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Tectonics

Structural analysis of the 'Internal' Units of *Cilento*, Italy: New constraints on the Miocene tectonic evolution of the southern Apennine accretionary wedge

Analyse structurale des Unités « Internes » du Cilento (Italie) : nouvelles contraintes sur l'évolution tectonique miocène du prisme d'accrétion de l'Apennin méridional

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ABSTRACT

Based on the structural analysis of the 'Internal' Units cropping out in the *Cilento* area (southern Italy), this article provides new geodynamic constraints on the Miocene tectonic evolution of the southern Apennine accretionary wedge. The studied sedimentary successions, forming part of the tectonically superposed *Nord-Calabrese* (in the hanging-wall) and *Parasicilide* Units, are characterized by three superposed fold sets. The analysis of the attitudes of the main structures allowed us to unravel the shortening directions experienced by the accretionary wedge in the Miocene time. The reconstructed deformation sequence, characterized by initial NW-SE shortening and subsequently by west-east and NE-SW shortening, is related to the inclusion of the studied successions into the accretionary wedge and to their subsequent tectonic emplacement on top of outer domains of the foreland plate. Accretionary wedge overthickening and uplift, probably associated with footwall imbrication involving carbonate units of the foreland plate, was followed by wedge thinning, which also enhanced the creation of accommodation space in wedge-top basin depocentres.

RÉSUMÉ

Une analyse structurale, effectuée sur les Unités « Internes » affleurant dans la région du *Cilento* (Italie méridionale), fournit des contraintes nouvelles sur l'évolution tectonique du prisme d'accrétion miocène de l'Apennin méridional. Les successions stratigraphiques analysées, appartenant aux unités tectoniques *Nord-Calabrese* (au toit) et *Parasicilide* (au mur), sont caractérisées par trois plissements. L'analyse des pendages des structures principales a permis d'éclaircir les directions de raccourcissement du prisme d'accrétion durant le Miocène. La reconstruction de la séquence de déformation, caractérisée par un raccourcissement initial NW-SE et des raccourcissements successifs ouest-est et NE-SW, est liée à l'accrétion des successions étudiées dans le prisme et au chevauchement conséquent sur les domaines apenniniques plus externes. Le surépaississement et soulèvement du prisme d'accrétion, probablement associés à l'imbrication tectonique des unités carbonatées du mur, ont été suivis par l'amincissement du prisme attesté par des

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failles normales qui recoupent les structures plicatives, et par la formation de bassins de « wedge-top ».

1. Introduction

The southern Apennines fold and thrust belt results from the convergence between the Africa-Apulian and European plates since Late Cretaceous time (Mazzoli and Helman, 1994, and references therein). The Apennine orogen comprises several superposed tectonic units characterized by Mesozoic-Tertiary shallow water to slope-facies carbonates (Apennine and Apulian carbonate platforms) and pelagic basin (Lagonegro) successions, resulting from the deformation of the Apulian continental paleomargin, as well as unconformably overlying Miocene-Pliocene wedge-top and foredeep basin deposits (Bonardi et al., 2009; Mazzoli et al., 2008). The orogenic pile is tectonically covered by remnants of an accretionary wedge (including the *Nord-Calabrese* and *Parasicilide* Units in Fig. 1) tectonically superposed onto the Apennine Platform domain in Early Miocene time (Bonardi et al., 2009; Ciarcia et al., 2009). The 'Internal' Units (Bonardi et al., 1988; Ciarcia et al., 2009) which include, besides the *Nord-Calabrese* and *Parasicilide* Units, the *Frido* and *Sicilide* Units (not exposed in the area of the present study), consist of sedimentary successions derived from oceanic (Neothethys) to thinned continental (Apulian) crust floored basins (Ciarcia et al., 2009). The *Nord-Calabrese* Unit and the metamorphic (HP-LT) *Frido* Unit also include remnants of the magmatic oceanic basement (Bonardi et al., 1988). All of these units, that were accreted as a result of NW-dipping subduction (Knott, 1987), are unconformably overlain by Miocene wedge-top basin deposits (*Cilento* Group, *Monte Pruno*, *Albidona* and *Monte Sacro* Fms) (Amore et al., 1988; Ciarcia et al., 2009; Selli, 1962). The *Parasicilide* Unit (or *Terreni ad Affinità Sicilide* Bonardi et al., 1988) crops out from the *Sele* River Valley (Ciarcia et al., 2009) to the *Torrente Pietra* Valley (Fig. 1), extending southeast of our study area, as also does the *Nord-Calabrese* Unit outside the *Cilento* area shown in Fig. 1 (Bonardi et al., 1988). The aim of this paper is to provide,

