Geology of the Aventino River Valley (eastern Majella, central Italy)

Published version:

DOI:10.1080/17445647.2014.899524

Festa et al., 2014, Journal of Maps, v.10 (4), 584-599, Doi: 10.1080/17445647.2014.899524

Geological map of the Aventino River Valley (eastern Majella, central Italy)

[1]Andrea Festa, [1-2]Cristina Accotto, [1]Francesco Coscarelli, and [1]Elisabetta Malerba, [3-1]Giulia Palazzin

[1] Dipartimento di Scienze della Terra, Università di Torino, Via Valperga Caluso, 35, 10125 Torino, Italy (email: andrea.festa@unito.it)
[2] GEODATA Engineering S.p.A., corso Duca degli Abruzzi, 48/E, 10129, Torino, Italy
[3] Institut de Science de la Terre d'Orléans, Université d'Orléans, 1A, rue de la Férollerie - 45071 – Orléans, France.

*Corresponding author:
Andrea Festa
E-mail: andrea.festa@unito.it

ABSTRACT

The Apenninic fold-and-thrust belt in Italy represents one of the several interconnected circum-Mediterranean orogens developed after the Late Cretaceous – early Cenozoic closure of the Tethys and the convergence between the European and the African plates. The Geological Map of the Aventino River Valley, at 1:25,000 scale, provides an original cartography of the outermost sector of Central Apennines in the Abruzzi region. Focusing on the detailed mapping of the crosscutting relationships between main regional thrust faults and tectonically-driven stratigraphic unconformities, the map describes the complex structural and stratigraphic relationships between the Outer Abruzzi units (i.e., Porrara Unit), Apulia – Adriatic deformed units (i.e., Majella and Casoli Units), and allochthonous Molise and Sicilide units. These tectono-stratigraphic relationships result from four main tectonic stages that occurred sequentially in a short time interval from late Messinian to early Pliocene.

Keywords: Central-Southern Apennines; Majella; Molise and Sicilide Units; Tectono-stratigraphic evolution.

1. INTRODUCTION

The Majella Mt., in southern Abruzzi region (central Italy; Fig. 1), is one of the most studied examples of exhumed hydrocarbon-reservoir of the Apennines (e.g., Crescenti et al., 1969; Accaire et al., 1986; Eberli et al., 1993; Ghisetti et al., 1993; Vezzani and Ghisetti, 1995; Bernoulli et al., 1996; Mutti et al., 1996; Donzelli, 1997; Vecsei and Sanders, 1999; Vecsei et al., 1998; Cipollari et al., 2003; Cosentino et al., 2005; Patacca and Scandone, 2007; Rusciadelli and Ricci, 2008, Agosta et al., 2009, 2010; Vezzani et al., 2010, Rustichelli et al., 2012, 2013; Iadanza et al., 2013). It consists of a N-S striking and double plunging anticline, representing the outermost and northernmost outcrops of the Apulia-Adriatic deformed foreland (e.g., Vezzani et al., 2010 and reference therein). To the East and South, the Majella anticline shows complex structural relationships with the allochthonous basinal succession of the Molise and Sicilide Units and with the platform succession of the Porrara Unit (Outer Abruzzi Apenninic platform units), respectively.

The existing geological cartography of the Majella region consists of both detailed (e.g., Donzelli, 1997; APAT, 2005a, 2005b; Miccadei et al., 2013; see also the unpublished internal report of the "Task Force Majella" project, see ENI E&P, 2000) and regional scale (e.g., Servizio Geologico d'Italia, 1970, Vezzani et al., 1993, 2004; Vezzani and Ghisetti, 1998; Patacca and Scandone, 2007; Vezzani et al., 2010) maps. However, only the regional scale maps are able to describe the complex structural relationships among the Majella anticline and the Porrara, Molise and Sicilide units as they occur to the east and south of the Majella Mt.

We present here the new "Geological Map of the Aventino River Valley", at 1:25,000 scale (see Geological Map), that is aimed to cover the lack of a detailed geological – structural cartography of the eastern sector of the Majella Mt. This is crucial for a better understanding of the structural and stratigraphic relationships between the Molise, Sicilide, Apulia – Adriatic deformed units (i.e., Majella and Casoli Units) and Porrara Unit (Outer Abruzzi Unit) in the context of the late Miocene – early-middle Pliocene tectono-stratigraphic evolution of the central Apennines in Italy.

2. METHODS

The geological map was realized in about seven years (2006-2012) of field work by means of a geological mapping at 1:10,000 scale and detailed stratigraphic and structural analyses. The definition of the complex structural setting of the mapped sector was defined through the mapping of the crosscutting relationships between main thrust faults and tectonically-driven stratigraphic unconformities, and documented in the attached geological map at 1:25,000 scale (see Geological Map), using Tables 147-I, 147-II, 147-III, 147-IV, 153-I and 153-II of the topographic maps *"Carta Topografica Regionale, Regione Abruzzo, 1985"* (Topographic Regional Map, Abruzzi Region, 1985) at 1:25,000 scale. The geological map includes the regional-structural scheme, stratigraphic columns of the lithostratigraphic successions of the different tectono-stratigraphic units and their structural relationships, the structural scheme of the mapped area, and five significant geological cross-sections.

3. REGIONAL SETTING

The Apennines represent one of the several interconnected circum-Mediterranean orogens, consisting of an east-to-northeast verging fold-and-thrust belt, developed after the Late Cretaceous – early Cenozoic closure of the Tethys and the convergence between the continental margin of the European plate (Corsica-Sardinia) and the Adria microplate (e.g., Cavazza et al., 2004; Vezzani et al., 2010; Festa et al., 2013). Since Late Cretaceous episodes of convergence, the most internal paleogeographic units (Ligurian and Sicilide units) were deformed and incorporated in the East-verging Apenninic accretionary wedge in relation with an oceanic ("B" type) subduction (e.g., Marroni et al., 2001; Vezzani et al., 2010). Paleogene paleogeographic restoration of the Central Apennines (Fig. 2) shows two main carbonate platforms (i.e., the Lazio-Abruzzi and Campania-Lucania platform, and the Apulia-Adriatic platform) and intervening pelagic basins: the Ligurian and Sicilide basins, to the West, and the Lagonegro, Sannio and Molise basins, to the East (e.g., Ciarapica and Passeri, 2002; Patacca and Scandone, 2007; Vezzani et al., 2010).The subsequent late Oligocene-early Pleistocene thrust accretion is shown by the East and Northeast migration of the Liguride and Sicilide units, up to the contractional deformation of the westernmost part of the Apulia-Adriatic continental margin (Adria microplate; e.g. Majella, Casoli, Porrara, Porrara). In central Apennines (Fig. 1), where the Ligurian Units are lacking, the Sicilide Units overlie a complex imbricate tectonic edifice consisting of N-verging and NE-to ENE-verging platform carbonate-to basinal thrust sheets (Matese, Sannio, Molise, Majella and Casoli units; see, e.g., Ghisetti and Vezzani, 1997; Vezzani et al., 1998, 2010; Patacca and Scandone, 2007).

The studied area is located in the Aventino River Valley in southeastern Abruzzi region (Central Apennines, Fig. 1 and Geological Map), where the platform carbonate-to basinal successions of the Apulia-Adriatic deformed units (i.e., Majella and Casoli Units), Jurassic-to early Pliocene in age, show complex structural relationships with the platform succession of the Outer Abruzzi Units (i.e., Porrara Unit; see Fig. 2) and the allochthonous Molise and Sicilide Units, which consist of basinal successions of late Oligocene-late Miocene, and late Cretaceous – early Miocene age, respectively.

4. DATA

Five tectono-stratigraphic units, with complex structural relationships, have been subdivided within the studied area. These units, which are the Casoli, Majella, Porrara, Molise and Sicilide Units, and the Thrust-top basin deposits, are described in the following with regards to their internal lithostratigraphy (Section 4.1) and structural relationships (Section 4.2).

4.1. Stratigraphy

The Majella and Casoli Units represent the structural culmination of the Apulia-Adriatic deformed foreland that emerges in the studied area within two main tectonic windows (e.g. Vezzani et al., 2010 and reference therein; Fig. 1). The ***Casoli Unit*** is the lowermost tectono-stratigraphic unit and is folded in a NW -striking open anticline, outlining by the alternating claystone and marly claystone of the Torrente Laio Flysch (e.g. Vezzani and Ghisetti, 1998; Vezzani et al., 2004, 2010) of uppermost lower Pliocene age (Gt. *punticulata* zone with Gt. *margariate*; Fig. 3). Subsurface data show that this succession overlies Messinian evaporites and a platform carbonate succession (see Geological Section 1) comparable with that of the Majella Unit (e.g., Mostardini and Merlini, 1986; Scisciani et al., 2000; Nicolai and Gambini, 2007; Patacca and Scandone, 2007; Patacca et al., 2008; Vezzani et al., 2010 and reference therein).

