova ophiolites also below the Triassic phyllites and the carbonates; such a setting, not based on documented field evidence but on an inferred 'geometrical relationship' [38, p. 7] is at variance with the observations reported in all the previous literature. Finally, the Eocene/Oligocene initiation of metamorphism in the rocks of the upper plate contrasts with the Lower Miocene fossil content of some of the successions [14,21,40].

## 3. Geological setting

Fig. 2 shows the tectonic scheme of northern Calabria according to our data. The Meso-Cenozoic successions illustrated above can be grouped into two tectonic units: the lower one is here referred to as Pollino–Ciagola Unit (PCU), the upper one as Lungro–Verbicaro Unit (LVU). The LVU is tectonically overlain by small klippen of the ophiolite-bearing and continental crust units of the Calabrian Arc (Diamante-Terranova, Malvito [1] and Sila [5] units). In the southern part of the area, Tortonian conglomerates seal the main tectonic boundaries.

The thrust surface separating the LVU from the PCU (Fig. 2) shows a general footwall flat geometry, the rocks immediately below the contact being usually represented by the stratigraphic top part of the footwall succession. Thrust geometry in the hanging wall (LVU) includes a frontal ramp, trending WNW–ESE from the area of San Nicola Arcella to San Basile. A main detachment surface occurs along the Carnian–Norian boundary, characterised by evaporites and siliciclastic deposits. A further detachment occurs higher up along the carbonate-siliciclastic boundary in the Neogene part of the succession.

Most of this reconstruction results from careful mapping in key areas [26], coupled with a critical reinterpretation of published maps and cross-sections, particularly those of Bousquet and Grandjacquet [6,7,21,22]. With respect to all previous works, however,

