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An outline of the geology of the Northern Apennines (Italy), with geological map at 1:250,000 scale

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ABSTRACT

An outline of the geology of the Italian Northern Apennines, to accompany a geological map at 1:250,000 scale covering the Emilia-Romagna, Marche, Tuscany and Umbria regions, is presented herein. The map is intended as a first result of a longer term project carried out by the Geological Surveys of the above regions, aimed to create a common geological map at 1:10,000 scale, useful for environmental planning and management.

The lithostratigraphic units are grouped in domains and successions (with references to main tectonic units), and a special effort was made to correlate similar lithostratigraphic units across the area. The enclosed geological map distinguishes stratigraphic successions deposited in: a) Ligurian Domain (Internal and External Ligurian domains); b) Subligurian Domain; c) Tuscan Domain (Tuscan Succession, Tuscan Metamorphic Succession, Cervarola-Falterona Succession, Modino Succession, Rentella Succession, Pseudoverrucano Succession); Umbria-Marche-Romagna Domain. Tectonic units derived from regional tectonic mélanges and shear zones (Sestola-Vidiciatico Unit), and units affected by HP metamorphism in the Tuscan Archipelago and southern Tuscany have been mapped. Distinguished younger successions are: a) Epiligurian Succession; b) Miocene-Pleistocene succession of the Tyrrhenian margin; c) Miocene-Pleistocene succession of the Po Plain and Adriatic margin. The main outcrops of magmatic rocks (Miocene-Pleistocene in age) and Quaternary alluvial, continental and coastal deposits have also been mapped. Main tectonic contacts (high-angle normal faults, main thrust and low-angle normal faults) are indicated. The 1:250,000 geological map of the Northern Apennines is freely available as PDF, raster and vector GIS data from the web site: https://www.geological-map.it.

Key words: *Northern Apennines, stratigraphy, tectonics, GIS.*

INTRODUCTION

This paper and the enclosed geological map are the result of a project involving the geological departments of the Emilia-Romagna, Marche, Toscana and Umbria regions, and the University of Siena.

The 1:250,000 geological map is compiled starting from the 1:10,000 geological databases produced by the Geological Surveys of the aforementioned regions and a significant work of reinterpretation, homogenization and generalization was carried out, integrated by data coming from literature and original field work. During generalization we also took into account the most important published geological maps at 1:250,000 or regional scale covering the area: Merla (1951); Compagnoni *et alii* (1980); Boccaletti & Coli (1982); Centamore (1986); Bigi *et alii* (1990); Cerrina Feroni *et alii* (2002b) and maps produced by the CARG Project of the Italian Geological Survey. Geology of the area outside of the administrative boundaries of the above regions is from Giammarino *et alii* (2002), Vezzani & Ghisetti (1998) and Cosentino & Pasquali (2012).

As all the geological boundaries of the map (stratigraphic contacts, faults, tectonic contacts) derive from original 1:10,000 maps, boundaries are coherent with the topography at 1:10,000 scale ("Carta Tecnica Regionale") produced by Emilia-Romagna, Marche, Toscana and Umbria regions. Until today no vector topographic map at 1:250,000 covering the whole area exists and the only map covering the entire area is the quite old Topographic Map at 1:250,000 scale produced by the Italian "Istituto Geografico Militare" (Florence). We used this map as the base map for printing and at a closer look of the printed map, some discrepancies could be locally present between geological boundaries and topography. We decided to keep these possible minor inconsistencies as the boundaries are coherent with the 1:10,000 map and are coherent if users work with downloaded GIS data.