The ***Majella Unit*** is a roughly N-S striking and double plunging regional scale anticline that, in the studied area, is represented only by its steeply dipping eastern limb. It consists (Fig. 3) of a shallow-water Upper Jurassic-Lower Cretaceous (i.e., Morrone di Pacentro Formation; Fig. 4A) to Upper Cretaceous (i.e., Monte Acquaviva Formation or Cima delle Murelle Formation *Auct.*; Fig. 4B) carbonate platform succession (with interbedded bauxite horizons; Fig. 4C). To the North, a Cenomanian-Maastrichtian (i.e, Scaglia “Tre Grotte Member” and Orfento formations) to middle Paleocene - early Oligocene (i.e., Santo Spirito Formation) platform-edge-proximal basin succession, including platform-sourced lenticular channelized breccias, rests in onlap contact above the platform succession (e.g., Bernoulli et al., 1996; Mutti et al., 1996; Lampert et al., 1997). It is followed upward by the Upper Oligocene – Lower Messinian Bolognano Formation (Figs. 3 and 4E). The latter is subdivided in three main informal members (i.e., *Lepidocyclina* limestones; *Bryozoan* limestones and *Orbulina* marls*; Lithothamnium* limestones and *Turborotalia Multiloba* marls; see, e.g., Brandano et al., 2012), each of which corresponds to a shallow-water depositional sequence (i.e., Mutti et al.,1997; Vecsei and Sanders, 1999, Brandano et al., 2012). Discontinuous horizons of resedimented gypsum, gypsum-arenite, grayish marl and siltstone of Messinan age (Gessoso-Solfifera Formation), rest unconformably onto the Bolognano Formation and are followed upward by the late Messinian Lago Mare clays (e.g., Cipollari et al., 2005; Cosentino et al., 2005, 2011). The Majella Unit succession is closed upward by the lower Pliocene Majella Flysch (see Vezzani et al., 1993; Vezzani and Ghisetti, 1998; Fig. 3) that consists of yellowish pelite (*Sphaeroidinellopsis* zone) with intercalations of sandstone, grading upward to badly stratified grayish clay and silty-clays (*Gt. margaritae zone;* Fig. 4G). The basal part of the Majella Flysch is locally marked by tens of meters thick megabeds of channelized bodies of conglomerate with limestone clasts (i.e., Palena conglomerates *Auct.; Sphaeroidinellopsis* zone; Fig. 4F).

The ***Porrara Unit*** , that represents a platform carbonate-to basinal succession originally located at the inner margin of the Adriatic-Apulia continental margin (e.g., Vezzani et al., 2010 and reference therein; see Fig. 2), is exposed along a narrow NNW-SSE ridge in the southwestern sector of the mapped area. It consists (Fig. 3) of a shallow-water Upper Jurassic - Lower Cretaceous carbonate platform succession with interbedded horizons of bauxite in the upper part (i.e., Bauxitic limestone; Fig. 4B). This succession is followed unconformably by platform edge and scarp facies of Late Cretaceous – Paleocene age, with Rudist fragments (Calcari micritici or “Micritic limestones”), and, after another unconformity contact, by the *“Bryozoan and Lithothamnium calcarenites”* of Langhian-to early Messinian age. The latter, that represent a shallow-water depositional sequence, pass upward to pelite with gypsum interlayers, bituminous marl and gypsum-arenite grading to the Messinian Porrara Flysch (see, e.g., Sartoni and Crescenti, 1964; Accordi, 1966; Crescenti et al., 1969; Parotto and Praturlon, 1975; Accordi and Carbone, 1988).

The Molise and Sicilide Units, that represent basinal successions deformed in the allochthonous thrust sheet of the central-southern Apennine orogenic wedge, crop-out in the central and eastern sector of the mapped area. They show repeated mutual imbrication (i.e., Frentani Tectonic Mélange of Vezzani et al., 2010), and together override the Majella and Casoli Units (see below). The ***Sicilide Units*** (Complesso Sicilide of Ogniben, 1960) represent internal units originally deposited in a Tethys-facing basin (see e.g., Ogniben, 1960; Patacca and Scandone, 2007; Vezzani et al., 2010 *cum biblio*; see Fig. 2). They consist of a Upper Cretaceous – lower Miocene chaotic succession (Fig. 3) with a block-in-matrix arrangement (i.e., Argille varicolori *Auct.*). The matrix consists of red, green and bluish claystone and shalestone (Fig. 5A), alternating with cm-to dm thick beds of greenish-gray calcilutite, red cherty limestone, brown calcarenite, manganiferous black limestone, and yellow-to orange quartzarenite. The blocks, from centimeters-to meters in size, are mainly of intra-formational origin, representing the product of intense disruption and fragmentation of the originally coherent succession (Fig. 5A). Thus, the Argille varicolori mainly represent a broken formation as in the External Ligurian Units of Northern Apennines (see also Codegone et al., 2012; Festa et al., 2010a, 2010b, 2012; Festa and Codegone, 2013). However, along the main thrusts, meters-to tens of meters wide exotic blocks (i.e., extra-formational origin; see Festa et al., 2012) occur, in forming a tectonic mélange (Fig. 5B). These blocks are mainly made of Upper Jurassic – Lower Cretaceous whitish micritic limestone (Maiolica), late Messinian resedimented gypsum and evaporitic limestone, Miocene conglomerate, calcarenite with *Orbulina spp.* and reworked fragments of *Nummulites spp.*, rare Oligocene-Miocene volcanoclastic arenite, and Pliocene claystone.

The ***Molise Units*** derive from the progressive deformation of the outermost external Apenninic basinal domains (e.g., Vezzani et al., 2010 and reference therein; see Fig. 2) and are characterized by a Tertiary basinal succession (Fig. 3). This succession consists of upper Oligocene – lower Miocene pinkish-reddish marly claystone with chert, alternating with calcilutite and calcarenite (i.e., the Argille policrome; Fig. 5C), that pass upward to Langhian – Serravallian calcirudite and thick-bedded bioclastic calcarenite (i.e., Gamberale - Pizzoferrato Formation; Fig. 5D). Serravallian – Tortonian well bedded whitish marly claystones (i.e., Tufillo Formation, *sensu* Crostella and Vezzani, 1964; Fig. 5E) and Tortonian – lower Messinian Orbulina marls (Fig. 5F) follow upward. The Molise succession is closed by the lower Messinian arenitic turbidites of the Agnone Flysch (Figs. 2 and 5G).

The Sicilide and Molise units are unconformably overlain by ***Thrust-Top Basin*** deposits (see also Ghisetti and Vezzani, 1998; Vezzani et al., 2004) that are, in turn, involved by later thrusting stages. These deposits have been subdivided into two main sequences (Fig. 3). The lower one (i.e., Rio Cupo conglomerate), consists of upper Messinian – lower Pliocene (?) coarse-grained sandstone and polygenic conglomerates (micritic limestone, chert, biocalcarenite, violet claystone of Ligurian affinity, quarzarenite and rare quartzite; Fig. 6A), alternating with grayish marl and thin levels of gypsum-arenites (Fig. 6B). The upper sequence is represented by matrix supported conglomerates (i.e., Palombaro sandstones, see also Vezzani et al., 2010) with intercalations of sandy-silty layers (early Pliocene; *Sphaeroidinellopsis* zone; Figs. 6C and 6D), grading upward to yellow sand with lenses of clast-supported conglomerate and microconglomerate (i.e., Sant'Agata conglomerate). The latter pass upward and laterally to bluish-grayish fossiliferous marly-claystone with sandy intercalations (early Pliocene; *Gt. puncticulata* and *Gt. margaritae* zone).
Upper Pliocene – lower Pleistocene (*Hyalinea baltica* and *G. inflata* zone) foredeep clay deposits (i.e. Mutignano Formation, see also Vezzani and Ghisetti, 1998) unconformably seal the tectonic superposition between the Majella, Casoli, Sicilide and Molise units (Fig. 3).

Post-orogenic ancient alluvial deposits (middle – Late Pleistocene), form various orders of terraces suspended at different altitude above the main streams and rivers (see also Miccadei et al., 2013), and Late Pleistocene-to Present alluvial and debris flow deposits. Three main types of talus deposits, ranging in age from middle Pleistocene-to Present, drape the eastern flank of the Majella Mt. (see also Miccadei et al., 2013).

4.2. Tectonic setting
The tectonic setting is described focusing especially on the crosscutting relationships between the main regional thrust faults and the tectonically-driven stratigraphic unconformities (Fig. 7A and Geological Map).

To the south, the NE-dipping monocline of the Porrara Unit overthursts, with NE-verging, the late Eocene-to early Pliocene portions of the Majella Unit succession (Figs. 7A and 8B). The age of the younger stratigraphic unit of the footwall succession (i.e., the Majella Flysch) constrains the age of this tectonic superposition to the early Pliocene (*Spharoidinellopsis zone*; Fig. 7B). The footwall unit, that is represented by the eastern limb of the N-S directed Majella anticline, shows a gradual increase of bedding dip, from south (Palena village sector) to north (Pennapiedimonte village sector) and from WNW (axial zone) to ESE (compare Geological Sections 1 to 4 in Geological Map). Four main fault sets (about NW-SE, NE-SW, N-S and E-W oriented) crosscut the Majella Unit (Fig. 7A). In particular, the E-W and N-S faults mainly correspond to early, pre-folding, structures as suggested by their passive rotation that accompanies the increase of bedding dip on the eastern limb of the regional anticline (e.g., Fig. 7E to the East of Taranta Peligna village, see also faults West of Fara S. Martino; see Scisciani et al., 2000; Aydin et al., 2010; Masini et al., 2011 for major details). The NW-SE directed faults cut the N-S faults with left-lateral component of movement (Fig. 7A).

