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Geology of the Pergola–Melandro basin area, Southern Apennines, Italy

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ABSTRACT

The Southern Apennines (SA) are part of the Apennine–Maghrebian chain, a segment of the circum-Mediterranean Alpine orogenic system. It is a NE-verging fold-and-thrust belt with an about N150°-striking axis developed since the late Oligocene–early Miocene. The Geological Map at 1:25,000 scale of the Pergola–Melandro basin area, presents a sector of the axial zone of the SA which represents a key area to reconstruct the tectonic evolution of this chain. The map describes the complex structural and stratigraphic relationships between the three main tectonic units forming this sector of the SA: (1) the carbonate slope succession of the Maddalena Mts Unit, interpreted as the eastern boundary of the Apennine carbonate Platform; (2) the Lagonegro Unit, resulting from the deformation of the homonym pelagic basin; (3) the strongly deformed *Argille Variegate* Group sandwiched between the two previous units. Three main contractional tectonic stages, occurring from middle Miocene to Pliocene, have been recognized. Since Pliocene times low-angle extensional tectonic contacts and tectono-gravitational detachments affected the tectonic pile.

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Brienza–Paterno thrust;
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1. Introduction

The Southern Apennines chain is a NW–SE-oriented segment of the Italian Apennines (Figure 1), consisting of an Adriatic-verging accretionary wedge derived from the Neogene compressional deformation of the Africa–Apulian passive margin. The allochthonous part of the chain consists of three main stacked tectonic elements which are the result of the deformation of Jurassic–Cretaceous to Miocene successions of the internal oceanic to transitional Liguride–Sicilide deep-sea domains (Liguride and Sicilide Complexes, after Ogniben, 1969), Triassic to Miocene carbonate platform and slope successions (Apennine carbonate Platform, after Mostardini & Merlini, 1986), and Triassic to Miocene Lagonegro Basin successions (Scandone, 1967, 1972).

According to Schiattarella, Di Leo, Beneduce, and Giano (2003, 2006) starting from the latest Miocene, the orogen underwent low-angle extension which led to the exhumation of the deepest non-metamorphic units constituted of Lagonegro successions. At such a stage of tectonic denudation, which mainly occurred during Pliocene times, pre-existing thrusts in the inner and axial zones of the chain could have been re-activated as extensional planes (Schiattarella, Di Leo, Beneduce, Giano, & Martino, 2006, 2013). Transpressional to transtensional tectonics were responsible for the Pliocene to early Pleistocene evolution of the SA, and generated the embryonal basins which led to

the formation of the Quaternary intermontane graben-like structures in the axial zone of the orogen (Giano, Gioia, & Schiattarella, 2014). Afterwards, such basins were affected by mid-Pleistocene high-angle extensional faults (Schiattarella, 1998).

In this context, the Pergola–Melandro basin, located in the axial zone of the SA, represents a key area to reconstruct the tectonic evolution of the chain and investigate the relationships between the main tectonic units forming this segment of the Apennines orogen. Along the western side of the basin, a main NW-trending thrust, referred to as the ‘Brienza–Paterno Thrust’ (BPT) by Pescatore, Renda, Schiattarella, and Tramutoli (1999), was recognized. It determines the superposition of the Mesozoic–Cenozoic slope carbonate deposits (Maddalena Mts Unit, after Castellano & Sgrosso, 1996; Ippolito, D’Argenio, Pescatore, & Scandone, 1975) of the Apennine Platform on the Lagonegro Basin successions. Deposits assigned to the *Argille Variegate* Group are sandwiched between these units.

In this paper, a geological map of the Pergola–Melandro basin at 1:25,000 scale is presented. This map is aimed at covering the lack of a detailed geological mapping of this sector of the SA and to reconstruct the cross-cutting relationships between the BPT and the other compressional structures observed both in the Lagonegro successions and in the slope carbonate rocks of the Apennine Platform.