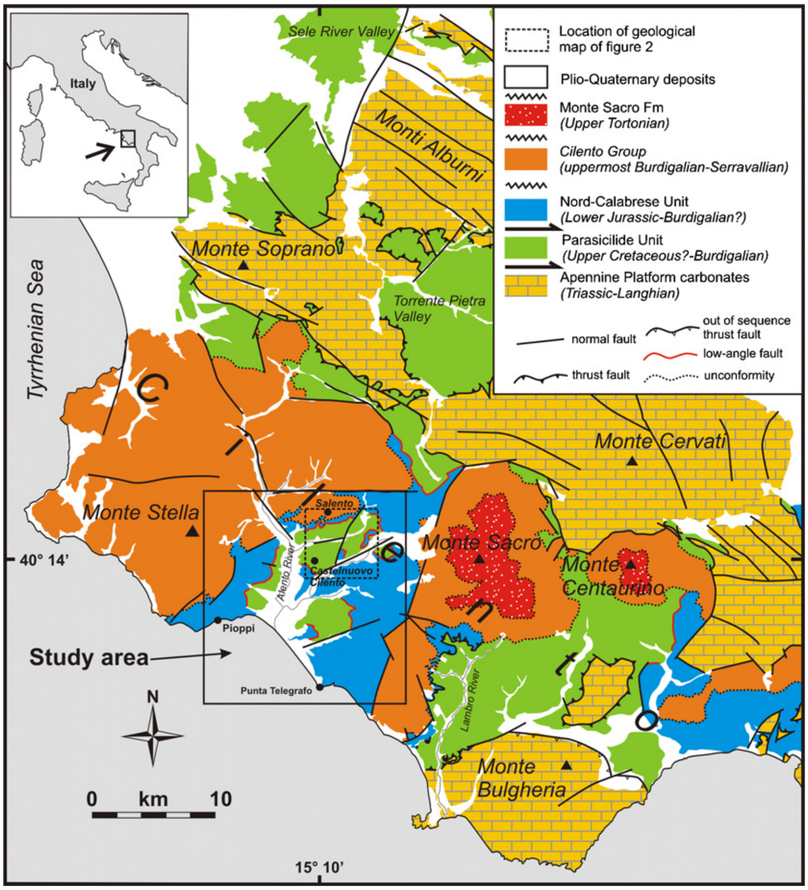

Fig. 1. Geological sketch map of the *Cilento* area (after Bonardi et al., 2009, modified).

Fig. 1. Carte géologique du *Cilento*, d'après Bonardi et al. (2009), modifiée.

for the first time, a structural analysis of both the *Parasicilide* and *Nord-Calabrese* Units cropping out in the *Cilento* area. The study area comprises the *Castelnuovo Cilento* village area, where the *Parasicilide* Unit crops out in a tectonic window exposed in the footwall to the *Nord-Calabrese* Unit (APAT, 2005; Cammarosano et al., 2000), and the areas around *Pioppi* and *Punta Telegrafo* (Figs. 1 and 2). The results of this study also provide new insights into the Miocene geodynamic evolution of the 'Internal' Units in the southern Apennine sector of the Neotethys realm.

2. Geologic setting

The *Parasicilide* Unit, otherwise known as *Castelnuovo Cilento* Unit in the *Cilento* area (Cammarosano et al., 2000), includes four formations (Ciarcia et al., 2009). These are (from bottom to top; Fig. 3):

(i) micaceous sandstones, clays, shales and marls of the *Postiglione* Fm;
(ii) marly limestones, marls and calcarenites of the *Monte Sant'Arcangelo* Fm;
(iii) marls and whitish limestones of the *Contursi* Fm;
(iv) sandstones of the *Arenarie di Albanella* Fm.

The ascertained age of these deposits ranges between the Middle Eocene and the Burdigalian (Ciarcia et al., 2009); however, the lower part of the succession could be as old as Upper Cretaceous (Bonardi et al., 1988; Ciarcia et al., 2009) (Figs. 2 and 3). The thickness of whole succession is about 800–1000 m.