In the southern part of the mapped sector (Fig. 7A), the tectonic contact between the Porrara and Majella Units is cut by a thrust fault, NE-SW striking and ESE dipping low angle, bounding at the base the Agnone Flysch (Messinian) of the Molise Units, and the repeated imbrication of Molise and Sicilide Units (Fig. 8A). The age of the Majella Flysch, that represents the younger term of the footwall unit, constrains to the early Pliocene (syn-to post *Gt. margaritae* zone) this tectonic episode (Fig. 7B). Toward the north, this regional thrust is progressively folded, reversed (north of Lama dei Peligni village) and crosscut by a E-vergent thrust fault (Fig. 7A and Geological Section1 to 4 in Geological Map) up to superpose, with E-verging, the upper part of the Majella Flysch (early Pliocene, *Gt. margaritae* zone) onto the Molise and Sicilide Units, and the Torrente Laio Flysch of the Casoli Unit whose age (early Pliocene, *Gt. punticulata* zone with *Gt. margaritae*) constrains the timing of this thrusting episode (Figs. 7B and 8C).

The central and eastern sectors of the geological map are characterized by the repeated imbrications between Molise and Sicilide Units whose timing is constrained by the unconformable deposition of the thrust-top basin succession (Fig. 7B). The lower sequence of the thrust-top basin succession (i.e., the Rio Cupo succession) of late Messinian – early Pliocene(?) age, rests unconformably on the Sicilide Units (Figs. 3 and 7A) and is tectonically superposed by the Molise Units (e.g., WNW of Gessopalena). This tectonic contact is unconformably sealed (e.g., west of Gessopalena village, SW of Palombaro village, South of Casoli Lake; Fig. 7A) by the upper sequence of thrust-top basin succession (i.e., Palombaro sandstones of early Pliocene age, *Sphaeroidinellopsis* zone, and Sant'Agata conglomerates of early Pliocene age, *Gt. punticulata* and *Gt. margaritae* zone). The latter has been subsequently folded (e.g., close to Palombaro) and/or involved (e.g., NE of Gessopalena) by later deformation associated with the above described thrusting of Majella Unit onto the Molise, Sicilide and Casoli Units (see Geological Section 1 in Geological Map).

In the northern sector of the mapped area, the Mutignano Formation (late Pliocene – early Pleistocene) seals unconformably the structural relationships between the Majella, Casoli, Sicilide and Molise Units (Figs. 3, 7A and 7B).

5. CONCLUSIONS

Our geological map describes in detail the tectonic superposition among the Outer Abruzzi Units (Porrara Unit), Apulia-Adriatic deformed units (Majella and Casoli Units), and allochthonous units (Sicilide and Molise units) in the eastern Majella sector in central Apennines of Italy. The crosscutting relationships between mapped thrust faults and stratigraphic unconformities allow defining four main tectonic stages that occur sequentially in a short time interval (i.e., late Messinian – early Pliocene; Fig. 7B). The first deformational stage (late Messinian – early Pliocene) was characterized by the tectonic superposition of the Molise Units onto the Sicilide Units and the overlying lower sequence of the thrust-top basin succession. During the second tectonic stage (early Pliocene, *Sphaeroidinellopsis* zone), the Porrara Unit overthrusts with NE-verging the Majella Unit. This superposition has been cut, during the third deformational stage (early Pliocene, syn-to post *Gt. margaritae* zone), by the NW-vergence thrusting of the Molise and Sicilide Units. Finally, since late early Pliocene (*Gt. puncticulata* zone with *Gt. margaritae*), the thrust surface superposing the Molise and Sicilide Units onto the Majella Unit has been progressively folded and crosscut by the an E-verging thrust fault up to superpose the Majella, Sicilide and Molise Units onto the the Casoli Unit.

6. SOFTWARE

The geological map has been digitalized using the ArcView 3.1 and then edited with Adobe Illustrator CS3.

ACKNOWLEDGEMENTS

We thank Livio Vezzani for his insightful comments and suggestions that greatly helped us improve both the map and the text. We would like to express our sincere thank to the Associate Editor Dick Berg, and the three Referees (Juliane

Cron, Giacomo Prosser, and Andrea Rustichelli) for their constructive and thorough reviews and useful comments, from which we have benefited greatly in revising both our manuscript and geological map.

REFERENCES

Accaire, H., Beaudoin, B., Cussey, R., Joseph, P. and Triboulet, S. (1986). Dynamique sédimentaire et structurale au passage plate-forme/bassin. Le faciès carbonates cretacés du Massif de la Maiella (Abruzzes, Italie). *Memorie della Società Geologica Italiana*, 36, 217-231.

Accordi, B. (1966). La componente traslativa nella tettonica dell'Appennino laziale-abruzzese. *Geologica Romana*,5, 355–406.

Accordi, G., and Carbone, F. (1988). Lithofacies map of Latium-Abruzzi and neighbouring areas. *C.N.R., Quaderni de "La Ricerca Scientifica"*, 114 (5), 7-215, scale 1:250,000, 1 sheet, with explanatory notes.

Agosta, F., Alessandroni, M., Tondi, E., and Aydin, A., (2009). Oblique normal faulting along the northern edge of the Majella anticline, central Italy: inferences on hydrocarbon migration and accumulation. *Journal of Structural Geology*, 31, 674-690.

Agosta, F., Alessandroni, M., Antonellini, M., Tondi, E., and Giorgioni, M., (2010). From fractures to flow: a field-based quantitative analysis of an outcropping carbonate reservoir. *Tectonophysics*, 490, 197-213.

APAT (2005a) - Sheet CARG 360 "Torre de' Passeri" of the Geological Map of Italy at 1:50.000 scale. *S.EL.CA, Firenze (Ed.).* 1 Sheet.

APAT (2005b) - Sheet CARG 369 "Sulmona" of the Geological Map of Italy at 1:50.000 scale. *S.EL.CA, Firenze (Ed.).* 1 Sheet.

Aydin, A., Antonellini, M., Tondi, E. and Agosta F. (2010). Deformation along the leading edge of the Maiella thrust sheet in central Italy. *Journal of Structural Geology*, 32, 1291-1304.

Bernoulli, D., Anselmetti, F., Eberli, G.P., Mutti, M., Pignatti, J.S., Sanders, D.G.K., and Vecsei, A. (1996). Montagna della Maiella: the sedimentary and sequential evolution of a Bahamian-type carbonate platform of the South-Tethian continental margin. *Memorie della Società Geologica Italiana*, 51, 7-12.

Brandano, M., Lipparini, L, Campagnoni, V. and Tomassetti, L. (2012). Downslope-migrating large dunes in the Chattian carbonate ramp of the Majella Mountains (Central Apennines, Italy). *Sedimentary Geology*, 255-256, 29-41.

Cavazza, W., Roure, F. and Ziegler, P.A. (2004). The Mediterranean area and the surrounding regions: active processes, remnants of former Tethyan oceans and related thrust belts. In W. Cavazza, F. Roure, W. Spakman, G.M. Stampfli & P.A. Ziegler (Eds.), *The TRANSMED Atlas: The Mediterranean Region form crust to mantle*. Springer, 1-29.

Ciarapica, G., and Passeri, L. (2002). The paleogeographic duplicity of the Apennines: Bollettino della Società Geologica Italiana- Volume Speciale 1, 67–75.

Cipollari, P., Cosentino, D., Di Bella, L., Gliozzi, E. and Pipponzi, G. (2003). Inizio della sedimentazione d'avanfossa nella Maiella meridionale: la sezione di Fonte dei Pulcini (Taranta Peligna). *Studi Geologici Camerti, Numero speciale 2003*, 63-71.

Cita, M.B. (1960). Studi sul Pliocene e sugli strati di passaggio dal Miocene al Pliocene. VII Planktonic foraminiferal biozonation of the Mediterranean Pliocene deep sea record. Rivista Italiana di Paleontologia e Stratigrafia, 81, 527-544.

Codegone, G., Festa, A., Dilek, Y. and Pini, G.A. (2012). Small-scale Polygenetic mélanges in the Ligurian accretionary complex, Northern Apennines, Italy, and the role of shale diapirism in superposed mélange evolution in orogenic belts. *Tectonophysics*, doi: 10.1016/j.tecto.2012.02.003.

Cosentino, D., Cipollari, P., Lo Mastro, S. and Giampaolo, C. (2005). High-frequency cyclicity in the latest Messinian Adriatic foreland basin: Insight into palaeoclimate and palaeoenvironments of the Mediterranean Lago-Mare episode. *Sedimentary Geology*, 178, 31-53.

Cosentino, D., Bertini, A., Cipollari, P., Florindo, F., Gliozzi, E., Grossi, F., Lo Mastro, S. and Sprovieri, M. (2011). Orbitally forced paleoenvironmental and paleoclimate changes in the late postevaporitic Messinian of the Central Mediterranean Basin. *Geological Society of America Bulletin,* 124 (3-4), 499-516.

Crescenti, U., Crostella, A., Donzelli, G. and Raffi, G. (1969). Stratigrafia della serie calcarea dal Lias al Miocene nella regione marchigiano-abruzzese (Parte II – Litostrtigrafia, biostratigrafia, paleogeografia). *Memorie della Società Geologica Italiana*, 8, 343-420.

Crostella, A. and Vezzani, L. (1964). La geologia dell'Appennino foggiano. *Bollettino della Società Geologica Italiana*, 83, 21–141.