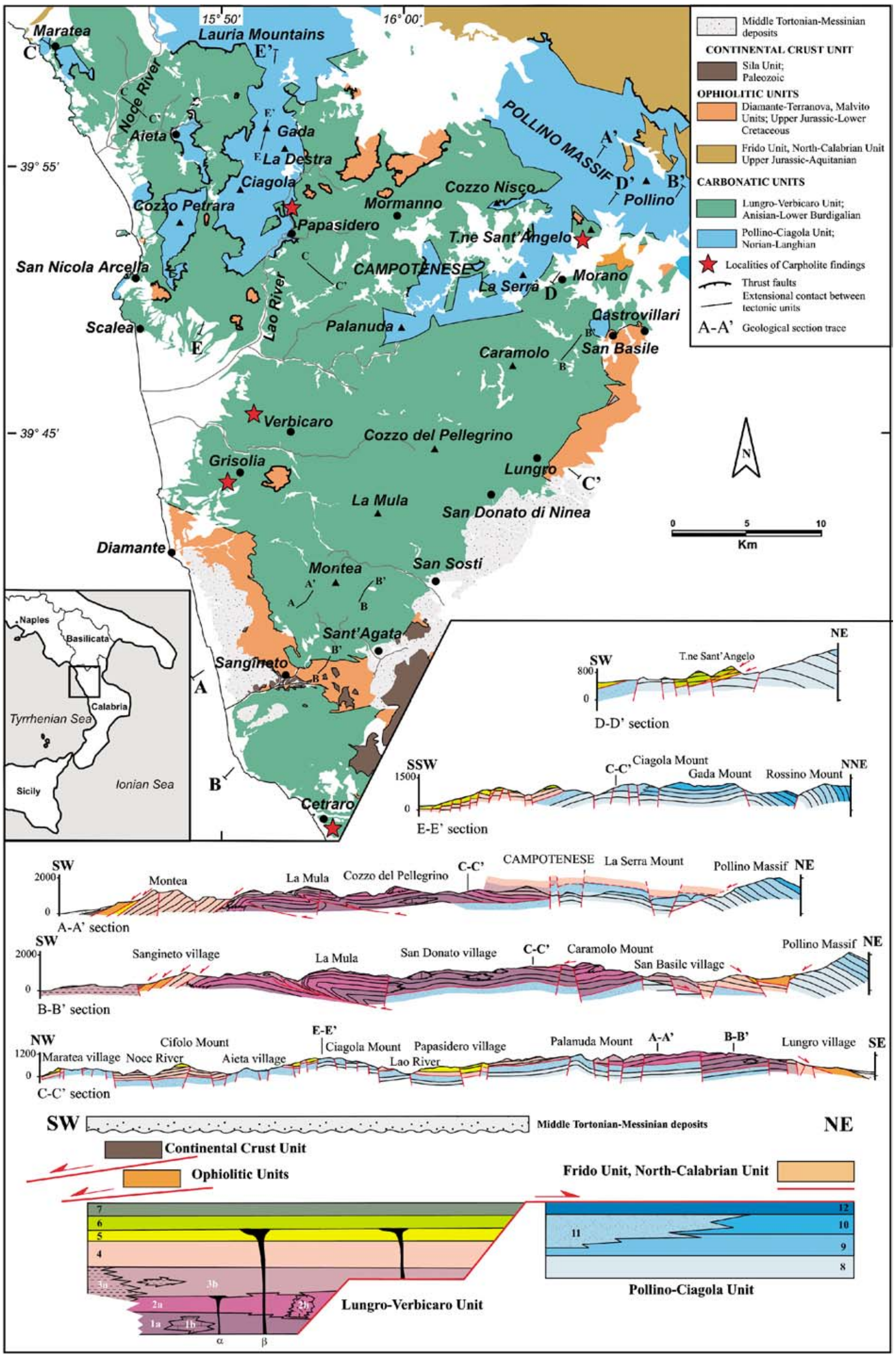


Fig. 2. Structural map, geological sections and stratigraphic-tectonic sketch of northern Calabria. Key to the stratigraphic-tectonic sketch. **1a**: Middle Triassic phyllites; **1b**: carbonate intercalations; **2a**: Ladinian–Carnian meta-limestones; **2a**: Carbonate build-ups of Monte Caramolo; **3a**: phyllites, carbonates and evaporites of Cetraro; **3b**: Carnian dolomites; **4**: Norian–Rhaetian dolomites, carbonatic conglomerates, limestones and marls; **5**: Jurassic cherty limestones and radiolarites; **6**: Upper Cretaceous–Aquitanian Colle Trodo formation; **7**: Lower Burdigalian siliciclastic deposits (Scisti del Fiume Lao); **8**: Norian–Rhaetian platform dolomites; **9**: Jurassic platform limestones; **10**: Cretaceous platform limestones; **11**: Jurassic–Palaeogene carbonatic conglomerates; **14**: Langhian Bifurto Formation; $\alpha$: Triassic basic volcanics; $\beta$: Jurassic–Cretaceous basic volcanics (limburgites).

three areas provided new evidence crucial for our geometric reconstruction: the Monte Palanuda, the San Basile village and the Timpone Sant'Angelo areas (see sections in Fig. 2). In these outcrops, it is possible to observe Carnian carbonates of the LVU, stratigraphically overlying the Anisian–Carnian phyllites and metacarbonates and grading upward to the Meso-Cenozoic Verbicaro succession Auct. The latter succession overrides deformed Palaeogene carbonates and Miocene siliciclastics of the PCU.

### *3.1. The Lungro–Verbicaro Unit*

This unit is made up of a thick succession, comprising the Anisian–Carnian metapelites and metacarbonates of the Lungro area [7,9], as well as the Verbicaro Unit [8]. The boundary between the Anisian–Carnian beds of Lungro and the Norian levels of the Verbicaro Unit, considered as a main overthrust [1,2,8], has been demonstrated to be basically stratigraphic [21,24,25]. Even though cataclasis and shear deformation occurs at this level, possibly related to both contractional and extensional tectonics, the former stratigraphic relationships are preserved in the Montea–Valle Abatemarco region. In the Sangineto–Cetraro, Lungro and San Basile areas, extensional tectonics strongly affects the succession and may be responsible for minor stratigraphic omissions [25].

#### *3.1.1. Stratigraphy*

The lower part of the stratigraphic succession (Fig. 2) consists of a thick pile of Middle Triassic phyllites and metarenites with carbonate intercalations, followed by meta-limestones and marly meta-limestones, eventually topped by Carnian layers comprising carbonates, evaporites and clastic deposits. The general stratigraphy and palaeoenvironmental interpretation have been recently reappraised by Iannace et al. [25]. Both siliciclastic input and evaporites increase toward the southwest (present coordinates). This Anisian–Carnian succession is followed by a thick dolomite interval, covering the Norian and the Rhaetian, consisting of platform, margin and slope to restricted basin facies [13,32]. In stratigraphic continuity, or locally above an angular unconformity, the post-Triassic part of the succession is represented by a cherty limestone succession of variable thickness, Jurassic in age [14]. We have found at different localities some beds of radiolarites [22], probably Dogger in age (O'Dogherthy, pers. commun.). A disconformity separates these layers from the upper part of the succession, represented by the Colle Trodo Formation [40], a resedimented unit evolving from Uppermost Cretaceous–Palaeocene coarse carbonates (*Brèche à silex* in [21] and *Brecce Poligeniche* in [14]) to calcareous and marly calcareous turbidites with red and green pelites and, finally, to metapelites and metarenites of Early Miocene age (*Flysch del Lao* Formation in [14] or *Scisti del Fiume Lao* in [6]). Basic lavas, represented by metabasalts with pillow structures and pyroxene-amphibole spessartitic dykes ('limburgites' Auct.), also occur, generally cutting through the Triassic and Jurassic formations of the unit. According to a single account [35], in a single outcrop, now destroyed, the magmatic rocks occur as dykes in the *Brecce Poligeniche* Formation. However, as clasts of basic rocks occur within the *Brecce Poligeniche*, a Jurassic or Cretaceous age appears to be most probable for the latter magmatism.