The *Nord-Calabrese* Unit is formed by a Lower Jurassic–Burdigalian? (Bonardi et al., 2009) ophiolite-bearing succession characterized, from bottom to top, by pillow lavas, slates, quartz-arenites, limestones and cherts of the *Timpa delle Murge* Fm, black shales and slates of the *Crete Nere* Fm, and finally limestones, marls and sandstones of the *Saraceno* Fm. The *Crete Nere* and *Saraceno* Fms, the only two formations of the *Nord-Calabrese* Unit cropping out in the *Cilento* area (Fig. 3), represent a dominantly siliciclastic and calciclastic succession deposited on oceanic crust (Neotethys) during both passive margin and younger foredeep basin stages (Bonardi et al., 1988; Bonardi et al., 2009).

The *Cilento* Group (Fig. 3) consists of an Uppermost Burdigalian to Serravallian, dominantly siliciclastic succession unconformably overlying previously deformed 'Internal' Units (Bonardi et al., 1988). This wedge-top basin succession includes the *Pollica* and *San Mauro* Fms both passing, laterally and southward, to the *Torrente Bruca* Fm (Amore et al., 1988) and, southeast of the area shown in Fig. 1, to the *Albidona* Fm (Selli, 1962). In the *Cilento* area the top of the succession (Fig. 3) consists of unconformable coarse-grained deposits of the Upper Tortonian *Monte Sacro* Fm (Selli, 1962).

3. Tectonic setting and structural analysis

3.1. Parasicilide Unit

In the study area, the *Parasicilide* Unit crops out – in a tectonic window – in the footwall to the *Nord-Calabrese* Unit. The tectonic contact separating the two units is not well exposed, therefore hindering a complete and detailed kinematic analysis; however, field relationships clearly show the tectonic superposition (Fig. 4a). The *Parasicilide* Unit is affected by an inhomogeneous deformation with strain localization occurring especially in the pelitic layers.

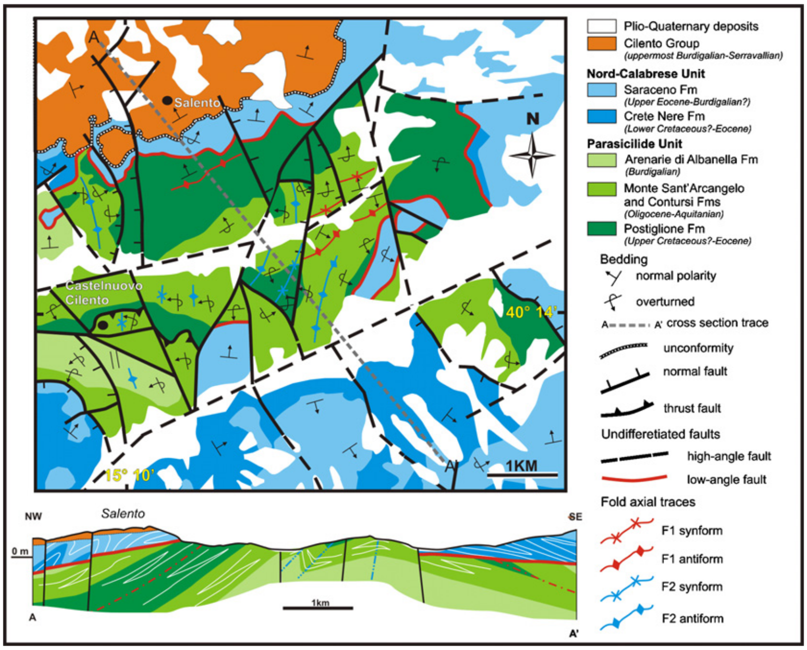

Fig. 2. Geological sketch map and cross section of the *Castelnuovo Cilento* area (after APAT, 2005, modified).

Fig. 2. Carte et coupe géologique de *Castelnuovo Cilento*, d'après APAT (2005), modifiée.