Donzelli G. (1997). Studio geologico della Maiella. Università degli Studi "G. D'Annunzio". *Tipografia R. Di Virgilio (ed.), Chieti Scalo*, 49 pp.

Eberli, G.P., Bernoulli, D., Sanders, D and Vecsei, A. (1993). From aggradation to progradation: the Maiella platform, Abruzzi, Italy. In T. Simo, R.W. Scott & J.P. Masse (Eds.), *Cretaceous Carbonate Platforms*. American Association of Petroleum Geologists Memoir, 56, 213-232.

ENI E&P (2000). Geological structure and tectonic evolution of the Maiella Mountain. *Internal Report ENI E&P, Task Force Maiella*, 38 pp.

Festa A., and Codegone G. (2013). Geological map of the External Ligurian Units in western Monferrato (Tertiary Piedmont Basin, NW Italy*). Journal of Maps*, 9, issue 1, 84-97.

Festa A., Dilek., Y., Codegone G., Cavagna, S., and Pini, G.A. (2013). Structural Anatomy of the Ligurian Accretionary Wedge (Monferrato, NW-Italy), and Evolution of Superposed Mélanges. *Geological Society of America Bulletin,* 125 (9/10), 1580-1598. Doi: 10.1130/B30847.1

Festa, A., Dilek, Y., Pini, G.A., Codegone, G., and Ogata, K. (2012). Mechanisms and processes of stratal disruption and mixing in the development of mélanges and broken formations: Redefining and classifying mélanges. *Tectonophysics*, doi:10.1016/j.tecto.2012.05.0

Festa, A., Pini, G.A., Dilek, Y., and Codegone, G. (2010a). Mélanges and mélange-forming processes: a historical overview and new concepts. *International Geology Review*, 52 (10-12),1040-1105. DOI: 10.1080/00206810903557704

Festa, A., Pini, G.A., Dilek, Y., Codegone, G., Vezzani, L., Ghisetti, F., Lucente, C.C., and Ogata, K. (2010b). Peri-Adriatic mélanges and their evolution in the Tethyan realm. *International Geology Review*, 52, 369–403, doi: 10.1080/00206810902949886.

Ghisetti, F. and Vezzani, L. (1997). Interfering paths of deformation and development of arcs in the fold-and-thrust belt of the Central Apennines (Italy). *Tectonics*, 16, 523-536.

Ghisetti, F. and Vezzani, L. (1998). Segmentation and tectonic evolution of the Abruzzi-Molise thrust belt (central Apennines, Italy). *Annale Tectonicae*, 12 (1-2), 97-112.

Ghisetti, F., Vezzani, L. and Follador, U. (1993). Transpressioni destre nelle zone esterne dell'Appennino centrale. *Geologica Romana*, 29, 73-95.

Iaccarino, S. (1985). Mediterranean Miocene and Pliocene planktic foraminifera. In Bolli, H.M., Saunders, J.B. & Prerch-Nielsen, K. (Eds.): Plankton stratigraphy. *Cambridge University Press*: 283-314.

Iadanza, A., Sampalmieri, A., Cipollari, P., Mola, M., and Cosentino, D. (2013). The "Brecciated Limestones" of Maiella, Italy: Rheological implications of hydrocarbon-charged fluid migration in the Messinian Mediterranean Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 390, 130-147.

Lampert, S.A., Lowrie, W., Hirt, A.M., Bernoulli, D. and Mutti, M. (1997). Magnetic and sequence stratigraphy of redeposited Upper Cretaceous limestones in the Montagna della Maiella, Abruzzi, Italy. *Earth and Planetary Science Letters*, 150, 79-93.

Marroni, M., Molli, G., Ottria, G. and Pandolfi, L. (2001). Tectono-sedimentary evolution of the External Liguride units (Northern Apennines, Italy): insight in the pre-collisional history of a fossil ocean-continent transition zone. *Geodinamica Acta*, 14, 307-320.

Masini, M., Bigi, S., Poblet, J., Bulnes, M., Di Cuia, R. and Casabianca, D. (2011). Kinematic evolution and strain simulation, based on cross-section restoration, of the Maiella Mountain: an analogue for oil fields in the Apennines. *Geological Society of London Special Publications*, 349, 25-44.

Miccadei, E., Piacentini, T., Dal Pozzo, A., La Corte, M. and Sciarra, M. (2013). Morphotectonic map of the Aventino – lower Sangro Valley (Abruzzo, Italy). *Journal of Maps*, 9, Issue 3, 390-409.

Mostardini, F. and Merlini, S. (1986). Appennino centro-meridionale. Sezioni geologiche e proposta di un modello strutturale. *Memorie della Società Geologica Italiana*, 35, 177-202.

Mutti, M., Bernoulli, D., Eberli, G.P. and Vecsei, A. (1996). Depositional geometries and facies associations in an upper Cretaceous prograding carbonate platform margin (Orfento supersequence, Maiella, Italy). *Journal of Sedimentary Research*, 66, 749-765.

Mutti, M., Bernoulli, D., and Stille, P. (1997). Temperate carbonate platform drowning linked to Miocene oceanographic events: Maiella platforms margin, Italy. *Terra Nova*, 9, 122–125.

Nicolai, C., and Gambini, R. (2007). Structural architecture of the Adria platform-and-basin system. In A. Mazzotti, E. Patacca & P. SCANDONE (Eds.), *Results of the CROP Project, Sub-project CROP 04 Southern Apeninnes (Italy).* Italian Journal of Geoscience, Special Issue 7, 21–37.

Ogniben, L. (1960). Nota illustrativa allo schema geologico della Sicilia nord-orientale. *Rivista Mineraria Siciliana*, 11, 183-212.

Parotto, M., and Praturlon, A. (1975). Geological summary of the Central Apennines. In Ogniben, L., Parotto, M., & Praturlon, A., (Eds.), *Structural Model of Italy: C.N.R., La Ricerca Scientifica*, 90, 257–311.

Patacca, E. and Scandone, P. (2007). Geology of the Southern Apennines. In A. Mazzotti, E. Patacca & P. SCANDONE (Eds.), *Results of the CROP Project, Sub-project CROP 04 Southern Apeninnes (Italy).* Italian Journal of Geoscience, Special Issue 7, 75-119.

Patacca, E., Scandone, P., Di Luzio E., Cavinato, G.P. and Parotto M. (2008). Structural architecture of the central Apennines: Interpretation of the CROP 11 seismic profile from the Adriatic coast to the orographic divide, Tectonics, 27, TC3006.

Rio, D., Sprovieri, R., and Di Stefano, E. (1994). The Gelasian stage: a proposal of a new chronostratigraphic unit of the Pliocene series. *Rivista Italiana di Paleontologia e Stratigrafia*, 100, 103-124.

Rusciadelli, G. and Ricci, C. (2008). New geological constraints for the extension of the northern Apulia platform margin west of the Maiella Mt. (Central Apennines, Italy). *Italian Journal of Geosciences*, 127, 375-387.

Rustichelli, A., Tondi, E., Agosta, F., Cilona, A., and Giorgioni, M. (2012). Development and distribution of bed-parallel compaction bands and pressure solution seams in carbonates (Bolognano Formation, Majella Mountain, Italy). *Journal of Structural Geology*, 37, 181-199.

Rustichelli, A., Tondi, E., Agosta, F., Di Celma, C., and Giorgioni M. (2013). Sedimentologic and diagenetic controls on pore-network characteristics of Oligocene-Miocene ramp carbonates (Majella Mountain, central Italy). *AAPG Bulletin*, 97 (3), 487-524.

Sartoni, S., and Crescenti, U. (1964). Ricerche biostratigrafiche nel Mesozoico dell'Appennino meridionale. *Giornale di Geologia*, 29, 161–388.

Scisciani, V., Calamita F., Bigi, S., De Girolamo, C. and Paltrinieri, W. (2000). The influence of syn-orogenic normal faults on Pliocene thrust system development: the Maiella structure (Central Apennines, Italy). *Memorie della Società Geologica Italiana*, 55, 193-204.

Servizio Geologico D'italia (1970). Sheet 147 "Lanciano" of the Geological Map of Italy at 1:100.000 scale. *Poligrafico dello Stato, Roma.*

Vecsei, A. and Sanders, D.G.K. (1999). Facies analysis and sequence stratigraphy of a Miocene warm–temperate carbonate ramp, Montagna della Maiella, Italy. *Sedimentary Geology*, 123, 103–127.

Vecsei, A., Sanders, D.K., Bernoulli, D., Eberli, G.P., Pignatti, J.S., 1998. Cretaceous to Miocene sequence stratigraphy and evolution of the Maiella carbonate platform margins, Italy. *SEPM Special Publication*, 60, 53-73.

Vezzani, L. and Ghisetti, F. (1995). Domini in compressione ed in distensione al retro dei fronti del Gran Sasso-M. Picca e del M. Morrone: il ruolo della zona di taglio Avezzano-Bussi (Appennino centrale). *Studi Geologici Camerti, Volume Speciale 1995/2*, 475-490.

Vezzani, L. and Ghisetti, F. (1998). Carta geologica dell'Abruzzo. *S.EL.CA., Firenze*, Scale 1:100.000, 2 sheets.

Vezzani, L., Casnedi, R. and Ghisetti, F. (1993). Carta geologica dell'Abruzzo nord-orientale. *S.EL.CA., Firenze*, Scale 1:100.000, 1 Sheet.