By no means this paper aims to deliver a comprehensive and exhaustive work about the geological evolution of the Northern Apennines, for this purpose and to appreciate the development of knowledge on the regional geology of the area please refer to the several published works, as Sestini (1970); Boccaletti *et alii* (1971); Alvarez *et alii* (1974); Kligfield (1979); Castellarin *et alii* (1985); Malinverno & Ryan (1986); Cremonini & Ricci Lucchi (1982); Principi & Treves (1984); Treves (1984); Vai (1987); Patacca & Scandone (1989); Pini (1999); Patacca *et alii* (1990); Doglioni *et alii* (1998); Vai & Martini (2001); Cerrina Feroni *et alii* (2004); Di Bucci & Mazzoli (2002); Crescenti *et alii* (2004); Finetti (2005); Molli (2008); Mantovani *et alii* (2009); Scrocca *et alii* (2007); Doglioni *et alii* (2010); Carminati & Doglioni (2012), with extensive reference lists. This work is intended instead to serve as a sort of explanatory note for the enclosed geological map, to illustrate the lithostratigraphic units represented in the map and discuss some stratigraphic and tectonic features that are still matter of debate, besides providing an updated bibliographic review.

A printed copy of the geological map is here enclosed, the map is also freely available as PDF, raster and vector GIS data from: https://www.geological-map.it and in the Italian Journal of Geosciences Supplementary Material.

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STRATIGRAPHY

We present here an overview of the main stratigraphic features of the Northern Apennines. Lithostratigraphic units are grouped in paleogeographic domains and successions, with references to the main tectonic units (Fig. 1, Fig. 2). In the following, in parentheses are indicated the labels of lithostratigraphic units as in the geological map (e.g. UM_{sc}).

More examples of regional correlations and grouping for lithostratigraphic successions of the Northern Apennines are in Sestini (1970); Boccaletti *et alii* (1987); Vai & Castellarin (1992); Vai (2001); Cerrina Feroni *et alii* (2002a).

Ligurian Domain

The Ligurian Domain consists of magmatic-sedimentary successions that represent the remnants of the Piedmont-Ligurian ocean. Following classical interpretations (Elter, 1975; Elter & Marroni, 1991; Bortolotti *et alii,* 2001; Marroni *et alii,* 2010, 2017, and references therein) we separate the Ligurian Domain in an Internal Ligurian Domain and an External Ligurian Domain (Fig. 3, Fig. 4); the External Ligurian Domain is further divided in Inner Successions and Outer Successions (Western and Eastern Successions of Marroni *et alii,* 2001). The lithostratigraphic units of the Ligurian Domain are grouped by some authors in "supergroups", as Vara Supergroup, Trebbia Supergroup, Parma Supergroup, Baganza Supergroup, Calvana Supergroup, etc.: refer to Abbate & Sagri (1970) and Bortolotti *et alii* (2001) for overview and references.

Successions in the Ligurian Domain are related to basin architecture and therefore directly inherited from modes of rifting, that during Middle Jurassic led to the formation of the Piedmont-Ligurian Ocean, for which different models for opening have been proposed. First Decandia & Elter (1972) proposed a passive rifting with