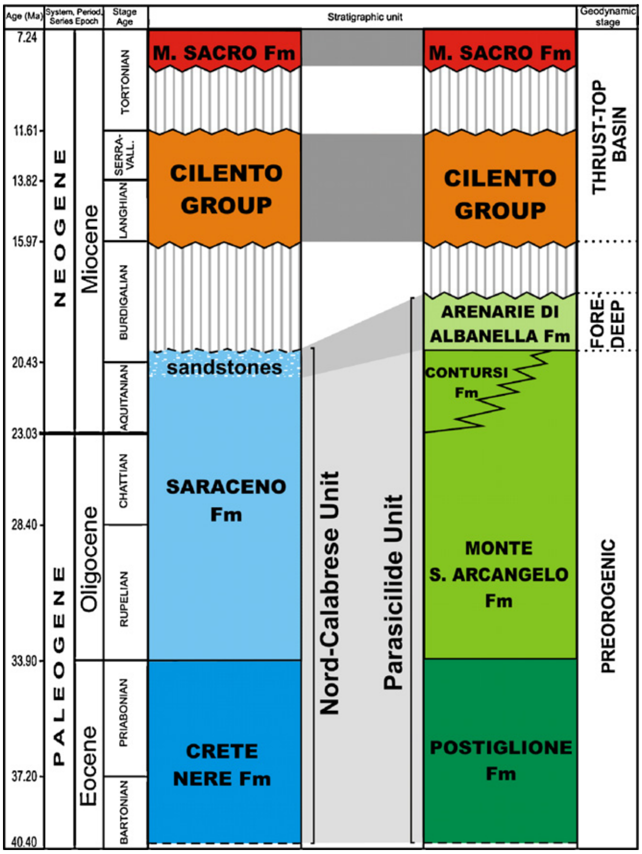

Fig. 3. Stratigraphic sketch of the basin successions cropping out in the *Cilento* area.

Fig. 3. Schéma stratigraphique des successions de bassin affleurent dans la région de *Cilento*.

Often the succession shows a chaotic appearance as a result of fracturing and variable degree of disruption of the competent beds. This is probably due to the fact that, during the superposed deformation events, the temperature was not high enough to allow the rocks to flow in a fully ductile fashion.

The first deformation episode produced chevron to sinusoidal isoclinal folds (F_1^{PS}) (Fig. 4b). An axial plane cleavage in pelitic rocks and a spaced, convergent cleavage in more competent lithologies are weakly developed. The isoclinal folds are refolded by open to tight kink folds (F_2^{PS}), generally displaying conjugate axial planes (Fig. 4b and c). Locally the F_2^{PS} folds are related to thrust faults showing minor displacements. The interference pattern between F_1^{PS} and F_2^{PS} folds (Fig. 4b) is comprised between types 2 and 3 of Ramsay's classification (Ramsay, 1967). Both F_1^{PS} and F_2^{PS} fold sets are refolded by gentle to open, rounded folds (F_3^{PS}) developed mainly in the steep F_2^{PS} limbs and showing sub-horizontal to moderately dipping axial planes (Fig. 4d). F_1^{PS} fold hinges (A_1^{PS}) display a girdle distribution around a NE-SW striking, sub-vertical plane (Fig. 5a), whereas poles to axial planes (AP_1^{PS}) are scattered (Fig. 5b). F_2^{PS} fold hinges (A_2^{PS}) are characterized by a dominant north-south trend (Fig. 5c), the related axial planes (AP_2^{PS}) showing both west and east dip directions and variable angles of dip (Fig. 5d). F_3^{PS} fold hinges (A_3^{PS}) are generally NW-SE trending (dominantly gently to moderately plunging to the south-east; Fig. 5e), while the related axial planes (AP_3^{PS}) tend to be sub-horizontal to moderately dipping in various directions (with a dominant north-east gentle dip; Fig. 5f).

3.2. Nord-Calabrese Unit

Two outcrop areas of the *Nord-Calabrese* Unit have been analyzed in this study: those of *Punta Telegrafo* and *Pioppi* (Fig. 1). In these areas the lower part of the Saraceno Fm, characterized by calcareous-pelitic turbidites, crops out. As it occurs for the *Parasicilide* Unit, the *Nord-Calabrese* Unit is also characterized by the superposition of three fold sets (F_1^{NC}, F_2^{NC} and F_3^{NC}) and associated planar and linear structures. In the pelitic layers, the main foliation consists of a slaty cleavage (S_1^{NC}) sub-parallel to F_1^{NC} fold axial planes (AP_1^{NC}). In the competent arenitic beds a spaced, disjunctive cleavage is present. F_1^{NC} folds display geometries ranging from tight to isoclinal (Fig. 4e and f). F_2^{NC} folds are characterized by larger interlimb angles with respect to preexisting F_1^{NC} folds (Fig. 4e and f). Fold interference patterns range from perfectly coaxial (type 3; Ramsay, 1967) for the *Crete Nere* Fm to moderately non-coaxial