Vezzani L., Festa, A. and Ghisetti, F. (2010). Geology and Tectonic evolution of the Central-Southern Apennines, Italy. *Geological Society of America Special Paper 469*, 58 p, including the "Geological-Structural Map of the Central-Southern Apennines (Italy)" at 1:250.000 scale, Sheets 1 and 2. doi: 10.1130/2010.2469

Vezzani, L., Ghisetti, F. and Festa, A. (2004), Carta geologica del Molise. *S.EL.CA., Firenze*, Scale 1:100.000, 1 Sheet.

FIGURES

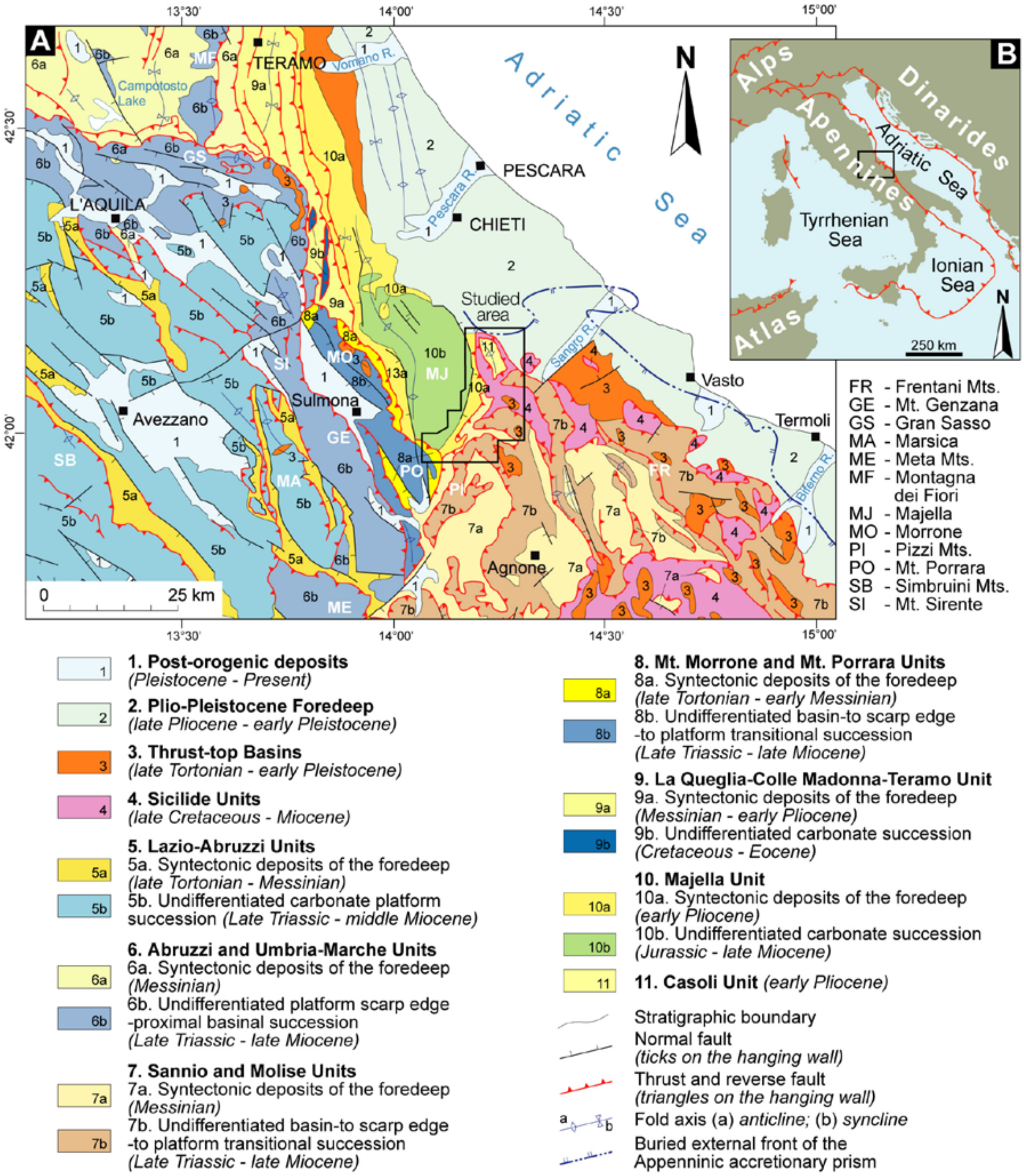

Figure 1 - Structural sketch map (A) of the Central-Southern Apennines (modified from Vezzani et al., 2010). (B) Location of Figure 1A.

[redacted]

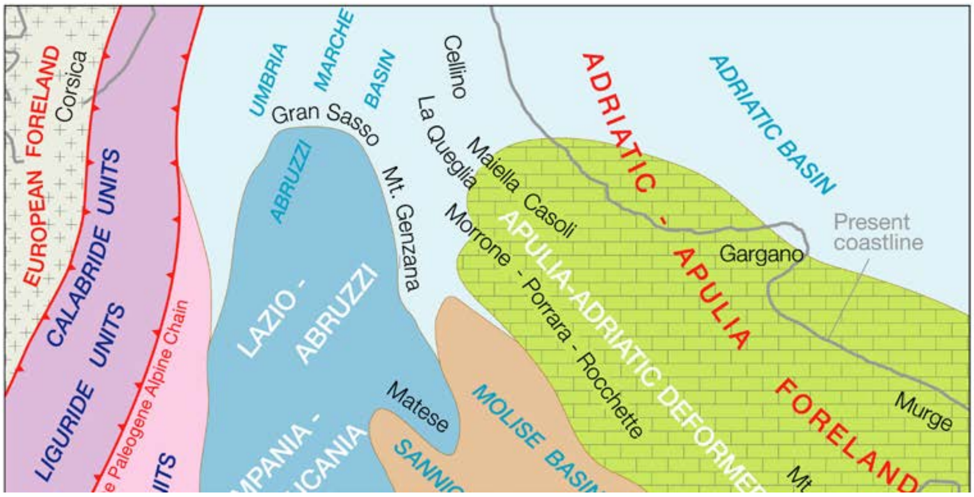

Figure 2 – Restoration of the paleogeography of the Central-Southern Apennines at Paleogene time, showing the distribution of carbonate platforms and intervening pelagic basins from which derive the major tectonic units of the Apenninic thrust-and-fold belt (modified from Vezzani et al., 2010).