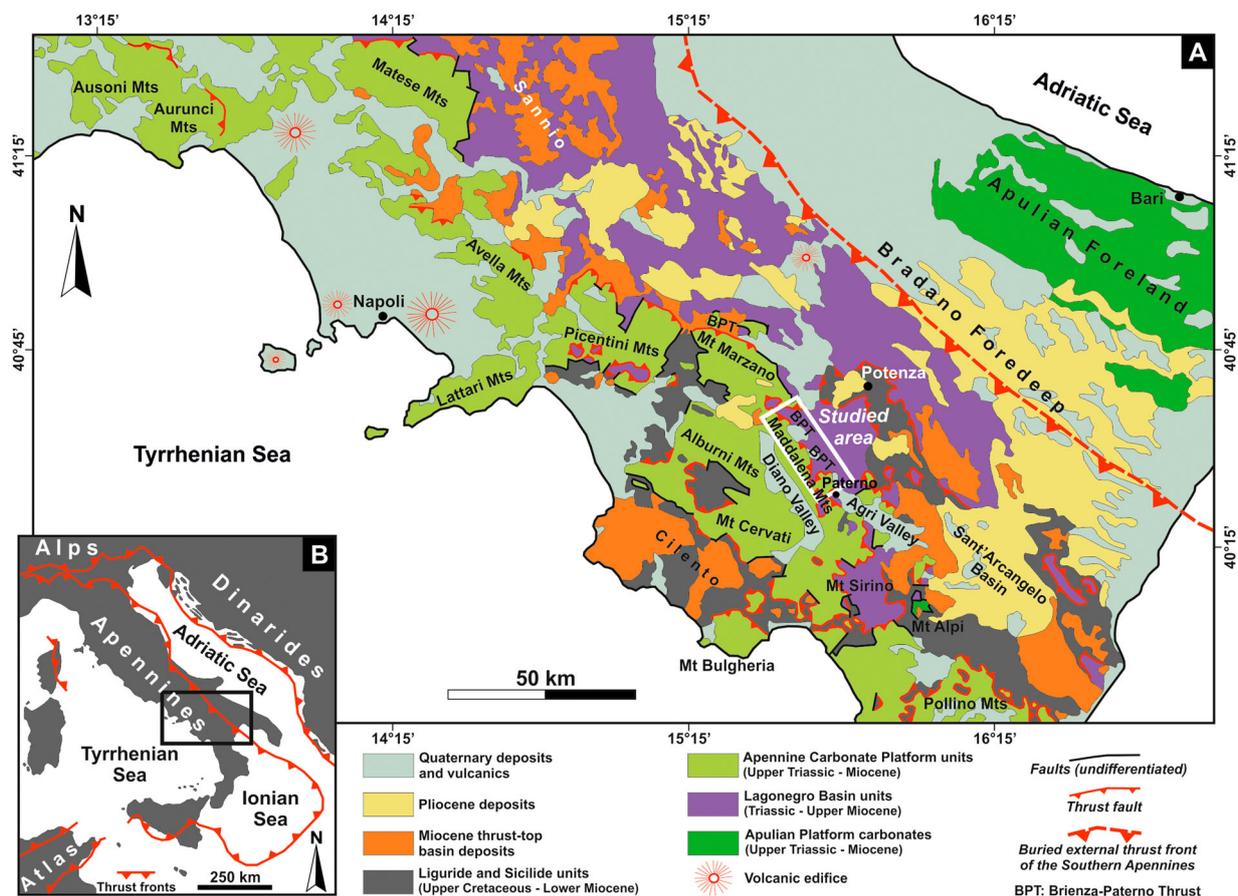


Figure 1. (a) Structural sketch map of the Southern Apennines (modified from Vitale & Ciarcia, 2013) and (b) location of Figure 1(a).

2. Methods

The geological map of the Pergola–Melandro basin area ($\sim 157 \text{ km}^2$) was produced by means of a geological survey at 1:10,000 (see [Main Map](#)). The collected data have been reported on the official topographic maps of Italy at 1:25,000 scale produced by the Italian ‘Istituto Geografico Militare’ (IGM). The geological map includes the regional geological scheme, stratigraphic sections of the lithostratigraphic successions of the different tectonic units and their structural relationships, the structural scheme of the mapped area, and eight geological cross-sections (some of which are modified after [Civile, Martino, & Zecchin, 2010](#)). Any tectonic unit is composed of either formal or informal lithoformations.

The Maddalena Mts Unit and the fine-grained siliciclastic deposits of the Miocene foredeep and thrust-top basins were sampled for biostratigraphic analysis and the main results of this study are reported on the [Main Map](#). The biostratigraphic schemes used to define the age of the Maddalena Mts Unit are those reported in [De Castro \(1991\)](#) and [Chiocchini, Farinacci, Mancinelli, Molinari, and Potetti \(1994, 2008\)](#). The age of the Miocene successions was determined on the basis of calcareous nannoplankton and planktonic foraminifera associations, following the biostratigraphic schemes of [Fornaciari, Di Stefano, Rio, and](#)

[Negri \(1996\)](#), [Iaccarino \(1985\)](#), and [Sprovieri et al. \(2002\)](#). Finally, petrographic analyses were performed on sandstone samples of the thrust-top basin successions and the *Argille Variegate* Group.

Measurements of outcrop-scale faults (meso-faults) have been collected at several structural sites and then reported using a stereographic projection for their structural analysis: the fault plans are represented as cyclographic traces and the kinematic indicators as poles, with arrows if the slip vector was measured. The meso-fault orientation data have been visualized using rose-diagrams in order to identify the main sets.

3. Geological setting

The SA ([Figure 1](#)) are part of the Apennine–Maghrebian chain. They form a NE-verging fold-and-thrust belt with an about N150°-striking axis. The Apennine chain is the result of deformation that affected the passive palaeomargin of Adria, a continental fragment linked to the African plate, during the convergence of the African and Eurasian plates (e.g. [Channell, D’Argenio, & Horvath, 1979](#); [D’Argenio, Channell, & Horvath, 1980](#)) from the late Oligocene–early Miocene ([Mazzoli et al., 2008](#); [Pescatore et al., 1999](#)). The classical restoration of the pre-orogenic (Triassic–Paleogene) palaeogeography of the SA, east of the neo-Tethyan

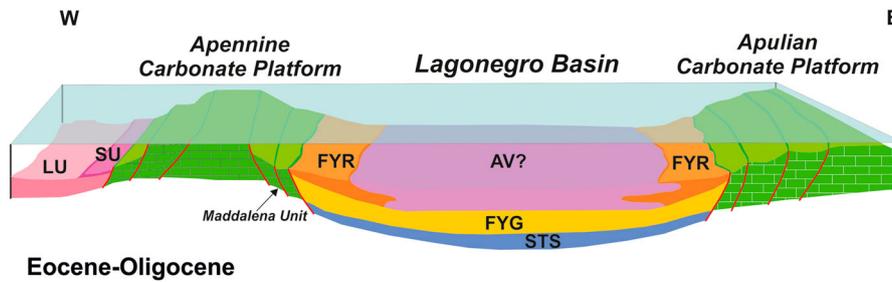


Figure 2. Paleogeographic reconstruction of the Southern Apennines during the Eocene-Oligocene time, showing the position of the main paleogeographic domains from which the major tectonic units forming the chain are derived (modified from Pescatore et al., 1999). Acronyms: LU – Liguride Units, SU – Sicilide Units, STS – *Scisti Silicei*, FYG – *Flysch Galestrino*, FYR – *Flysch Rosso*, AV – *Argille Variegata Group*.