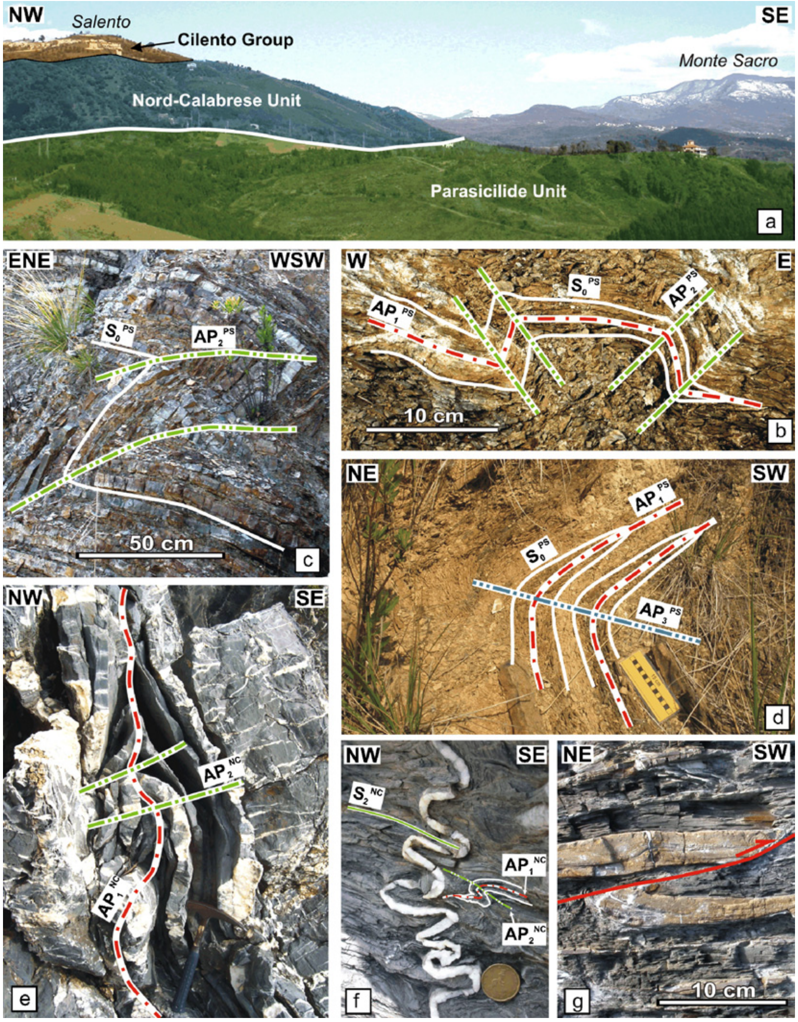

Fig. 4. Examples of structural features in the *Parasicilide* (a to d) and *Nord-Calabrese* (e to g) Units. (a) North-directed view of the *Castelnuovo Cilento* tectonic window. (b) Superposition of conjugate second stage kink folds (F_2^{PS}) on first stage isoclinal fold (F_1^{PS}) (*Salento*). (c) F_2^{PS} kink fold (*Castelnuovo Cilento*). (d) Superposition of third stage fold (F_3^{PS}) on isoclinal F_1^{PS} fold (*Castelnuovo Cilento*). (e) Superposition of F_2^{NC} folds on F_1^{NC} isoclinal fold (*Punta Telegrafo*). (f) F_2^{NC} ptigmatic folds with crenulation cleavage (S_2^{NC}) (*Punta Telegrafo*). (g) Thrust fault, showing minor displacement, associated with third stage folds (*Pioppi*).

Fig. 4. Exemples de structures de déformation dans les Unités *Parasicilide* (a–d) et *Nord-Calabrese* (e–g). (a) La fenêtre tectonique de *Castelnuovo Cilento* (vue vers le nord). (b) Superposition de plis « kink » conjugués F_2^{PS} sur un pli isoclinal F_1^{PS} (*Salento*). (c) Pli « kink » F_2^{PS} (*Castelnuovo Cilento*). (d) Superposition d'un pli F_3^{PS} sur un pli isoclinal F_1^{PS} (*Castelnuovo Cilento*). (e) Superposition des plis F_2^{NC} sur un pli isoclinal F_1^{NC} (*Punta Telegrafo*). (f) Plis ptigmatiques F_2^{NC} et clivage de crénulation S_2^{NC} (*Punta Telegrafo*). (g) Chevauchement avec modeste déplacement associé à la troisième phase de plissement (*Pioppi*).