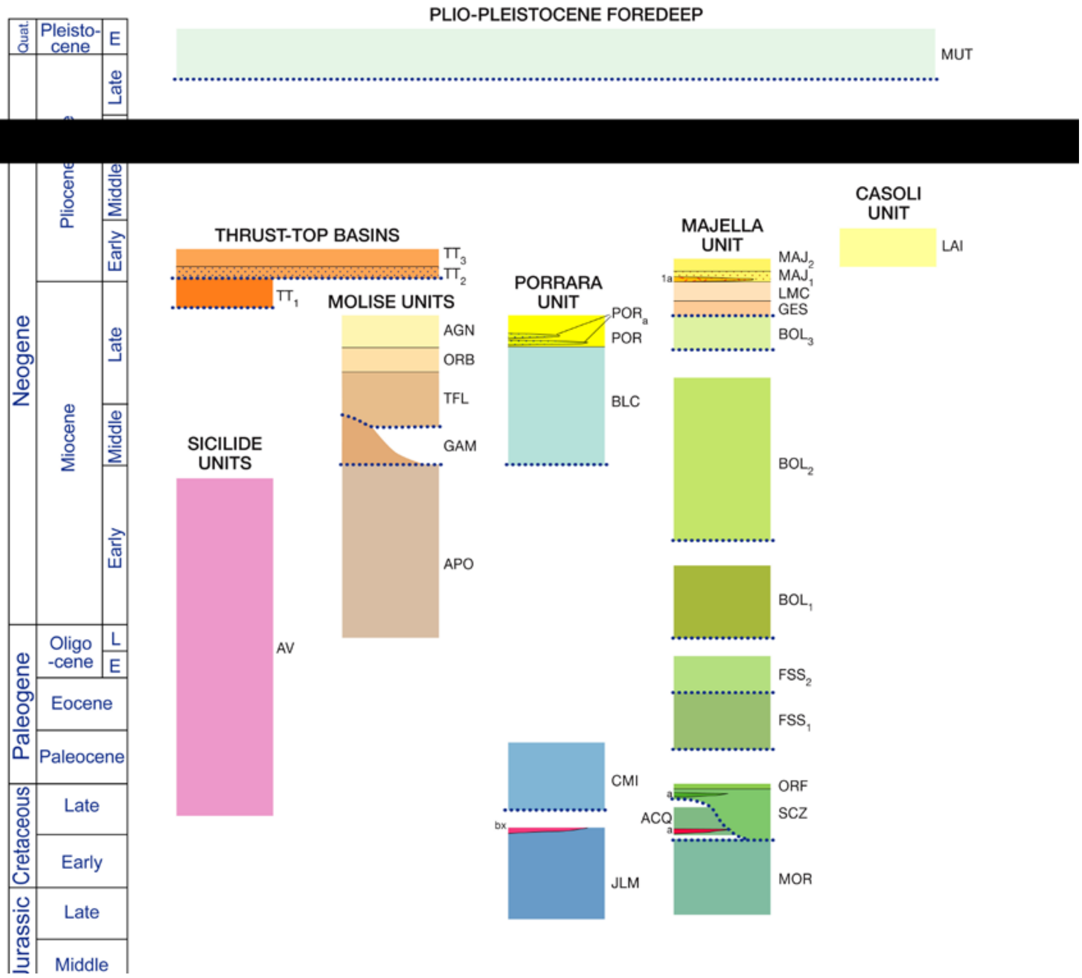

Figure 3 - Stratigraphic columns of the different tectono-stratigraphic units in the Aventino River Valley, eastern Majella. Acronyms, that are the same as in the legend of the geological map, are: **Plio-Pleistocene Units**: MUT – Mutignano Formation; **Thrust-Top basin**: TT_1 – Rio Cupo conglomerates, TT_2 – Palombaro sandstones, TT_3 – Sant'Agata Conglomerates; **Molise Units**: AGN - Agnone Flysch, ORB – Orbulina marls, TFL – Tufillo Formation, GAM – Gamberale – Pizzoferrato Formation, APO – Argille policrome; **Sicilide Units**: AV – Argille varicolori; **Porrara Unit**: POR – Porrara Flysch (a: conglomerate), BLC: *Bryozoan* and *Lithothamnium* calcarenite, CMI: Calcari micritici, JLM: Bauxitic limestones (bx: bauxite); **Majella Unit**: MAJ_2 – Majella Flysch (upper sequence), MAJ_1 – Majella Flysch (lower sequence; a: conglomerate), LMC: Lago Mare clays, GES - Gessoso-Solfifera Formation (a: resedimented gypsum and gypsum-arenite), BOL_3 – Bolognano Formation (*Lithothamnium* limestones and *Turborotalia Multiloba* marls), BOL_2 – *Bryozoan* limestones and Orbulina marls, BOL_1 – *Lepidocyclina* limestones, FSS_2 – Santo Spirito Formation (*Nummulites* limestones), FFS_1 – Santo Spirito Formation (*Alveoline* limestones), ORF – Orfento Formation, SCZ – Scaglia Formation (a: megabreccia orizons), ACQ – Monte Acquaviva Formation (a: bauxite), MOR – Morrone di Pacentro Formation; **Casoli Unit**: LAI – Torrente Laio Flysch; Dotted line: unconformity.

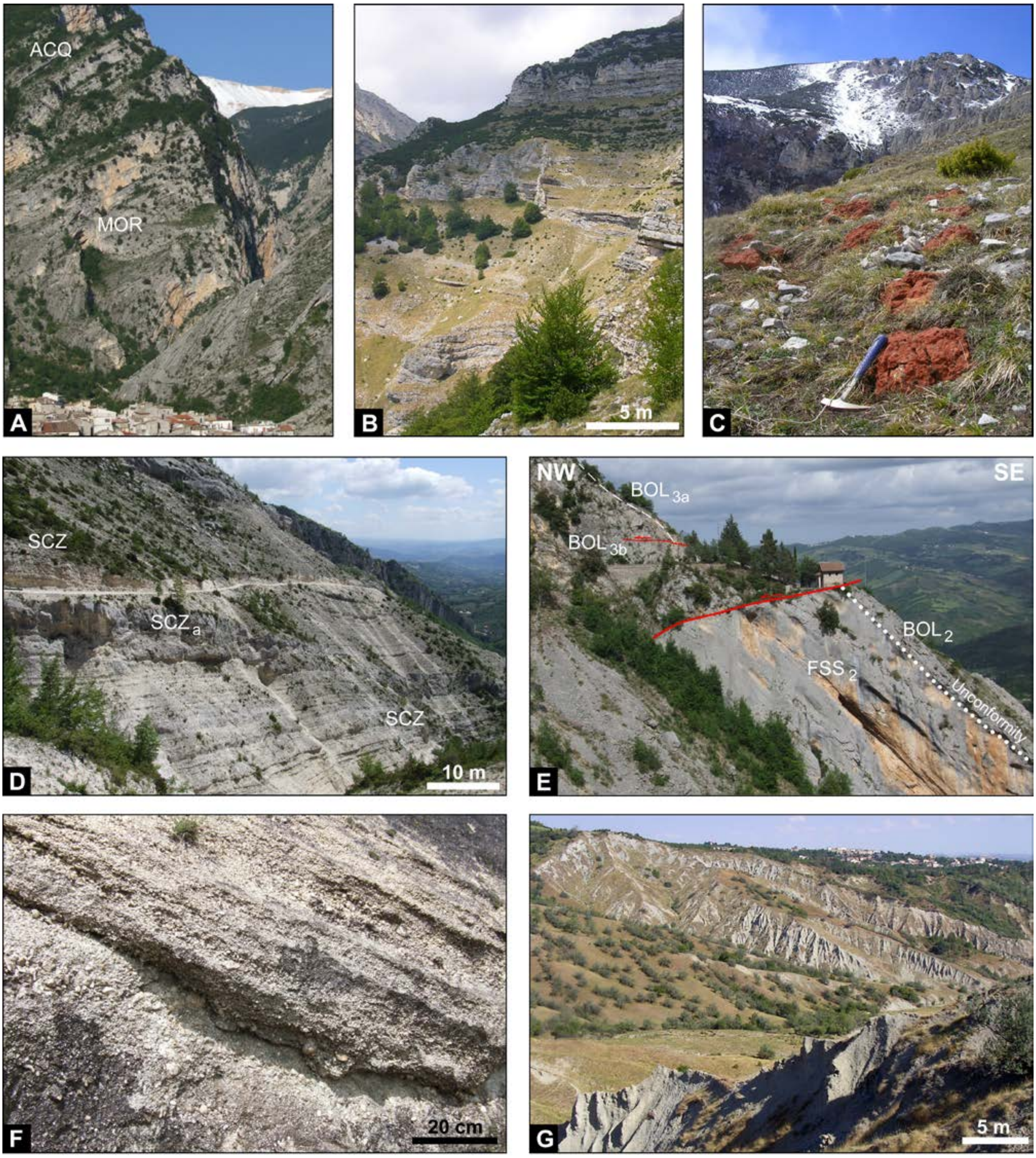

Figure 4 – Stratigraphic succession of the Majella Unit. (A) Massive aspect of the micritic limestone of the Morrone di Pacentro Formation (MOR, Late Jurassic - Early Cretaceous), well exposed to the right hydrographic flank of the Santo Spirito valley (close to Fara S. Martino village), passing upward to decimeters-to meters thick beds of the Monte Acquaviva Formation (ACQ, Late Cretaceous); (B) Whitish biocalcarenite and calcirudite in decimeters thick beds of the Monte Acquaviva Formation (Late Cretaceous; Serviera Valley, West of Cima della Stretta); (C) Disrupted horizon of bauxites (reddish clasts) in the lower part of the Monte Acquaviva Formation (close to Cima Macirenelle); (D) Whitish hemipelagic calcilutite of the Scaglia Formation (SCZ; Cenomanian – Maastrichtian), in decimeters thick beds, including a tens of meters thick horizon of channelized megabreccias (SCZ_a) that consists of platform blocks and rudist fragments (Tre Grotte Valley, West of Pennapiedimente); (E) Unconformity contact

(dotted white line) between the thick horizons rich in *Nummulites* of the Santo Spirito Formation (FFS_2, late Eocene – early Oligocene) and the overlying *Bryozoan* limestones of the Bolognano Formation (BOL_2, Burdigalian – Tortonian), cut by a low-angle and-NNW dipping rotated normal faults (red line; see Section 4.2). The hanging wall of the fault consists of the upper sequence of the Bolognano Formation (BOL_{3a} – *Turborotalia Multiloba* marls, early Messinian age; BOL_{3b} – *Lithothamnium* limestones, Tortonian – early Messinian) (Sacrario dei Caduti locality, close to Taranta Peligna village); (F) Close-up of the conglomerate consisting of platform sourced calcareous clasts, forming the tens of meters thick megabeds horizons intercalated in the lower part of the Majella Flysch (early Pliocene, *Sphaeroidinellopsis* zone) (close to Lama dei Peligni village); (G) Typical exposure of the badly stratified grayish clays and silty-clays of the upper part of the Majella Flysch (early Pliocene,*Gt. margaritae* zone) (close to Pennapiedimonte village).