palaeo-ocean (Casero et al., 1988) or internal basin (D’Argenio, Pescatore, & Scandone, 1973), has shown that the Adria margin was composed of alternating carbonate platforms and deep-sea basins (Bonardi et al., 2009; D’Argenio et al., 1973; Mostardini & Merlini, 1986; Sgroso, 1998). The more convincing model suggests the presence of a unique Mesozoic-Cenozoic pelagic basin (the Lagonegro Basin *Auct.*) interposed between two shallow-water carbonate platforms (Figure 2) known as the Apennine Platform to the west and the Apulian Platform to the east (Cello & Mazzoli, 1999; Mostardini & Merlini, 1986; Ogniben, 1969; Pescatore et al., 1999). The progressive propagation of the contractional deformation towards the foreland is documented by the development of a series of Miocene to Pleistocene foredeep basins, progressively younger eastward, and of thrust-top basins on top of the advancing allochthonous units (Bonardi et al., 2009; Matano, Critelli, Barone, Muto, & Di Nocera, 2014; Patacca & Scandone, 2001; Vitale & Ciarcia, 2013). The SA consists of a pile of thrust sheets formed by Mesozoic to Cenozoic sedimentary rocks detached from their basement (Casero et al., 1988; D’Argenio et al., 1973; Mazzoli et al., 2000; Menardi-Noguera & Rea, 2000; Monaco, Tortorici, & Paltrinieri, 1998; Mostardini & Merlini, 1986; Patacca & Scandone, 2001; Pescatore et al., 1999; Scrocca, 2010), overthrust, during the early Pliocene, on the Apulian Platform, which was later, in its inner part, involved in a contractional deformation (Cello, Tortorici, Martini, & Paltrinieri, 1989; Di Nocera, Matano, Pescatore, Pinto, & Torre, 2011; Patacca & Scandone, 2007; Shiner, Beccacini, & Mazzoli, 2004). Near the early-middle Pleistocene boundary, the forward migration of the thrust belt ceased and the chain underwent a generalized uplift process (Cinque, Patacca, Scandone, & Tozzi, 1993; Hippolyte, Angelier, & Roure, 1994).

The Pergola–Melandro basin represents a NW–SE intramontane tectonic depression superimposed on the fold-and-thrust belt of the SA, located in the axial zone of the Campania-Lucania Apennines (Figure 1). The western side of the basin consists of a ~25 km

long segment of the N150° oriented Maddalena Mts carbonate ridge. It is composed of upper Jurassic to Eocene shelf-margin deposits lying on Triassic–early Jurassic neritic dolostones (D’Argenio et al., 1973; Pappone, 1988; Scandone, 1964; Scandone & Bonardi, 1968; Sgroso, 1966). This succession is inferred to represent the more external domain of the Apennine Platform (Iannace & Zamparelli, 2002; Pappone, 1988; Pescatore et al., 1999; Scandone, 1964, 1967; Scandone & Bonardi, 1968). The carbonate, siliceous, and terrigenous pelagic Lagonegro succession, ranging from early–middle Triassic to early Miocene (Miconnet, 1988; Pescatore et al., 1999; Scandone, 1967, 1972), mainly crops out on the eastern side of the basin. The tectonic juxtaposition of the Maddalena Mts Unit on the Lagonegro successions (i.e. BPT) was recognized at the toe of the slope located at the western side of the basin (Radina, 1965; Scandone, 1967, 1972; Sgroso, 1966; Signorini, 1939).

4. Data

4.1. Stratigraphy

4.1.1. Maddalena Mts unit

This carbonate succession is up to about 1000 m thick and includes several stratigraphic gaps (Figure 3). Three informal lithostratigraphic units were mapped: 1- Maddalena Mts dolostone (Norian-early Jurassic), 2- *Ellipsactinia* bearing limestone (late Jurassic?-early Cretaceous), and 3- recrystallized limestone (Albian-Eocene). Another informal Jurassic lithostratigraphic unit, the ‘oolitic limestone’, was identified only at Vietri di Potenza village.

The Maddalena Mts dolostone, up to 500 m thick, consists of shallow-water stromatolitic dolostones (Figure 4(a)) and rare layers of limestone and dolomitic limestone.

A stratigraphic gap separates these deposits from an overlying upper slope facies succession characterized by resedimented carbonates. The lower part of the slope succession consists of the ‘*Ellipsactinia* bearing limestone’. This unit, up to 100 m thick, is composed