The top of the succession, represented by the *Scisti del Fiume Lao* Formation, has been loosely included [1] in the ophiolite-bearing Frido Unit of the Calabria–Lucania borderland. Even though the basal contact of the *Scisti del Fiume Lao* is often sheared, the stratigraphic relationship with the underlying formation can be observed at least at three sites: Contrada Alberosa, Tremoli, and Colle Trodo (Fig. 2). Above a few metres of turbiditic calcarenites, there are green and grey metapelites and marls with thin intercalations of brown metarenites with parallel and cross laminations. Calcarenite and calcirudite beds occur throughout the succession. Biostratigraphic analysis of the nannoplankton allowed us to date this interval as not older than Aquitanian–Lower Burdigalian, based on the presence of the index species marker *Discoaster druggii* and *Helicosphaera carteri*.

#### *3.1.2. Structures and metamorphism*

The LVU is characterised by polyphased deformation and metamorphism. Evidence for an early HP–LT metamorphism is provided by the presence of Fe–Mg carpholite that we have found in quartz veins in

Fig. 2. Carte structurale, coupes et esquisse stratigraphique–tectonique de la Calabre du Nord. La numération dans l'esquisse stratigraphique–tectonique est la suivante. **1a** : Métapélites du Trias moyen ; **1b** : intercalations carbonatées ; **2a** : métacalcaires du Ladinien–Carnien ; **2a** : récifs du Monte Caramolo ; **3a** : métapélites, évaporites et carbonates de Cetraro ; **3b** : dolomies du Carnien ; **4** : Dolomies, calcaires et marnes du Norien–Rhétien ; **5** : Calcaires à silex et radiolarites du Jurassique ; **6** : formation de Colle Trodo ; **7** : dépôts silicoclastiques du Burdigalien Inférieur ; **8** : dolomies de plate-forme du Norien–Rhétien ; **9** : calcaires de plate-forme du Jurassique ; **10** : calcaire de plate-forme du Crétacé ; **11** : niveaux conglomératiques du Jurassique–Paléogène ; **14** : formation du Bifurto du Miocène ; $\alpha$ : roches volcaniques basiques du Trias ; $\beta$ : roches volcaniques basiques (limburgites) du Jurassique–Crétacé.

the Lower Miocene *Scisti del Fiume Lao* Formation. The Fe–Mg carpholite, identified through optical microscopy and XR diffraction, consists of quite large crystals (up to several centimetres) grouped into radial aggregates nucleating from within the veins. Microprobe analyses indicate variable compositions related to an isothermal decompression path [34]. The occurrence of Fe–Mg carpholite is quite widespread across the whole area (Fig. 2) and is consistent with that of blue amphibole in the limburgites [35], as well as in greenstones contained in the Triassic phyllites [30].

The main deformation of the LVU is characterised by substantial strain localisation phenomena and dynamic recrystallisation in most limestones. It occurred under blueschist to greenschist facies conditions, as indicated by the mineral assemblages [18,19] associated with the related structures. These include:

- a dominantly flat-lying foliation, to which a mineral/stretching lineation is locally associated;
- metric to millimetric, recumbent, isoclinal intrafolial folds;
- boudinage of competent (mostly dolomite) beds;
- low- to moderately-dipping extensional shear-zones.

These structures, which appear to be associated with a dominantly coaxial strain, are mostly consistent with a bulk deformation dominated by vertical shortening and horizontal extension. It seems likely that much of the deformation records the early part of the exhumation-related tectonic evolution, as it retains kinematic coherence with structures developed under progressively lower pressure conditions.

Late structures include both regional and minor buckle folds and thrusts, probably associated with tectonic emplacement of the studied rocks onto more external units of the Apennines, and to further deformation affecting the whole tectonic edifice. Folds are mostly inclined to overturned, and ranging from open to tight. Tectonic fabrics associated with parasitic folds to major structures include a discontinuously developed crenulation cleavage in the less competent lithologies and, locally, a spaced cleavage in competent beds.

### 3.2. The Pollino–Ciagola Unit

The Pollino–Ciagola Unit (PCU) as defined here comprises not only the Pollino Massif and the Monte Ciagola–Monte Gada ridge carbonate successions, as mapped in [2,4], but also several outcrops previously referred to as the San Donato (Campotenese, Cozzo Petrara, Lao River Valley), Verbicaro (Serra Vingiolo and Punta Scalea), and Monti della Maddalena (Lao River Valley) Units.