(intermediate 2–3 type; Fig 4e and f) for the *Saraceno* Fm. A crenulation cleavage (S_2^{NC}) occurs in the pelitic layers (Fig. 4f). F_3^{NC} open to tight folds are often associated with SW verging thrust faults showing moderate displacements (Fig. 4g). F_1^{PS} fold hinges (A_1^{PS}) show a girdle distribution characterized by dominant steep plunges (Fig. 5g), whereas poles to axial planes form two clusters of dominantly south-east and north-west steeply dipping planes (Fig. 5h). F_2^{NC} fold hinges are sub-horizontal and NE-SW trending (Fig. 5i), while F_2^{NC} fold axial planes (AP_3^{NC}) mainly dip to the north-west (Fig. 5j). F_3^{NC} fold hinges dominantly plunge moderately to the NW (Fig. 5k), whereas F_3^{NC} axial plane poles (AP_3^{NC}) show a girdle distribution around a NE-SW oriented great circle (Fig. 5l).

4. Discussion

The reconstructed tectonic setting of the study area is characterized by the tectonic superposition of the *Nord-Calabrese* Unit onto the *Parasicilide* Unit (Fig. 1). The tectonic contact clearly truncates folds, both in footwall and hanging-wall successions, thus suggesting that it postdates at least the early folding events in both units (as it may be seen in Fig. 2). This contact could either represent a late, out of sequence thrust fault, or a late low-angle normal fault related to horizontal extension affecting the previously overthickened and uplifted accretionary wedge. Early exhumation of the *Parasicilide* Unit in various sectors of the *Cilento* area (e.g., *Monte Sacro* and *Monte Centaurino*,

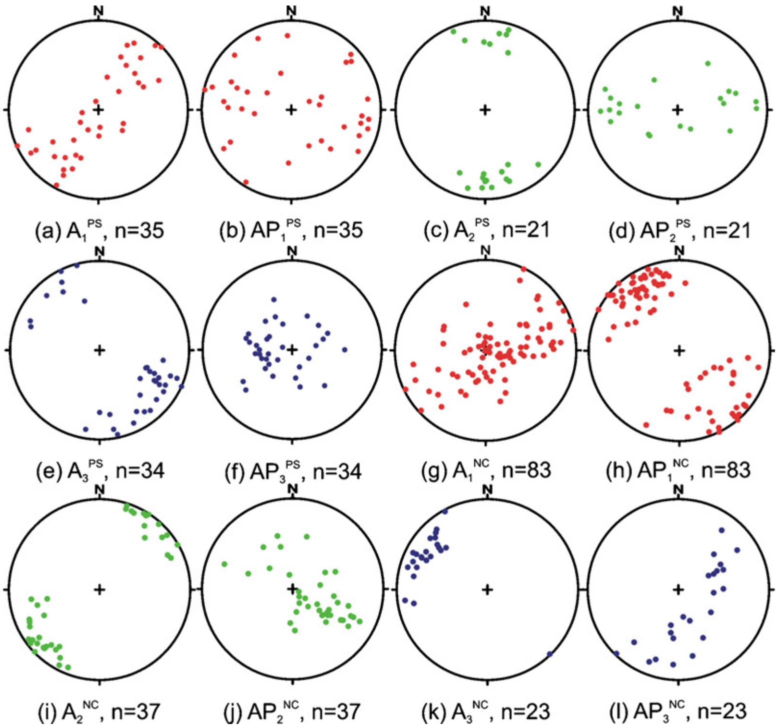

Fig. 5. Orientation data (lower hemisphere, Schmidt net) for main deformation structures in the *Parasicilide* (a to f) and *Nord-Calabrese* (g to l) Units. A_1, A_2, A_3: axes of first, second and third folding stage, respectively; AP_1, AP_2, AP_3: axial planes of first, second and third folding stage, respectively. PS: *Parasicilide* Unit; NC: *Nord-Calabrese* Unit.