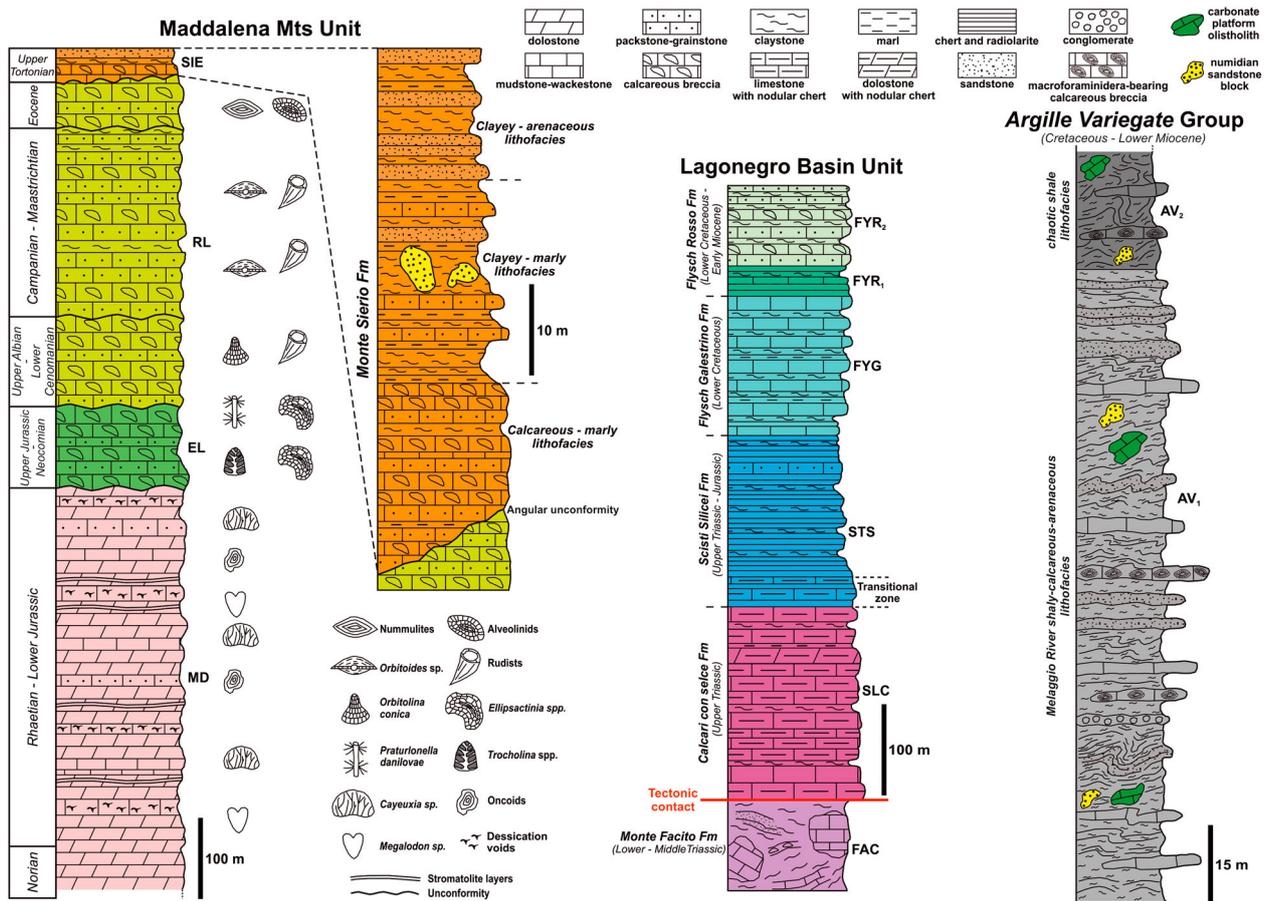


Figure 3. Stratigraphic columns showing the tectonic units cropping-out in the Pergola-Melandro basin. Acronyms (see [Main Map](#)) are: Thrust-Top basin: SIE – Monte Sierio Formation; Maddalena Mts Unit: RL – recrystallized limestone, EL – Ellipsactinia bearing limestone, MD – Maddalena Mts dolostone; Lagonegro Basin Unit: FAC – Monte Facito Formation, SLC – *Calcarei con selce*, STS – *Scisti Silicei*, FYG – *Flysch Galestrino*, FYR₁ – Cherty Member of the *Flysch Rosso*, FYR₂ – Calcareous Member of the *Flysch Rosso*; *Argille Variegata* Group: AV₁ – ‘Melaggio River shaly-calcareous-arenaceous’ lithofacies, AV₂ – ‘chaotic shales’ lithofacies.

of carbonate breccias and calcarenites containing abundant *Ellipsactinia*. The third lithostratigraphic unit, the ‘recrystallized limestone’ (up to 400 m thick), consists of recrystallized calcarenites, calcirudites, and carbonate breccias (*Calcarei Cristallini Auct.*) (Figure 4(b)).

On the basis of the biostratigraphic information (see legend of the [Main Map](#)), three lithologically homogeneous intervals of different age were recognized within the ‘recrystallized limestones’: late Albian-early Cenomanian, Campanian-Maastrichtian and Eocene.

The Jurassic ‘oolitic limestone’, about 250 m thick, consists of oolitic and pseudo-oolitic massive limestones with rare layers of breccias.

Small and chaotic pelitic outcrops, containing scattered blocks of Burdigalian-Langhian Numidian quartzarenites (*sensu* Patacca, Scandone, Bellatalla, Perrilli, & Santini, 1992) and blocks or discontinuous strata of calcarenites, calcilutites, calcareous breccias with benthic macroforaminifera, and marls were mapped above the Maddalena Mts ridge. These pelitic deposits, generally showing a tobacco colour, lie above several portions of the Maddalena Mts succession. On this basis, they were

assigned to the Maddalena Mts foredeep Bifurto Formation (Selli, 1957), Burdigalian-Langhian in age (Patacca et al., 1992). The chaotic assemblage of this formation, the relationships with the bedrock, and the irregular geometry of its basal contact suggest its involvement in tectono-gravitational detachment phenomena.

4.1.2. Lagonegro unit

Five lithostratigraphic units, forming the classical Lagonegro Unit succession, were recognized (Figure 3). The oldest succession was assigned to the early-middle Triassic Monte Facito Formation (Ciarapica & Passeri, 2000; Ciarapica, Birilli, Fratoni Panzanelli, Passeri, & Zaninetti, 1990). The contacts between the Monte Facito Fm. and the other Lagonegro lithostratigraphic units are marked by low-angle extensional planes. This formation consists of shallow- to deep-water siliciclastic deposits made up of varicoloured shales with quartz-mica sandstone layers, calcarenites, calcilutites, marls, polygenic breccias, conglomerates, and cherts. This succession contains isolated biogenic calcareous build-ups.

The late Triassic *Calcarei con selce* Formation (Rigo, Preto, Franceschi, & Guaiumi, 2012; Scandone, 1967,



Figure 4. (a) Maddalena Mts Triassic-early Jurassic dolostone (MD), cropping-out at San Salvatore Mt. Note the presence of stromatolite layers; (b) upper Cretaceous recrystallized limestone (RL) of the Maddalena Mts Unit, cropping-out at Castel di Lepre site, south of the Pergola village; (c) *Calcari con selce* (SLC) of the Lagonegro Unit at La Cuzza Mt.; (d) transition between the *Calcari con selce* (SLC) and *Scisti Silicei* (STS) along the State Road 94, NW of Vietri di Potenza village; (e) *Scisti Silicei* (STS) of the Lagonegro Unit near Savoia di Lucania village; (f) upper lithofacies of the *Argille Variegata* Group (AV₂, 'chaotic shale' lithofacies), cropping-out along the Fragneto creek, NW of Brienza village; (g) thin section (parallel nicols, ca. 120x) of the sandstones found in the Monte Sierio Formation. Note the rounded radiolarian (a) and the volcanic glass fragments with shard shape (b).

1972), up to 250 m thick, consists of turbiditic calcilutites and calcarenites containing chert beds and nodules, with pelitic and marly intercalations (Figure 4(c)).

A transitional zone, between 20 and 40 m thick, was found between the *Calcari con selce* Fm. and the overlying *Scisti Silicei* Fm. This zone (included here in the *Scisti Silicei* Fm.) is composed of alternating calcarenites, calcilutites, calcareous breccias, and layers of cherts and radiolarites (Figure 4(d)).