#### 3.2.1. Stratigraphy

The carbonate succession cropping out in the Pollino Massif is the typically Apenninic, Mesozoic–Cenozoic carbonate platform succession [39]. It mainly consists of some 2000 m of lagoonal carbonate beds recording virtually continuous shallow water sedimentation from Late Triassic to Middle Eocene, with only some breaks in the Late Cretaceous and Palaeocene. The shallow water carbonates are covered by the Lower Miocene, probably Burdigalian, open shelf calcarenites (Cerchiara Formation [40]) followed by not-older-than Langhian siliciclastic, turbiditic deposits (Bifurto Formation [31, 40]).

The stratigraphic successions of the PCU in the Ciagola–Gada ridge, Aieta, Maratea and Campotenese areas have been considered as the lateral equivalent of the platform succession cropping out in the Pollino Massif [7,14]. Our field and microfacies studies, still in progress, confirm this early suggestion. The Upper Triassic beds are almost everywhere represented by peritidal dolomites with abundant fenestral facies and bivalve and gastropod-rich beds locally topped (Serra Vingiolo, Monte la Serra) by megalodontid-bearing limestones of Latest Triassic age. The Jurassic levels contain either wackestones and packstones with foraminifers, algae and oncoids (Colle Liguori, La Destra) or a high-energy calcareous facies rich in corals and echinoid fragments (Monte la Serra, Maratea, Aieta). The Cretaceous is dominated by coarse floatstones and rudstones with rudistid and gastropod fossils (*Nerinea* sp.). It is not clear whether the Palaeogene is represented in the area; however, calcareous breccias with *Nummulites* sp., both in the clasts and in the matrix, occur in the Campotenese area. These breccias rapidly evolve to thinly bedded calcarenites and marls, and finally to heavily deformed macroforaminifer-bearing marls, pelites and rare beds of quartzarenites.

#### 3.2.2. Structures

The carbonates of the PCU in the Pollino Massif are mainly affected by large-scale gentle to open folds and high-angle faults. However, most of the outcrops considered in the present study are also affected by ductile deformation localized in narrow zones [23,45]. As a general rule, the degree of deformation increases from the massive platform successions toward the resedimented slope facies to the southwest. The highest strain values are reached in the horizons closer to the siliciclastic, stratigraphically younger beds. Strain localisation led to the development of a main foliation ranging from a slaty cleavage in the pelitic beds to a shape fabric produced by flattening of the clasts in the calcareous resedimented facies [46]. A stretching lineation is often observed on the foliation surface. In very thin calcarenite beds, small-scale isoclinal folds also occur, whose axes are roughly parallel to the stretching lineation. It seems likely that these structures formed in the footwall to the LVU, the latter unit – and those further occurring on top of it – providing the tectonic load enhancing ductile deformation. At some localities (e.g., Cozzo Nisco), the main foliation within the PCU can be observed to be roughly parallel to the tectonic contact with the overlying LVU.

Close to tight folds are superposed onto the previous structures, also affecting the main foliation. The crenulation cleavage associated with these folds is well developed in the pelitic beds, whilst it is substituted by a more discontinuous and spaced cleavage in the calcarenite beds.

## 4. Discussion and conclusions

A new structural-stratigraphic framework has been obtained for the study area based on the integration of detailed stratigraphic, structural and petrologic studies with a thorough critical analysis of pre-existing works. The tectonic setting unravelled by our work represents a significant simplification with respect to that so far accepted for this area. We wish to acknowledge here that our work has re-evaluated data and interpretations by the French and Italian researchers who extensively mapped the area in the 1960s and whose results have been generally overlooked in favour of more recent and sometimes less documented works.

The tectonic interpretation proposed here, as well as the new stratigraphic and structural data, show several points of good coherence concerning the sedimentary and structural-metamorphic evolution of the entire belt. In fact, the carbonate successions of the PCU document a persisting shallow platform environment replaced toward the southwest by successions dominated by slope facies. This trend seems to continue in the LVU, in which slope and especially pelagic facies are dominant. It is interesting to observe that in this latter unit the transition from platform to pelagic environments seems to occur progressively earlier from northeast to southwest (present coordinates). Moreover, in the southwest radiolarite beds have been found, representing probably the most distal part of the basin during the Jurassic. These trends suggest that the more subsiding areas were located to the southwest. Our suggestion of a Jurassic or Cretaceous age for the basic volcanics (limburgites) is a further clue for the proximity of these areas to an oceanic realm. In summary, our reconstruction depicts a well-ordered succession of facies at the edge of a continental margin.