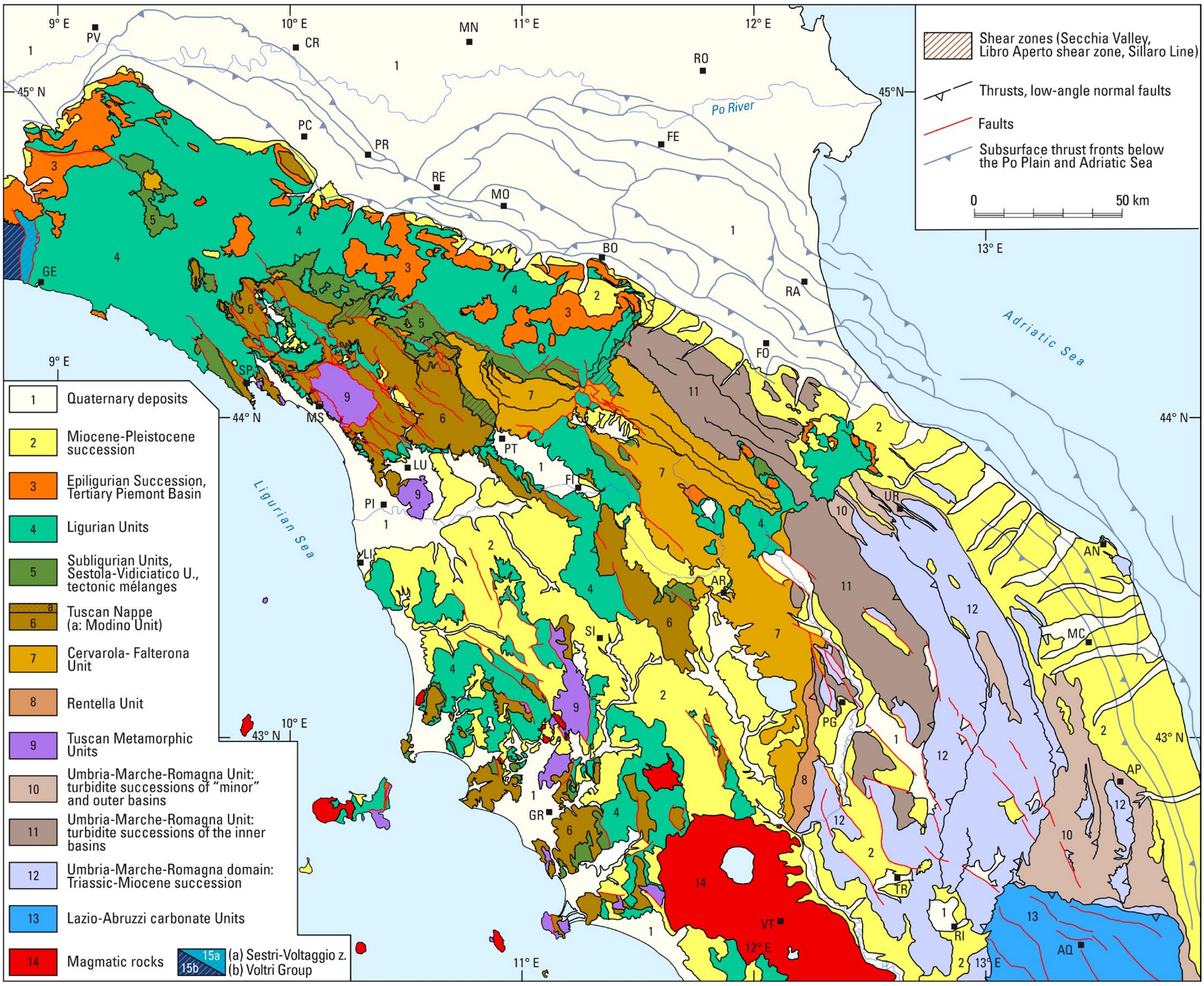

Fig. 1 - Tectonic map of the Northern Apennines. Subsurface thrust fronts from Bigi *et alii* (1990).