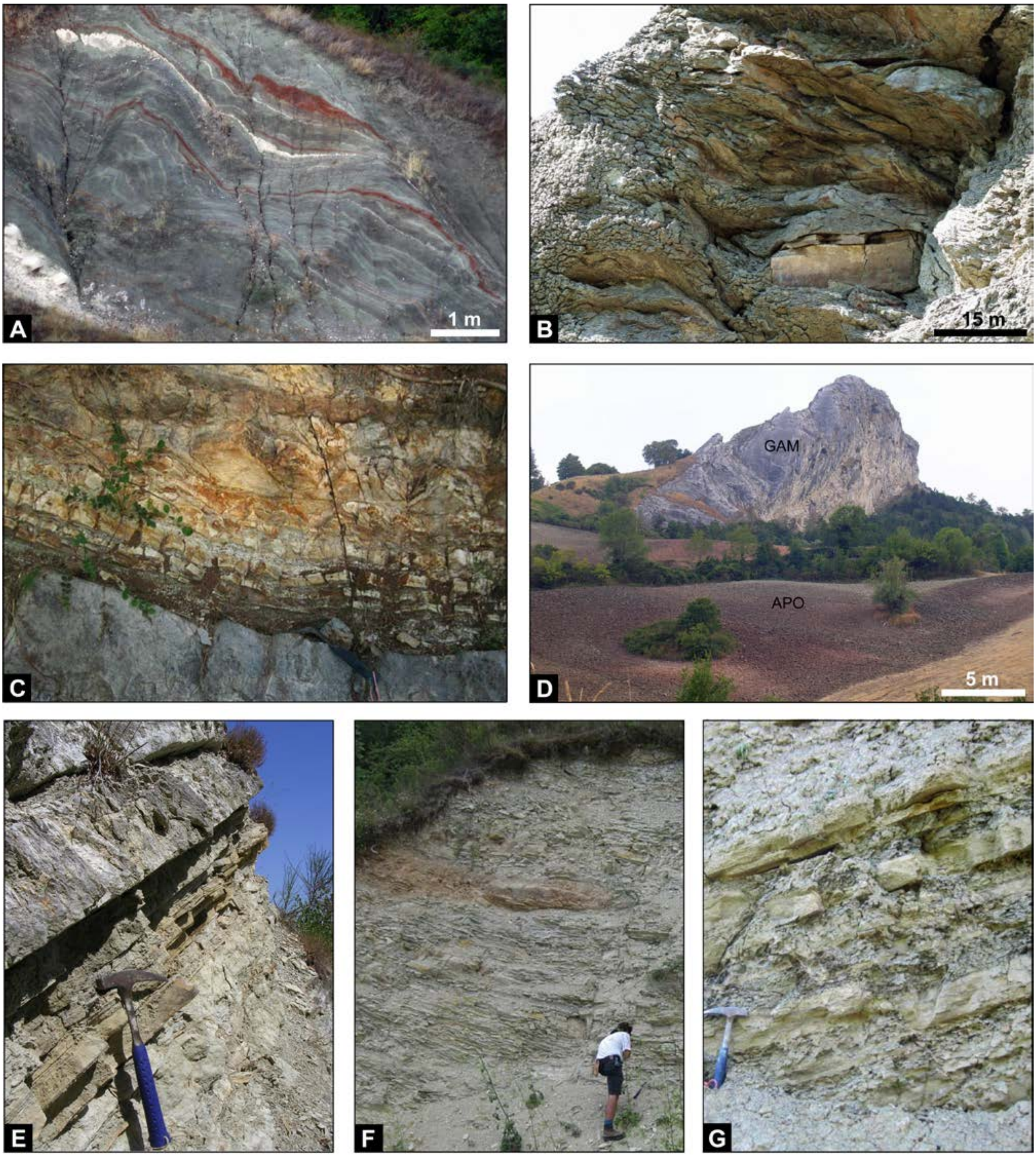

Figure 5 – Stratigraphic succession of the Sicilide (A and B) and Molise (C-to G) Units. (A) Alternating varicolored claystone layers of the Argille varicolori (Late Cretaceous – early Miocene) deformed by layer-parallel extensional fabric with pinch-and-swell structures and boudinage of the reddish shaly layers and white calcilutite horizons (East of la Morgetta locality, close to Fallascoso village); (B) Typical block-in-matrix fabric of the Argille Varicolori with tabular limestone blocks in a clayish matrix affected by pervasive scaly cleavage (south of Colle Luna, Casoli tectonic window); (C) Alternating reddish and whitish-yellowish thin layers of marly claystone, chert, and calcilutite of the Argille policrome (late Oligocene – early Miocene) (Torbido Valley, close to Colledimacine). Hammer for scale; (D) Tens of meters thick horizon of calcirudite and bioclastic calcarenite of the Gamberale - Pizzoferrato Formation (GAM, Langhian – Serravallian), overlying the reddish clays of the Argille policrome (APO, late Oligocene

– early Miocene) (la Morgia locality, close to Gessopalena); (E) Well-bedded alternating marly claystone and calcarenite of the Tufillo Formation (Serravallian – Tortonian) (close to Palombaro village); (F) Thin bedded, white calcilutite of the Orbulina marls (close to Casoli village); (G) Close-up ot the alternating yellowish turbiditic sandstone and clay of the Agnone Flysch (early Messinian) (Cupo Valley, close to Colledimacine).

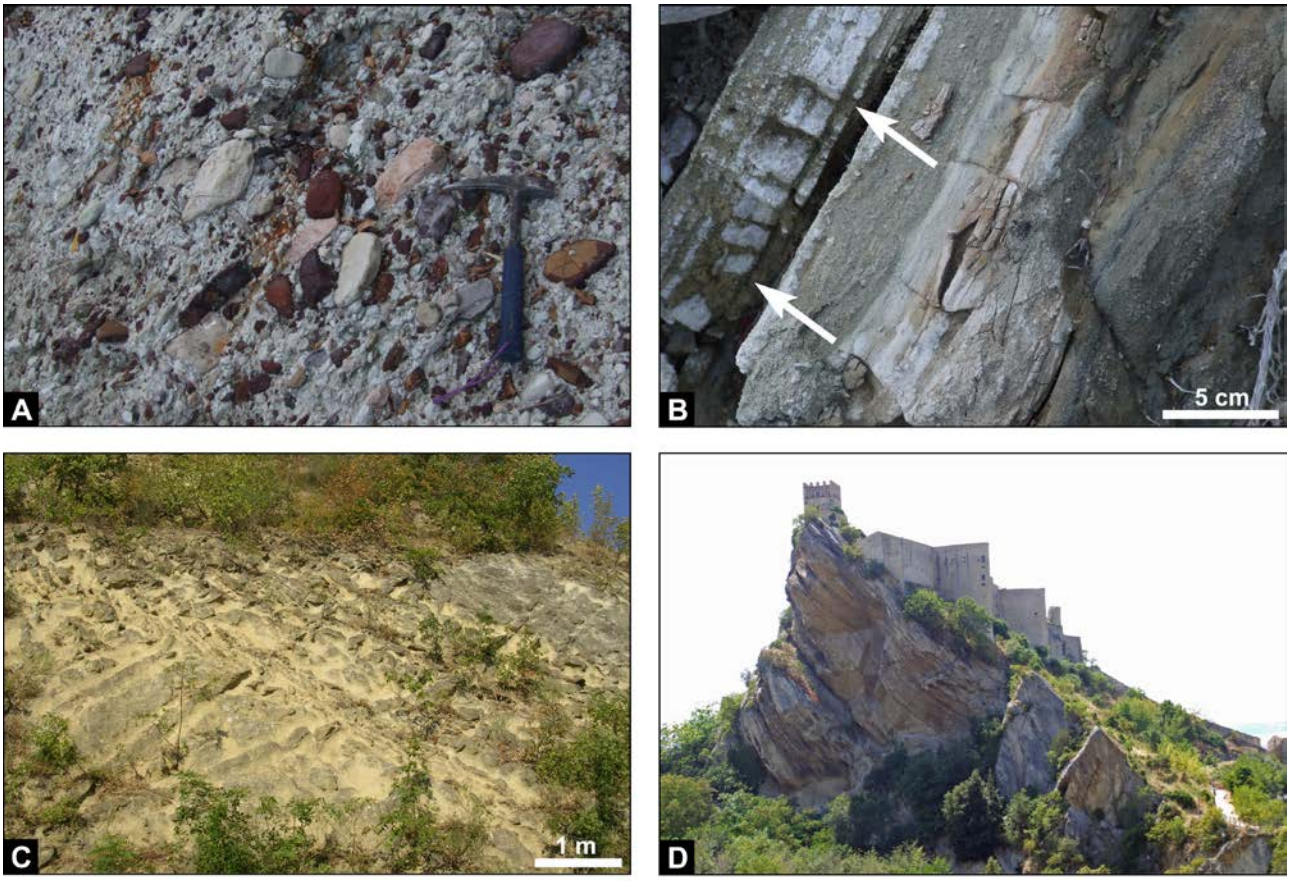

Figure 6 – Stratigraphic succession of the Thrust-Top Basin units. (A) Polygenic Rio Cupo conglomerates (late Messinian – early Pliocene?) with whitish clasts of micritic limestone, pinkish biocalcarenite, violet claystone of Ligurian Unit affinity (Aventino River, close to Lama dei Peligni; (B) Close-up of a fine-grained horizons interbedded within the polygenic Rio Cupo conglomerates, showing grayish marls and decimeters thick gypsum-arenite beds (white arrows) (Aventino River, close to Lama dei Peligni); (C) Yellowish sandstone of the Palombaro sandstones (early Pliocene, *Sphaeroidinellopsis* zone) close to Palombaro village and in massive horizons at the base of the Roccascalegna castle (D).