The tectono-metamorphic history recorded by the LVU comprises HP–LT metamorphism, followed by decompression and final greenschist facies re-equilibration during dominantly extensional deformation. Structural development and evolution occurred throughout the whole exhumation history, starting from high-pressure (blueschist facies) conditions and continuing during decompression reaching greenschist facies conditions. Our analysis suggests an early development of structural features and their continued modification during ongoing exhumation. Fe–Mg carpholite, which we found in several outcrops of Lower Miocene metapelites, has been recently proved to be a reliable indicator of significant underthrusting of continental margin successions close to oceanic complexes [20,37,42]. We have to acknowledge that the first quotations of carpholite in Calabria are due to De Roever [16] and Busato and Giampaolo [10], who described the mineral in outcrops at the time attributed to the Frido Unit and now interpreted by us as part of the LVU. Also the findings of Fe–Mg carpholite by Rossetti et al. [38] can be reconciled with our reconstruction, because their samples come from the Triassic phyllites that we include in the LVU. Other papers briefly mentioned the presence of blue amphiboles, another HP–LT index mineral, in the limburgites [35] and in metabasalts contained in the Triassic phyllites [30].

The occurrence of HP–LT minerals in the Lower Miocene *Scisti del Fiume Lao* Formation, in the Triassic phyllites and in the limburgites contained in the Jurassic carbonates, poses serious problems to the recent model of Rossetti et al. [38]. In fact, these minerals occur in both lower and upper plate as defined by the latter authors, this eliminating the inferred metamorphic break that represents the core of the model. Actually, the model of Rossetti et al. [38] appears to be flawed by insufficient stratigraphic constraints. In the description of the belt, the latter authors emphasize the importance of metapelites and ophiolites, disregarding the stratigraphy of the thick carbonate successions. These, representing the backbone of the mountain belt, are depicted in the tectonostratigraphic scheme by Rossetti et al. [38, Fig. 2] as dismembered slices included within a tectonic mélange. The reconstruction carried out in the present paper, which is a refinement of early suggestions by previous authors [24,25], shows instead that many stratigraphic and facies relationships are well preserved.

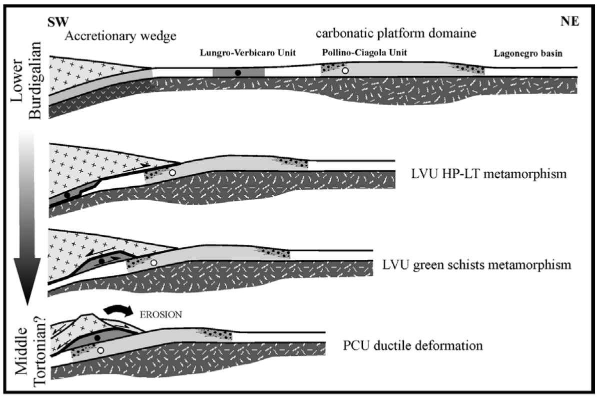


Fig. 3. Interpreted main steps of the geodynamic evolution of the studied area.

Fig. 3. Étapes principales dans l'évolution géodynamique de la zone étudiée.

The carbonate units (LVU and PCU), tectonically underlying the ophiolite nappes, retain an overall internal stratigraphic coherence despite the fact they underwent deep tectonic burial, HP–LT metamorphism and subsequent exhumation.

The final tectonic emplacement of the LVU over the PCU occurred under low-temperature conditions, but with the development of ductile deformation in the footwall and thrusts and folds in the hanging wall. In the PCU (Ciagola–Gada and Maratea areas) and in the LVU, a marked strain localisation is dominant, with local good preservation of sedimentary and palaeontological features, a characteristic that has been observed in other continental margin successions involved in underthrusting to considerable depths [41].

In Fig. 3 we attempt to frame these well-constrained data and interpretations within a possible geodynamic evolution emphasizing the points that are still open. During the Aquitanian–Burdigalian, while the Calabria crystalline and ophiolitic units are already piled up, the LVU succession is still exposed on the seafloor and receives sedimentation by a siliciclastic input. Subsequently, the LVU experiences deep underthrusting and tectonic burial. Ar/Ar ages obtained by Rossetti et al. [38] on three samples from Cetraro fit reasonably well the maximum age of metamorphism as constrained by our stratigraphic data. The much older age provided by a fourth sample dated by Rossetti et al. [38] should be discussed after a more precise topographic localisation.