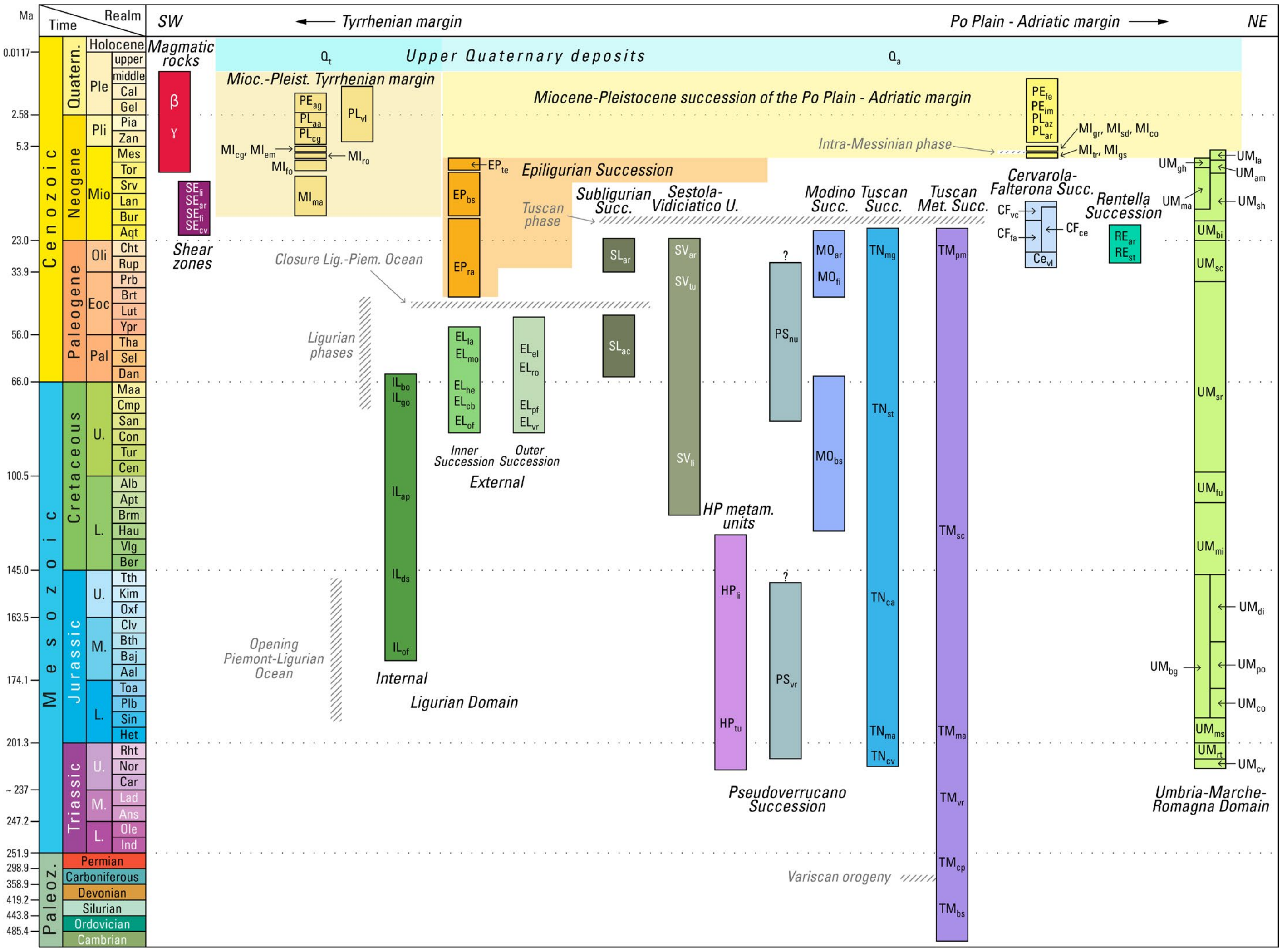

Fig. 2 - Successions, tectonic units and main deformation events in the Northern Apennines. Labels of map units are indicated.

delamination of the continental crust by faults located at the crust-mantle boundary, this results in a wide area of continental mantle to be unroofed and exposed on the seafloor and to development of an oceanic area bounded by a pair of symmetrical continental margins characterized by high-angle ocean-dipping normal faults. Later Lemoine *et alii* (1987) proposed a model where opening occurred by asymmetrical extension of the lithosphere by simple shear, with development of a low-angle detachment fault crossing the whole continental crust into the lithospheric mantle (Fig. 4a). This low-angle detachment separated the continental lithosphere in an upper and lower plate with very different tectonic and stratigraphic (uplift/subsidence) evolution: the Adria margins is the lower plate for this detachment. Similar to what documented in the Alps (Froitzheim & Manatschal, 1996), in the hanging wall of this detachment portion of upper plate crust are found ("extensional allochthons"). This model was later adopted by various Authors (Hoogerduijn Strating *et alii*, 1993; Marroni *et alii*, 1998, etc.).