The late Triassic-Jurassic *Scisti Silicei* Formation (Amodeo, 1999; Di Leo, Dinelli, Mongelli, & Schiattarella, 2002; Miconnet, 1988; Scandone, 1967, 1972) consists of alternating varicoloured radiolarites and cherts (Figure 4(e)) up to 200 m thick. Intercalations of calcareous breccias and calcarenites were also found.

A turbiditic succession up to 400 m thick, assigned to the early Cretaceous *Flysch Galestrino* Formation (Scandone, 1967, 1972), overlies the *Scisti Silicei* Fm.

It consists of siliceous shales intercalated with marls, calcilutites and calcarenites.

The succession continues with the slope-to-basin talus deposits assigned to the *Flysch Rosso* Formation, early Cretaceous-early Miocene in age (Carbone, Di Stefano, & Lentini, 2005; Cocco et al., 1974; Gallicchio et al., 1996; Lentini, Carbone, Di Stefano, & Guarnieri, 2002; Scandone, 1967, 1972). Two members were mapped: the lower cherty member (40 m thick) consists of varicoloured cherts with intercalations of siliceous shales; the upper calcareous member, up to 150 m thick, consists of a turbiditic succession composed of calcareous breccias, re-crystallized calcarenites and calcirudites alternating with marls and shales.

4.1.3. *Argille variegata* group

Basinal deposits assigned to the early Cretaceous-early Miocene *Argille Variegata* Group (C.I.S., 2006;

here after AV) were recognized in the study area. Two informal lithofacies were mapped: a 'chaotic shale' lithofacies and the 'Melaggio River shaly-calcareous-arenaceous' lithofacies (Figure 3). The first lithofacies consists of pervasively tectonized deposits showing a block-in-matrix arrangement (Cowan, 1985). These deposits, having little or no internal coherence, are composed of varicoloured shales (Figure 4(f)) and contain blocks and dismembered beds of marls, cherty limestones, silicified calcilutites, calcarenites, benthic macroforaminifera-bearing calcareous breccias, and quartz-feldspathic sandstones. This lithofacies also includes blocks, up to few metres in size, of Numidian quartzarenites and Cretaceous and Paleogene shallow-water limestones interpreted here as olistoliths of the carbonate platform.

The 'Melaggio River shaly-calcareous-arenaceous' lithofacies, up to 130 m thick, is composed of shales and siltstones with rare discontinuous beds of silicified calcilutites, calcarenites, marly limestones, calcareous breccias with benthic macroforaminifera, and turbiditic sandstones. It shows a less chaotic arrangement compared to that of the previous facies, although blocks of Numidian sandstones and olistoliths of the carbonate platform may be present.

Since the relationship between the two lithofacies is unclear, a geological survey was performed near Paterno village (upper Agri Valley, Figure 1). It showed that the 'chaotic shale' lithofacies stratigraphically overlies the shaly-calcareous-arenaceous lithofacies (Civile, 2005). This confirms that these lithofacies are part of the same succession, which is assigned to the AV due to its lithological characteristics and structural position. This unit tectonically overlies several Lagonegro formations and locally the Triassic–early Jurassic carbonate succession of the Maddalena Mts Unit (south of Vietri di Potenza village; see Main Map). It is also sandwiched between the Maddalena Mts and Lagonegro units. Some authors consider the AV succession of the Lucanian Apennines as part of the Sicilide Complex of internal provenance (Carbone, Catalano, Lazzari, Lentini, & Monaco, 1991; Cinque et al., 1993; Lentini et al., 2002; Monaco et al., 1998; Ogniben, 1969; Sgrosso, 1998). Other palaeogeographic reconstructions considered an external position, suggesting that the AV are part of the uppermost Lagonegro Basin succession (Bonardi et al., 2009; Casero et al., 1988; Di Nocera et al., 2011; Mattioni et al., 2006; Mostardini & Merlini, 1986; Pescatore et al., 1999).

On the basis of the results of the geological survey it is not possible to define the original palaeogeographic position of this unit, so we present two different hypotheses for the tectonic evolution of the study area (see Main Map).

4.1.4. Thrust-top basin deposits

4.1.4.1. Monte Sierio Formation. Miocene turbidite deposits, assigned to the Monte Sierio Formation (Patacca et al., 1992; here after MSF), show the most complete succession, 60 m thick, north of Il Crocifisso di Brienza Mt. Three lithofacies have been recognized (Figure 3): a lower calcareous-marly lithofacies, 20 m thick, a clayey-marly lithofacies, 25 m thick, and an upper clayey-arenaceous lithofacies, 15 m thick. The sandstones of this formation contain volcanic glass, with Y and X-shaped shards (Figure 4(g)). Their origin is probably related to the coeval magmatism of Sardinia, where two different igneous stages developed during Cenozoic times. The oldest (late Eocene–middle Miocene) is connected to the NW-directed Apennine subduction, whereas the youngest volcanism (middle Miocene–Quaternary) seems geochemically unrelated to active or recent subduction processes (e.g. Lustrino et al., 2013).

The presence of the planktonic foraminifera *Globorotalia cf. suterae* allows us to assign a late Tortonian age to the MSF. This is also confirmed by fission track data (7.5 ± 1.8 My after Aldega et al., 2005; Mazzoli et al., 2008) obtained in the same area.

The MSF outcrops usually consist of the lower calcareous-marly lithofacies, which unconformably overlies the Maddalena Mts carbonate succession. The upper part is generally lacking or is strongly chaotic at the toe of the Maddalena Mts Ridge, and overlies the Maddalena Mts Unit, the Lagonegro Unit and AV. These chaotic deposits might be the result of tectono-gravitational detachments. The MSF is interpreted as a thrust-top basin fill postdating the first deformation phase that affected the Maddalena Mts Unit during Serravallian-Tortonian times (Bonardi et al., 2009; Castellano & Sgrosso, 1996; Castellano, Putignano, Sgrosso, & Sgrosso, 2000).