Tectonic exhumation is mainly associated with extensional deformation, as witnessed by the main fabrics of the LVU, which we interpret as resulting from vertical shortening. A substantial part of the exhumation and extensional deformation occurred prior to the final emplacement of the LVU on top of the PCU, as the latter does not record comparable metamorphic conditions. The contact between the LVU and the PCU is best interpreted as a thrust, which emplaces older on younger rocks and relatively high-pressure units on top of lower pressure ones. Therefore, it can be envisaged that the exhuming LVU rock body, while experiencing ductile thinning, was bounded by a thrust at the base and was overlain by an extensional detachment. This could be tentatively located within the ophiolitic units overlying the LVU. In these units, in fact, a major, 'normal-sense' pressure break is well known to occur ([12], and references therein) and has been recently interpreted as a regional extensional detachment, based on structural data gathered south of our study area [37]. Rapid cooling occurring in the immediate footwall of an extensional detachment could also explain the preservation of Fe–Mg carpholite in the topmost part of the LVU [28]. In the footwall to such a detachment, internal deformation of the LVU appears to have been dominated by coaxial strain.

The subsequent evolution of the system occurred at shallow crustal levels, leading to the development of buckle folds and thrusts at a whole range of scales, as it is typical of the Apennines fold and thrust belt. Tortonian coarse clastics seal this evolution.

The main point that we consider still open to discussion concerns the palaeogeographic link between the original sedimentary domains pertaining to the LVU and PCU, and their relationships to oceanic areas. The more conservative interpretation of our data would indicate that the LVU sedimentary domain was bordered on one side by an oceanic realm, whereas on the other it made transition to the PCU domain. This seems to be supported by several facies analogies, especially in the Tertiary successions and by the coherence of the general facies trends. In such a hypothesis, both units would represent the most distal part of the Apulian continental margin. This interpretation needs not only further stratigraphic/sedimentologic evidence, but also a better characterisation of the thermobarometric conditions experienced by the PCU, in order to infer the approximate original length of the corresponding underthrust segment of the continental margin and check whether the estimated length is in agreement with a contiguous position of the LVU and PCU sedimentary domains.

A more articulated palaeogeographic reconstruction might involve the existence of an oceanic branch (Lucanian Ocean [5,33]) between the LVU and PCU domains. This scenario might be supported by the existence of ophiolitic units characterized by a sedimentary cover continuous up to the Early Miocene, testifying to a Burdigalian deformation. Moreover, available data suggest the possible existence of an age gap between the deformation of the LVU (which might be as old as Aquitanian–Early Burdigalian) and the PCU (Serravallian) in more external areas. The major weaknesses of this hypothesis are the lack of outcrops showing Lucanian ophiolites sandwiched between LVU and PCU, and of a direct dating of the youngest sediments of the PCU in the study area.

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## References

[1] L. Amodio Morelli, G. Bonardi, V. Colonna, D. Dietrich, G. Giunta, F. Ippolito, V. Liguori, S. Lorenzoni, A. Paglionico, V. Perrone, G. Piccaretta, M. Russo, P. Scandone, E. Zanettin Lorenzoni, A. Zuppetta, L'Arco calabro-peloritano nell'orogene appennino-maghrebide, Mem. Soc. Geol. It. 17 (1976) 1–60.

[2] G. Bigi, D. Cosentino, M. Parotto, R. Sartori, P. Scandone, Structural Model of Italy, CNR, Italy, 1991.

[3] G. Bonardi, G. Cello, V. Perrone, L. Tortorici, E. Turco, A. Zuppetta, The evolution of the northern sector of the Calabria-Peloritani Arc in a semiquantitative palinspastic restoration, Boll. Soc. Geol. It. 101 (1982) 259–274.

[4] G. Bonardi, B. D'Argenio, V. Perrone, Carta Geologica dell'Appennino Meridionale in scala 1:250 000, Mem. Soc. Geol. It. 41 (1988) 1341.

[5] G. Bonardi, W. Cavazza, V. Perrone, S. Rossi, Calabria–Peloritani Terrane and Northern Ionian Sea, in: G.B. Vai, P. Martini (Eds.), Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins, Kluwer Academic Publishers, Dordrecht/Boston/London, 2001, pp. 287–306.

[6] A.N. Burton, Carta geologica della Calabria alla scala 1:25 000. Relazione generale, Cassa per il Mezzogiorno, Servizio Bonifiche, Roma, 1971.

[7] J.-C. Bousquet, La tectonique tangentielle des séries calcaires-dolomitiques du Nord-Est de l'Apennin Calabro-Lucanien (Italie Meridionale), Geol. Romana X (1971) 23–51.

[8] J.-C. Bousquet, C. Grandjacquet, Structure de l'Apennin calabro-lucanien (Italie méridionale), C. R. Acad. Sci. Paris, Ser. D 264 (1969) 204–207.

[9] J.-C. Bousquet, J. Mégard Galli, J.H. Zorn, Quelques éléments de datation du Trias moyen et de l'Apennin Calabro-Lucanien, Geol. Rom. 17 (1978) 71–83.