Fig. 5. Projections stéréographiques des principales structures de la déformation dans l'Unité *Parasicilide* (a–f) et l'Unité *Nord-Calabrese* (g–l). A_1, A_2, A_3: axes, respectivement, de la première, deuxième et troisième phase de plissement; AP_1, AP_2, AP_3 planes axiales, respectivement, de la première, deuxième et troisième phase de plissement. PS : Unité *Parasicilide* ; NC : Unité *Nord-Calabrese*.

Fig. 1) where this unit is unconformably overlain by the *Cilento* Group strata (Bonardi et al., 1988) is consistent with tectonic omission produced by extension. Accretionary wedge uplift was probably related to footwall imbrication involving the inner (i.e. southwestern) portion of the Apennine Platform carbonates. This process could also have been responsible for the development of regional, broad NE-SW trending folds in the *Alento* River area (Fig. 1) that refolded the whole tectonic pile overlying the Apennine Platform carbonates and also appears to control the outcrop pattern of the *Parasicilide* Unit in the tectonic window of *Castelnuovo Cilento*.

The structural analysis allowed us to unravel three main folding stages in both analyzed tectonic units. The first two folding events are weakly non-coaxial for the *Parasicilide* Unit, indicating NW-SE and west-east shortening, respectively, whereas they are broadly coaxial and resulting from NW-SE shortening for the *Nord-Calabrese* Unit. The girdle distributions of F_1^{PS} and F_1^{NC} axes (Fig. 5a and g) can be interpreted as two branches of small circles (flexural slip fold; Ramsay and Huber, 1987; p. 483) indicating a rotation of F_1^{PS} and F_1^{NC} axes around the F_2^{PS} and F_2^{NC} axes, respectively. The original angles between the two mean fold axes, of *ca.* 45° for the *Parasicilide* Unit and *ca.* 10° for the *Nord-Calabrese* Unit, have been estimated – as a first approximation and taking into account the limitations of the method – by measuring the angle between the mean directions of horizontal F_1^{PS}–F_1^{NC} axes and F_2^{PS}–F_2^{NC} axes, respectively. These two folding events can be related to horizontal shortening of the *Nord-Calabrese* and *Parasicilide* successions as they were accreted into the subduction complex. NW-SE shortening of the 'Internal' Units successions is also recorded in the *Sele* River Valley (Ciarcia et al., 2009). Furthermore, in northern *Calabria* (south-east of the area shown in Fig. 1) the innermost portions of the Apennine Platform domain record top-to-the-east-northeast thrusting (Iannace et al., 2007) in Burdigalian time (Vitale and Mazzoli, 2009).

The third folding event unravelled in both the *Nord-Calabrese* and *Parasicilide* Units can be correlated, in terms of fold style and orientation, with that characterizing the stratigraphically overlying *Cilento* Group Fm (Zuppetta and Mazzoli, 1997). This folding stage can be interpreted as a result of late shortening related to the overthrusting of the accretionary wedge, together with the unconformable wedge-top basin deposits, onto the Apennine Platform domain. Based on the youngest deposits of the *Cilento* Group involved in folding, this deformation stage can be dated as post-Serravallian.

The first folding stage has generated, at a regional scale, a train of south-east-vergent overturned folds with parasitic folds in the *Parasicilide* Unit, as shown in the cross section of Fig. 2. These structures have been refolded by F_2^{PS} folds and subsequently crosscut by low-angle

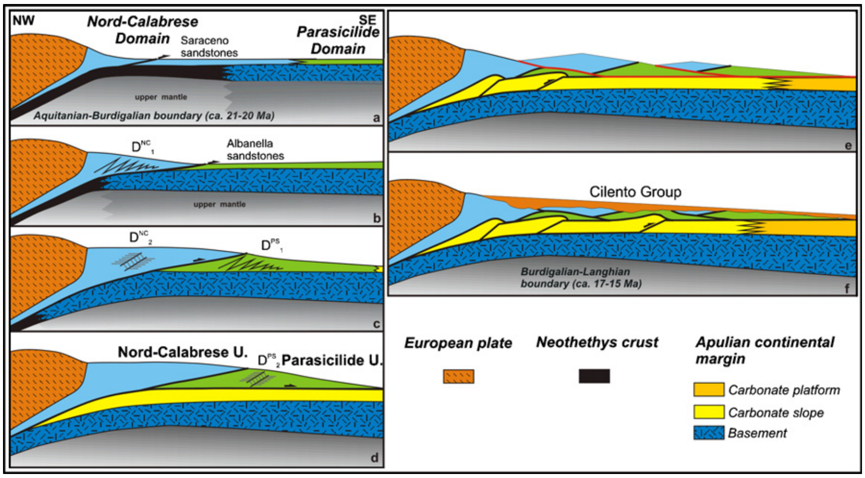

Fig. 6. Cartoon showing reconstructed geodynamic evolution of the 'Internal' Units in the studied segment of the southern Apennines.