4.1.4.2. Castelvete formation. Siliciclastic turbidite deposits, consisting of quartz-feldspathic sandstones and pelites with levels of conglomerates, were mapped in the northernmost part of the study area. These deposits contain olistoliths of the carbonate platform, up to hundreds of metres in size, and unconformably overlie the three main tectonic units and seal the BPT. This succession, on the basis of its lithological features and stratigraphic position, is assigned to the Castelvete Formation (Bonardi et al., 2009; Cocco et al., 1974; Pescatore, Sgrosso, & Torre, 1970). It is interpreted as a thrust-top basin fill (Bonardi et al., 2009; Sgrosso, 1998), early Messinian in age (Amore et al., 2003).

4.1.5. Quaternary continental deposits

Terraced alluvial deposits were identified in the central part of the Pergola–Melandro basin. In the northern part of the basin, the alluvial deposits are composed

of pelites with intercalations of matrix-supported polygenic conglomerates and sands. Polygenic and heterometric clast-supported conglomerates are dominant in the central and southern parts of the basin. These early–middle Pleistocene deposits are up to 150 m thick to the north and up to 80 m thick in the Brienza village zone (Martino & Schiattarella, 2006). South of Brienza village, a large alluvial fan ca. 30 m thick, no

older than middle Pleistocene (Giano & Martino, 2003), was mapped.

4.2. Tectonic setting

The BPT, which superimposes the slope carbonate facies of the Apennine Platform (Maddalena Mts Unit) on the Lagonegro Unit, shows a trend ranging between N130°–

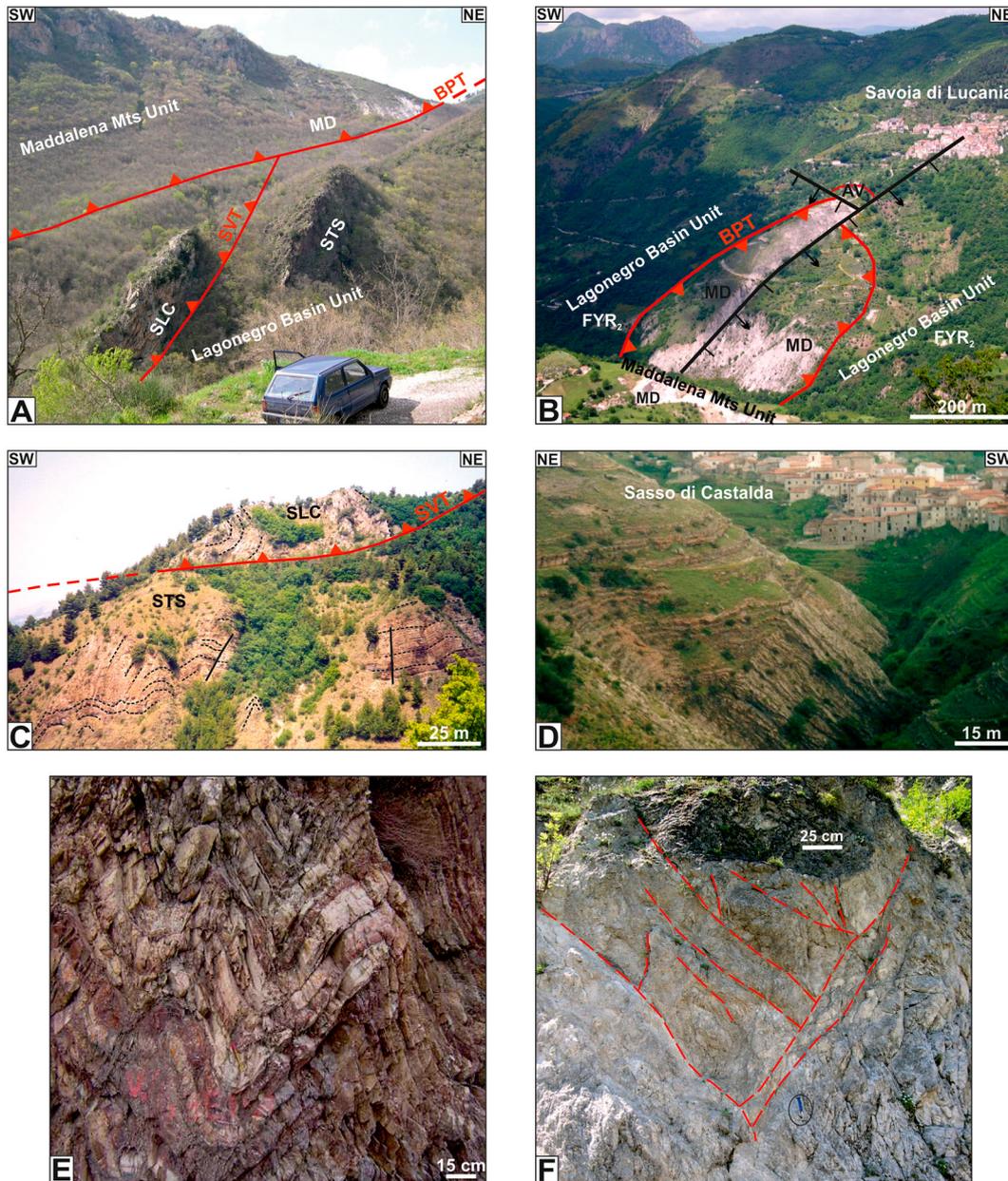


Figure 5. (a) The BPT that superimposes the Maddalena Mts Unit, consisting of the upper Triassic–early Jurassic Maddalena Mts dolostone (MD), on the deposits of the Lagonegro Basin at Monte San Salvatore. Two superposed Lagonegro tectonic slices, composed of the *Calcari con selce* (SLC) and of the *Scisti Silicei* (STS), and separated by the Savoia di Lucania–Vetri di Potenza Thrust (SVT), are present in the footwall of BPT (modified from Civile et al., 2010); (b) BPT dissected by normal faults (black lines) near the Savoia di Lucania village, where the upper Triassic–early Jurassic Maddalena Mts dolostone (MD) of the Maddalena Mts Unit are superposed on the Lagonegro deposits of the *Flysh Rosso* (FYR₂). A thin tectonic slice of the *Argille Variegata* Group is also present (AV₁ ‘Melaggio River shaly-calcareous-arenaceous’ lithofacies); (c) Klippe of the *Calcari con selce* (SLC) superposed on the *Scisti Silicei* (STS) by means of the SVT, near the Savoia di Lucania village. Folds dissected by the SVT are present both in the footwall and in the hanging-wall of the thrust-fault (modified from Civile et al., 2010); (d) the km-scale SCA, ca. N130° oriented (modified from Civile et al., 2010); (e) trains of decimeter-scale buckling meso-folds in the *Scisti Silicei* (STS) near Savoia di Lucania village. The folds are dissected by numerous fault planes; (f) positive flower structure in the late Triassic–early Jurassic Maddalena Mts dolostone (MD) near Passo Croce di Marsico.