[10] S. Busato, C. Giampaolo, Ferrocarpholite from Mormanno (northern Calabria, Italy), Periodico di Mineralogia 52 (1983) 403–426.

[11] G. Cello, C. Invernizzi, S. Mazzoli, Structural significance of tectonic processes in the Calabrian Arc, Southern Italy: evidence from the oceanic-derived Diamante Terranova Unit, Tectonics 15 (1996) 187–200.

[12] G. Cello, S. Mazzoli, Kinematics of primary contacts between low- and relatively high-pressure rocks in orogens, J. Struct. Geol. 18 (1996) 519–522.

[13] A. Climaco, M. Boni, A. Iannace, V. Zamparelli, Platform margins, Microbial/Serpulids Bioconstructions and Slope-to-basin Sediments in the Upper Triassic of the 'Verbicaro Unit' (Lucania and Calabria, Southern Italy), Facies 36 (1997) 37–56.

[14] B. Compagnoni, A.V. Damiani, Note illustrative della Carta Geologica d'Italia. Foglio 220 Verbicaro, Servizio Geologico d'Italia, 1971.

[15] E. Cortese, Descrizione geologica della Calabria, Mem. descr. Carta Geol. It. IX (1895).

[16] E.W.F. De Roever, G. Piccarreta, F.F. Beunk, Blue amphiboles from NW and Central Calabria, Italy, Period. Mineral. 43 (1974) 1–37.

[17] M. D'Errico, L'evoluzione tettono-stratigrafica dell'Unità di Verbicaro Auct. tra il Giurassico ed il Miocene e sue relazioni con le unità interne Appenniniche, PhD thesis, Università di Napoli Federico II, Naples, Italy, 2005, 172 p.

[18] J.F. Dewey, M.L. Helman, E. Turco, D.H.W. Hutton, S.D. Knott, Kinematics of the western Mediterrean, in: M.P. Coward, D. Dietrich, G. Park (Eds.), Alpine Tectonics, Spec. Publ. Geol. Soc. Lond. 45 (1989) 265–283.

[19] D. Dietrich, La geologia della Catena Costiera Calabra tra Cetraro e Guardia Piemontese, Mem. Soc. Geol. It. 95 (1976) 61–141.

[20] G. Giorgetti, B. Goffé, I. Memmi, F. Nieto, Metamorphic evolution of Verrucano metasediments in northern Apennines: new petrological constraints, Eur. J. Mineral. 10 (1998) 1295–1308.

[21] C. Grandjacquet, M.-J. Grandjacquet, Géologie de la zone de Diamante–Verbicaro (Calabre), Geol. Rom. I (1962) 297–314.

[22] C. Grandjacquet, Données nouvelles sur la tectonique tertiaire des massifs calabro-lucaniens, Bull. Soc. géol. France 4 (1962) 695–706.

[23] A. Iannace, S. Vitale, Ductile shear zone on carbonates: the *calcaires plaquettés* of northern Calabria (Italy), C. R. Geoscience 336 (2004) 227–234.

[24] A. Iannace, M. Boni, V. Zamparelli, The Middle–Upper Triassic of the San Donato Unit Auct. (Northern Calabria): stratigraphy, palaeogeography and tectonic implications, Riv. Ital. Paleontol. Stratigr. 101 (1995) 301–324.

[25] A. Iannace, F.J. Garcia-Tortosa, S. Vitale, The Triassic metasedimentary successions across the boundary between Southern Apennines and Calabrian Arc (Northern Calabria, Italy), Geol. J. 40 (2005) 155–171.

[26] A. Iannace, M. D'Errico, S. Vitale, Carta Geologica 1:100 000 della Calabria Settentrionale, Studi Geol. Camerti, nuova serie 2 (2004).

[27] F. Ietto, R. Romano, Middle Triassic age and lithostratigraphy of the Diplopora marbles from the San Donato Unit Auct. (Catena Costiera, Calabria, Italy), Boll. Soc. Paleontol. Ital. 40 (2001) 17–24.

[28] L. Jolivet, C. Faccenna, B. Goffé, M. Mattei, F. Rossetti, C. Brunet, F. Sorti, R. Funiciello, J.-P. Cadet, N. d'Agostino, T. Parra, Midcrustal shear zones in postorogenic extension: Example from northern Tyrhenian Sea, J. Geophys. Res. 103 (1998) 143–160.

[29] S.D. Knott, Structure, kinematics and metamorphism in the Liguride Complex, southern Apennines, Italy, J. Struct. Geol. 16 (1994) 1107–1140.

[30] G. Maciotta, A. Zuppetta, O. Zeda, Caratteri petrografici e significato geotettonico delle metavulcaniti basiche triassiche dell'Unità di San Donato (Calabria), Boll. Soc. Geol. It. 105 (1985) 195–202.