Fig. 6. Schéma de la reconstruction de l'évolution géodynamique des Unités « Internes », dans le segment de l'Apennin méridional étudié.

Table 1
Correlation and timing of deformation stages for the studied tectonic units.

Tableau 1
Corrélation et âge des phases de la déformation dans les unités tectoniques étudiées.

	Burdigalian			Post-Serravallian
Parasicilide Unit		D^{PS}_1	D^{PS}_2	D^{PS}_3
Nord-Calabrese Unit	D^{NC}_1	D^{NC}_2		D^{NC}_3

tectonic contacts (thrusts or low-angle normal faults) presently separating the *Nord-Calabrese* Unit in the hanging-wall from the generally overturned succession of the *Parasicilide* Unit in the footwall (e.g., *Castelnuovo Cilento* tectonic window). Dramatic fold truncation suggests significant tectonic excision of the *Parasicilide* footwall succession. Deformation stages for the various analyzed successions, their interpreted correlation and chronology are summarized in Table 1.

In order to insert the envisaged structural evolution in a more general framework, a tentative reconstruction of the geodynamic evolution of the Apennine accretionary wedge between the Late Aquitanian and the Early Langhian is provided (Fig. 6). In a first stage (Fig. 6a), the *Nord-Calabrese* succession is covered by the foredeep deposits of the *Saraceno* Fm (sandstones). Subsequently the *Nord-Calabrese* Unit is accreted into the accretionary wedge and deformed by overall NW-SE shortening (D^{NC}_1) developing isoclinal F^{NC}_1 folds (Fig. 6b). During this stage foredeep sedimentation occurs on top of the *Parasicilide* domain with the deposition of the *Arenarie di Albanella* Fm. In Burdigalian time (Fig. 6c) the *Nord-Calabrese* Unit experiences continued NW-SE shortening (D^{NC}_2) and the *Parasicilide* Unit is accreted into the wedge (D^{PS}_1), leading to the development of F^{PS}_1. During the Burdigalian (Fig. 6d) the inner sector of the Apennine Platform carbonate domain is overthrusted by the accretionary wedge, while sedimentation of the *Bifurto* Fm (Selli, 1957) occurs in the newly developed foredeep. The *Parasicilide* Unit is deformed by roughly east-west shortening (D^{PS}_2) and F^{PS}_2 folds are developed. Later (Fig. 6e) the accretionary wedge undergoes horizontal stretching and vertical shortening, probably due to previous overthickening and footwall imbrication at the expenses of the tectonically underlying Apennine Platform carbonate succession, producing uplift of the 'Internal' Units. Low-angle extensional detachments associated with synorogenic extension favor the development of accommodation space in wedge-top basin depocentres (Fig. 6f) that are filled by the *Cilento* Group deposits.

5. Conclusions

This work, representing the first comprehensive structural analysis of the *Nord-Calabrese* and *Parasicilide* Units in the *Cilento* area, unravelled a complex deformation history for these units, within the general framework of the geodynamic evolution of the Miocene Apennine accretionary wedge. The *Parasicilide* succession has been overthrusted by the *Nord-Calabrese* Unit in the Burdigalian and then accreted into the wedge. Shortening within the *Nord-Calabrese* and *Parasicilide* Units is recorded by three-fold sets in both units, recording NW-SE (D^{NC}_1 and D^{NC}_2) and then NE-SW (D^{NC}_3) for the *Nord-Calabrese* Unit and NW-SE (D^{PS}_1), west-east (D^{PS}_2) and then NE-SW (D^{NC}_3) shortening for the *Parasicilide* Unit. Accretionary wedge overthickening and uplift, probably associated with thrusting involving carbonate footwall units, was followed by wedge thinning, which produced the accommodation space for the sediments of the *Cilento* Group in a series of wedge-top depocentres.

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