140° and N150°–170° (see [Main Map](#)) and a thrust plane dipping to the SW between 5° and 35°. In the northern sector of the study area, the BPT places the Maddalena Mts Unit on two Lagonegro tectonic slices, with the interposition of the AV and detachment bodies of the *Flysch Rosso* Fm. ([Figures 5\(a\)](#), [5\(b\)](#) and geological cross-sections 2–4). In this area, several thin carbonate *klippen* with variable dip directions of the thrust surfaces were mapped, suggesting a folding of the BPT (see [Main Map](#) and geological cross-sections 1 and 2). In the Brienza village area, the analysis of the kinematic indicators associated with the thrust plane shows a reactivation in extension of this structure, as also observed in the Savoia di Lucania zone. In the Brienza area, the BPT cuts the pre-deformed Maddalena Mts succession of Il Crocifisso di Brienza Mt., which was folded to form a roughly E–W trending anticline verging to the NNW (geological cross-section 5). This structure was later involved along its eastern limb by a N140°–150° trending tight fold that produced a local overturn of the succession (see [Main Map](#)). The younger fold might be related to the BPT activity, whereas the older one should be considered as the effect of an about 80° counterclockwise rotation ([Gattacceca & Speranza, 2002](#)) of an original N–S trending folding due to the late Miocene opening of the Tyrrhenian back-arc Basin ([Sartori, 2003](#)). Therefore, the E–W trending folds surveyed in the carbonate succession could be interpreted as a relict structure not related to the roughly N-directed thrusting, Pliocene in age, reported by several authors (e.g. [Schiattarella, 1998](#); [Vitale et al., 2016](#)). A different refolding sequence is in fact reported by other authors (e.g. [Ferranti, Gialanella, Heller, & Incoronato, 2005](#); [Vitale et al., 2016](#)), in which about E–W-trending folds seem to post-date all the other sets. Since the Plio-Pleistocene counterclockwise rotation estimated for the SA is less than 20° ([Gattacceca & Speranza, 2002](#)), the present-day NW–SE striking regional-scale thrusts probably had an original trend of about N160°–170°.

In the southern part of the study area, the BPT superimposed the Maddalena Mts Unit on the Lagonegro succession with the interposition of the AV (see [Main Map](#) and geological cross-section 8).

Another important thrust-fault, the Savoia di Lucania-Vietri di Potenza Thrust (SVT), was recognized within the Lagonegro succession in the northern part of the study area (see [Main Map](#) and geological cross-sections 1–4). This structure develops with a N125°–130° trend, and dips to the SW between 30° and 50°. Its northernmost part shows a N205°–210° trend and a dip direction to the NW, with an inclination of 20–25°. The SVT cuts previously deformed Lagonegro successions ([Figure 5\(c\)](#)).

In the Lagonegro deposits, 5 km-scale anticlines were mapped from north to south: Savoia di Lucania Anticline (SLA), Brienza Anticline (BA), Sasso di Castalda Anticline (SCA, [Figure 5\(d\)](#)), Tigliano Mt.

Anticline (TA) and Melaggio River Anticline (MA) (see [Main Map](#) and geological cross-sections 1–4, 6–8). These folds show N120°–130° to 160°–170° axial trends and their limbs are affected by hectometre-to-metre scale parasitic meso-folds ([Figure 5\(e\)](#)).

Low-angle extensional tectonic contacts placing younger deposits on older deposits were mainly recognized at the base of the *Flysch Rosso* Fm. (see [Main Map](#) and geological cross-sections 1–4, 8). They produced thin tectonic slices in places located just in the footwall of the BPT. The basal low-angle contacts show planes with a variable dip direction which cross-cuts previous tectonic structures. These contacts also affect the *Flysch Galestrino* and the *Calcari con selce* formations located along the south-eastern margin of the study area. These tectonic contacts are interpreted as low-angle normal faults or detachment faults which generated tectonic elision because of denudational processes.

The fault systems statistically more common are those oriented N–S, N40–70°, N120°±10°, N130°–170° and E–W (see [Main Map](#)) with prevailing normal and oblique offsets. The western side of the Pergola–Melandro basin is controlled by kilometre-scale normal faults with a variable trend between N120°–140° and 155°–180°. The eastern side of the basin is mostly affected by N40°–70° and by N120°–140° trending faults.

The Quaternary deposits are affected by N160°–170° trending lineaments and by less common N60°–80° and N110°–120° trending faults (see [Main Map](#)). The main left-lateral transpressive faults were mapped in the southern part of the study area at the toe of the Maddalena Mts ridge ([Figure 5\(f\)](#)), and north-eastward of the Vietri di Potenza village.

The meso-fault analyses include over 400 measurements distributed on 14 structural sites ([Figure 6](#)). The recognized fault sets in the pre-Quaternary bedrock, which are all polyphasic, show a predominant strike-slip (pitch 0–25°) and oblique (pitch 25–70°) kinematics, whereas the faults affecting the alluvial Pleistocene deposits are represented by high-angle planes with a prevailing extensional kinematics.