[31] E. Patacca, P. Scandone, M. Bellatalia, N. Perilli, U. Santini, The Numidian Sand event in the Southern Apennines, in: Mem. Sci. Geol. All. al. XLIII, 1992, pp. 297–337.

[32] E. Perri, A. Mastrandrea, C. Neri, F. Russo, A Micrite-Dominate Norian Carbonate Platform from Northern Calabria (Southern Italy), Facies 49 (2003) 101–118.

[33] V. Perrone, Une nouvelle hypothèse sur la paléogéographie et l'évolution tectonique des Unités de Verbicaro et de San Donato (région calabro-lucanienne, Italie) : implications sur la limite Alpes–Apennin en Calabre, C. R. Acad. Sci. Paris, Ser. IIa 322 (1996) 877–884.

[34] V. Perrone, A. Martín-Algarra, S. Critelli, F.A. Decandia, M. D'Errico, A. Estevez, A. Iannace, M. Lazzarotto, M. Martín-Martín, I. Martín-Rojas, S. Mazzoli, A. Messina, G. Mongelli, S. Vitale, N.M. Zaghloul, 'Verrucano' and 'Pseudoverrucano' in the central-western Mediterranean Alpine chains, in: G. Moratti, A. Chalouan (Eds.), Geology and active tectonics in western Mediterranean and North Africa, Geol. Soc. Spec. Publ. (in press).

[35] D. Pierattini, P. Scandone, M. Cortini, Età di messa in posto ed età di metamorfismo delle 'limburgiti' nord calabresi, Boll. Soc. Geol. It. 94 (1975) 367–376.

[36] H.W. Quitzow, Diabas-Porphirite und Glaukophangesteine in der Trias von Nordkalabrien, Nachrbl. Ges. Wiss. Göttingen, Math. Phys. Kl. IV n. s. I (9) (1935) 83–118.

[37] F. Rossetti, C. Faccenna, B. Goffé, P. Monié, A. Argentieri, R. Funiciello, M. Mattei, Alpine structural and metamorphism signature of the Sila Piccola Massif nappe stack (Calabria, Italy): Insights for the tectonic evolution of the Calabrian Arc, Tectonics 20 (1) (2001) 114–133.

[38] F. Rossetti, B. Goffé, P. Monié, C. Faccenna, G. Vignaroli, Alpine orogenic *PTt* deformation history of the Catena Costiera area and surrounding regions (Calabrian Arc, southern Italy): the nappe edifice of Northern Calabria revised with insights on the Tyrrhenian–Apennine system formation, Tectonics 23 (1) (2004) TC 6011.

[39] S. Sartoni, U. Crescenti, Ricerche biostratigrafiche nel Mesozoico dell'Appenino meridionale, G. Geologia 29 (2) (1964) 161–302.

[40] R. Selli, Sulla trasgressione del Miocene nell'Italia Meridionale, G. Geol., Ser. (2) 26 (1957) 1–54.

[41] B. Stockert, Stress and deformation in subduction zones: insight from the record of exhumed metamorphic rocks, in: M.R. De Meer, M.R. Drury, J.H. De Bresser, G.M. Pennock (Eds.), Deformation Mechanisms, Rheology and Tectonics: Current Status and Future Perspectives, Geol. Soc. Spec. Publ. 200 (2002) 255–274.

[42] T. Theye, J. Reinhardt, B. Goffé, L. Jolivet, C. Brunet, Ferro- and magnesio-carpholite from the Monte Argentario (Italy): First evidence for high-pressure metamorphism of the metasedimentary Verrucano sequence, and significance for $P$–$T$ path reconstruction, Eur. J. Mineral. 9 (1997) 859–873.

[43] J.P. Van Dijk, M. Bello, G.P. Brancaleoni, G. Cantarella, V. Costa, A. Frixia, F. Golfetto, S. Merlini, M. Riva, S. Torricelli, C. Toscano, A. Zerilli, A regional structural model for the northern sector of the Calabrian Arc (southern Italy), Tectonophysics 324 (2000) 267–320.

[44] S. Vitale, Revisione delle unità carbonatiche in Calabria settentrionale: analisi strutturale e studio della deformazione finita, PhD thesis, Università di Napoli Federico II, Naples, Italy, 2005, 198 p.

[45] S. Vitale, A. Iannace, 3D finite strain analysis of the Pollino-Ciagola Unit (Calabria–Basilicata boundary, southern Italy), Studi Geologici Camerti, nuova serie 2 (2004) 153–167.

[46] S. Vitale, S. Mazzoli, Influence of object concentration on finite strain and effective viscosity contrast: insights from naturally deformed packstones, J. Struct. Geol. (in press).