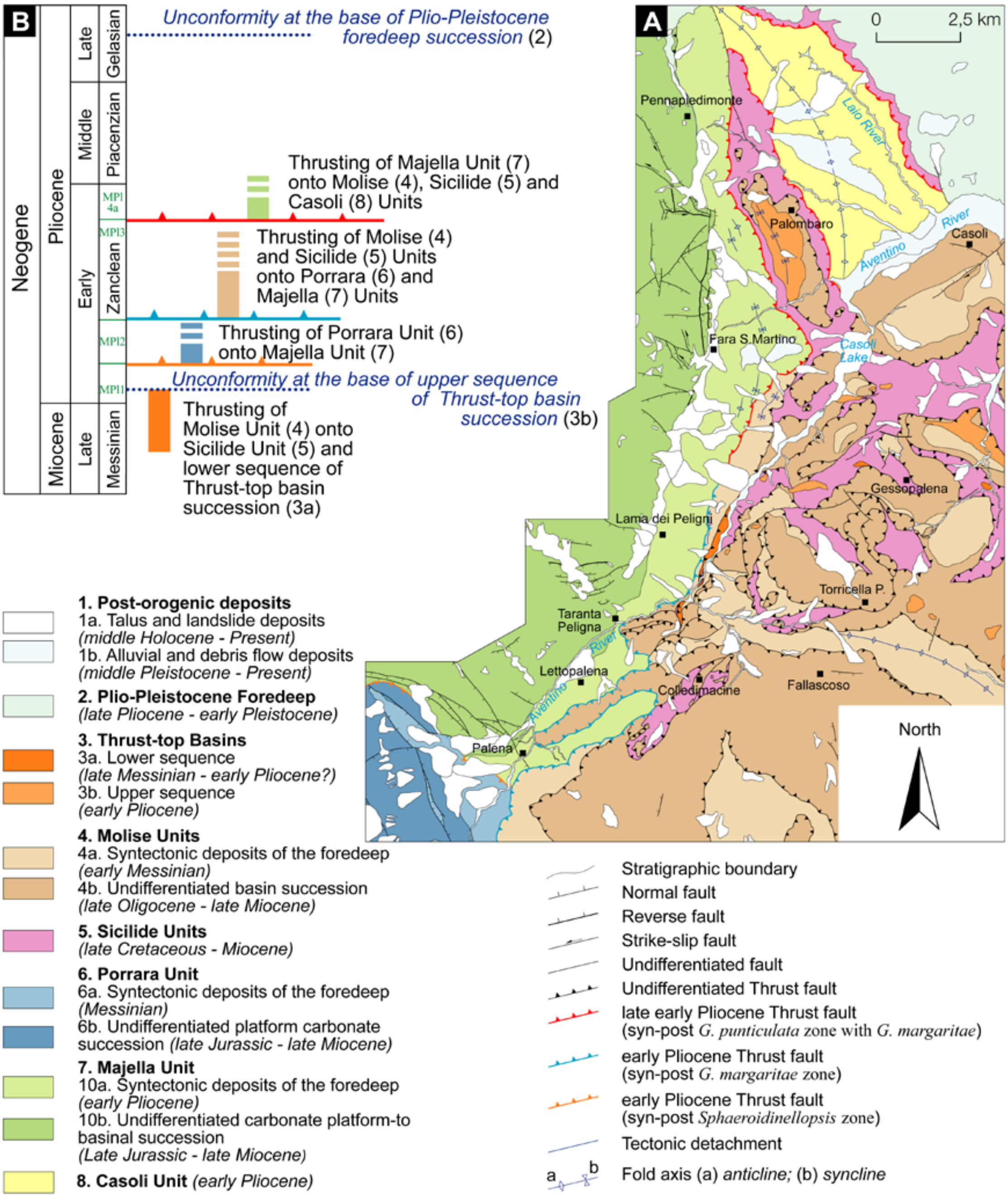

Figure 7 – (A) Structural scheme, showing the crosscutting relationships between different faulting stages (indicated with different colors) and stratigraphic unconformities (see text for a complete explanation). These relationships allow defining the different tectonic stages as summarized in the time column (B) in the left side of the figure. Foraminferal zones) MPl1: *Sphaeroidinellopsis acme*, MPl2: Gt. *margaritae*; MPl3: Gt. *puncticulata &* Gt. *margaritae*; MPl4a: Gt. *puncticulata* (see Cita, 1975; Iaccarino, 1994; Rio et al., 1994).

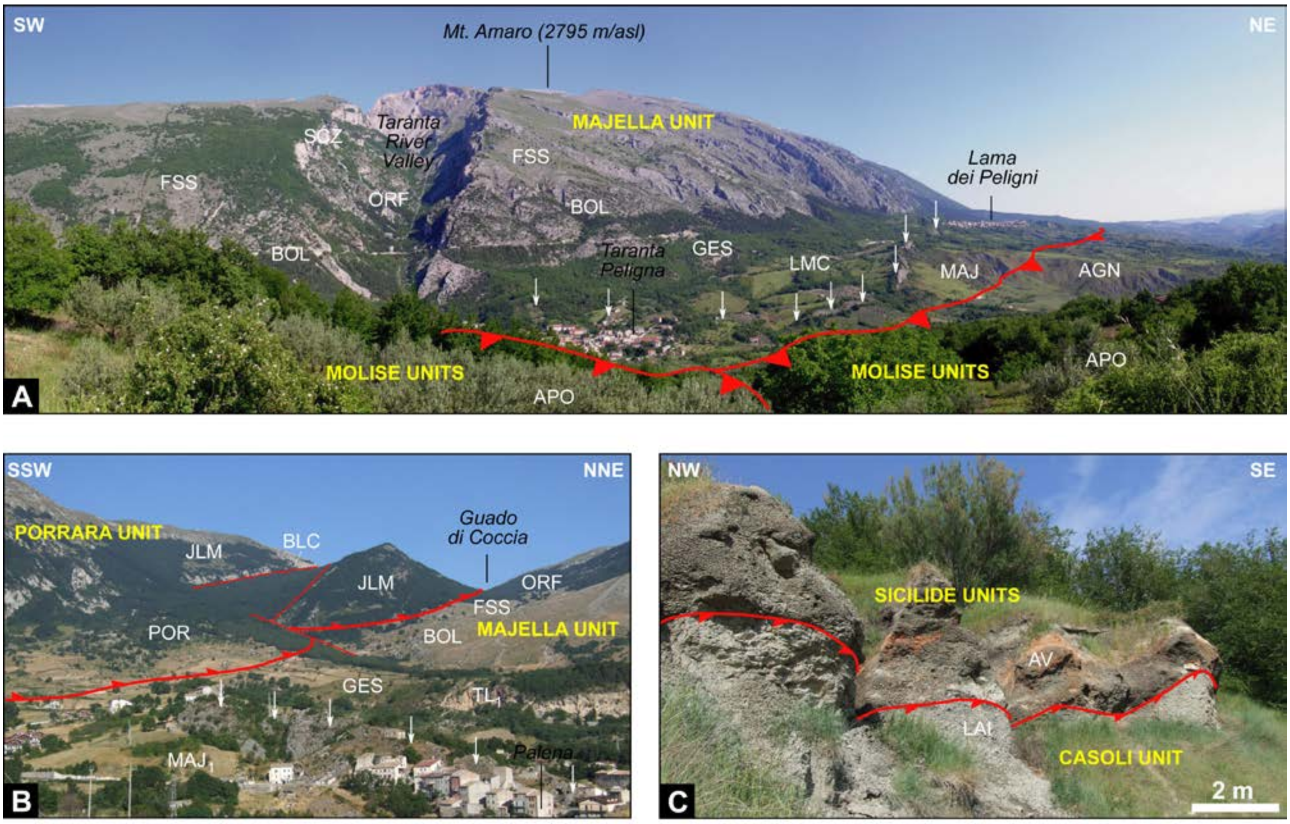

Figure 8 – (A) Panoramic view of the eastern flank of the Majella Mt. and Aventino River Valley (between Taranta Peligna and Lama dei Peligni villages), showing the overthrust of the Molise Units onto the upper part of the Majella Flysch (early Pliocene, *Gt. margariate* zone) of the Majella Unit. The eastern flank of the Majella Mt, corresponding to the limb of the regional N-S directed anticline, is characterized by the eastward dip of the calcareous Cretaceous – late Miocene succession (ORF: Orfento Formation; SCZ: Scaglia Formation; FSS: Santo Spirito Formation; BOL: Bolognano Formation), passing upward to the Messinian evaporitic (GES: Gessoso – Solfifera Formation) and post-evaporitic (LAC: Lago – Mare clays) succession. White arrows mark the decimeters thick horizons of the channelized limestone conglomerate (*Sphaeroidinellopsis* zone) at the base of the lower Pliocene Majella Flysch (MAJ). The Molise Units, in the hanging wall of the main NNE-SSW striking and ESE-dipping regional thrust, are represented by repeated imbrications of units consisting of different intervals of a basinal succession comprised between the upper Oligocene – lower Miocene Argille policrome (APO) and the lower Messinian Agnone Flysch (AGN); (B) Panoramic view of the tectonic superposition of the Porrara Unit (CMI: Calcari micritici, Late Cretaceous – Paleocene; BLC: *Bryozoan* and *Lythothamnium* calcarenites; POR: Porrara Flysch, early Messinian) onto the southern termination of the Majella Unit (ORF: Orfento Formation; SCZ: Scaglia Formation; FSS: Santo Spirito Formation; BOL: Bolognano Formation; GES: Gessoso – Solfifera Formation; MAJ_1: Majella Flysch; white arrows indicate the Palena Conglomerate). The thrust, that is NW-SE striking and WSW-dipping, is displaced by a E-W-striking normal fault. Well-cemented and poorly-to moderate sorted talus deposits (TL_1) crop-out close to the Palena village; (C) Overthrust of the upper Cretaceous Argille Varicolori (AV) of the Sicilide Unit above the lower Pliocene whitish clays of the Torrente Laio Flysch (LAI) of the Casoli Unit. The thrust strikes about NW-SE striking and dips to the ENE-(eastern flank of the Casoli tectonic window, south of Colle Luna).