5. Conclusions

The geological survey of the Pergola–Melandro basin has allowed us to define the main tectonic stages that occurred in the axial zone of the SA. The first stage was characterized by the development of NW–SE trending folds in the Maddalena Mts Unit which at present show an about E–W orientation produced by the counterclockwise rotation due to the late Miocene opening of the Tyrrhenian Sea. This folding occurred between Serravallian to middle Tortonian, as suggested by the Burdigalian–Langhian age of the Maddalena Mts foredeep deposits (Bifurto Fm.) and the late Tortonian age of the oldest thrust-top deposit (MSF). A second

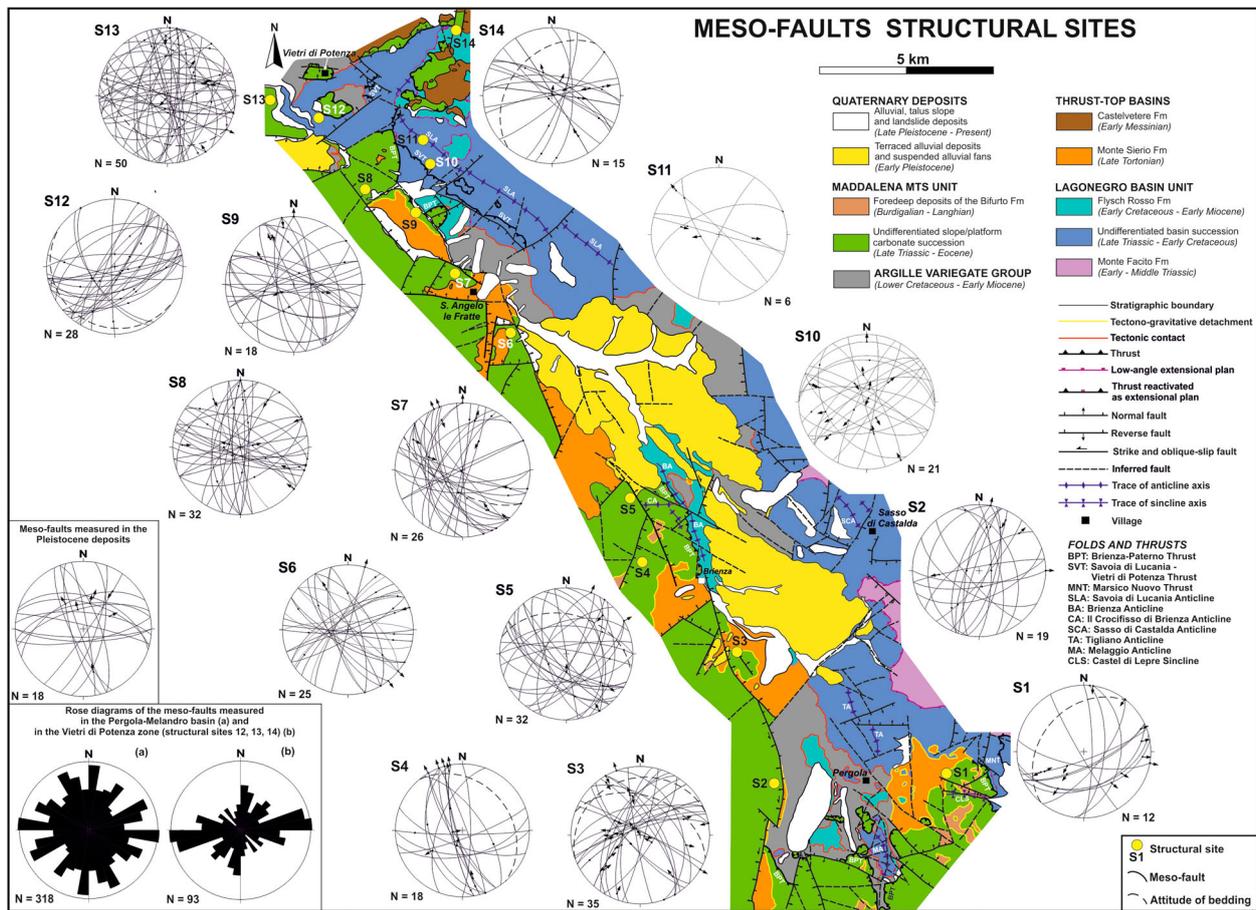


Figure 6. Structural scheme of the study area indicating the meso-faults structural sites collected in the Maddalena Mts and Lagonegro Basin units. The stereonet with the meso-faults measured in the Pleistocene alluvial deposits, and the rose-diagrams showing the orientation of all meso-faults measured in the pre-Pleistocene successions of the Vietri di Potenza area and in the remaining part of the basin, are shown on the left.

contractional stage, late Tortonian–early Messinian in age, generated a major shortening by the development of NW-trending folds and thrusts as part of the main SA mountain building. This phase locally produced the refolding of the previous E–W structures. The main thrust of the study area, the BPT, was probably active during the final part of this stage. This structure in fact cuts pre-deformed successions both in the hanging-wall and in the footwall. The geological survey did not allow us to define the original palaeogeographic position of the AV, which shows a tectonic contact with the substrate, represented by both the Maddalena Mts and Lagonegro units. If the AV deposits are considered of internal origin (Sicilide Complex), the BPT would represent an envelopment (i.e. out-of-sequence) thrust (*sensu* Bally, Gordy, & Stewart, 1966) cutting a previously piled nappe. As an alternative hypothesis, these predominantly shaly deposits belong to the Lagonegro Basin and were shifted from their original position after the occurrence of the thrust emplacement of the Apennine Platform over the already deformed Lagonegro Basin. This event could have produced off-scraping of the upper portion of the succession of the AV (‘chaotic shale’ lithofacies).

The early Messinian Castelvetero Formation seals the tectonic stack of the tectonic units identified in the study area. A third Pliocene NNE-directed shortening event would have produced the refolding of some of the NW-trending Apennine structures. The structural setting is complicated by low-angle tectonic contacts, interpreted as normal or detachment faults which produced both thin tectonic slices and elision because of denudational processes mainly during Pliocene times (soon after the third tectonic stage). In this context, pre-existing thrusts (e.g. the BPT) have been re-activated as extensional planes. Finally, wide tectono-gravitational detachments affected the clay- and shale-dominated units during late mountain-building processes in the late Pliocene-early Pleistocene time-span, being their contacts with the bedrock cut by the high-angle faults responsible for the mid-Pleistocene uplift of this sector of the chain.

Software

The geological map and associated geological cross-sections were digitized and edited using CorelDRAW X6.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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