Hereafter, we discuss the stratigraphy of the Ligurian Domain, more general information can be found in Abbate *et alii* (1970); Beccaluva *et alii* (1984); Piccardo *et alii* (1994); Principi (1994); Abbate *et alii* (1986); Cortesogno *et alii* (1987); Hoogerduijn Strating & Van Wamel (1989); Hoogerduijn Strating (1990); Malavieille *et alii* (2016); Fonnesu & Felletti (2019).

Internal Ligurian Domain

The Internal Ligurian Domain is represented by successions deposited in the Piedmont-Ligurian oceanic basin (Fig. 4b), now dismembered and outcropping in different tectonic units, like the Gottero Unit, Bracco-Val Graveglia Unit, Colli-Tavarone Unit, etc.

The successions consist of a basal ophiolite sequence (IL_{of}) with mantle peridotites (serpentinized lherzolites) intruded by Jurassic isotropic and layered gabbros. Peridotites and gabbros are intruded by gabbros, diorite and plagiogranite dikes and stocks. The top of the peridotites is covered by tectono-hydrothermal breccias (ophicalcites) and sedimentary breccias that testify to the exposure of peridotites at the seafloor. This succession is then covered by basalts (pillow-lavas) (Decandia & Elter, 1972; Abbate *et alii*, 1980; Beccaluva *et alii*, 1984; Cortesogno *et alii*, 1987).

The sedimentary cover of the ophiolite sequence starts with pelagic deposits represented by cherts and marls Callovian to Tithonian in age (IL_{ds}), the cherts derived from pelagic siliceous ooze reworked by oceanic bottom currents. Upsection pelagic shales, marlstones and limestones follow (IL_{ap}: Calpionella Limestones and Palombini Shales) and derive from distal carbonate and mixed siliciclastic-carbonate turbidites and pelagites that grades upward in a thick turbiditic succession of mainly siliciclastic composition; the whole succession is Cretaceous in age.

During Late Cretaceous-earliest Paleocene time deposition of coarse-grained sandstone siliciclastic turbidites occurs, interpreted as the proximal portion of deep-water fan system developed at the foot of the European continental margin at the transition with the ocean basin. This results in a thick succession of alternating arkoses, sandstones and shales (IL_{go}: Gottero Sandstones, Nilsen & Abbate, 1984; Marini, 1991, 1994; Pandolfi, 1996; Fonnesu & Felletti, 2019) and the Montecatini Sandstones in the southern Tuscany (Bertini *et alii,* 2000; Nirta *et alii,* 2005).

The youngest rocks (Late Cretaceous-Paleocene) of the Internal Ligurian Domain are trench deposits represented by thin-bedded turbidites interbedded with ophiolite-bearing slide and debris flows (IL_{bo}: Bocco Shale) interpreted as developed from reworking of oceanic lithosphere and its sedimentary cover already incorporated in a Cretaceous accretionary wedge (Marroni & Pandolfi, 2001; Marroni *et alii,* 2017).

External Ligurian Domain

The External Ligurian Domain represents the portion of the Piedmont-Ligurian Ocean close to the Adria continental margin (Fig. 4b). Successions of the External Ligurian Domain are characterized by the absence of the pre-Cretaceous succession (no ophiolite suite at the base) and by thick Upper Cretaceous carbonate flysch deposits (Helminthoid Flysch), with underlying associated sedimentary mélanges ("*Complessi di base*"). In the Inner Succession (Fig. 3) the sedimentary mélanges often contain blocks of rocks of oceanic crust origin (lherzolites, gabbros, basalts, etc.) indicating a position closer to the Internal Ligurian Domain, whereas in the Outer Succession blocks are represented almost exclusively by rocks of continental origin (sandstones, conglomerates, platform carbonate deposits, etc.; Salti del Diavolo Conglomerates), ophiolite rocks are scarce and an origin next to the Adria continental margin can be proposed (Marroni *et alii,* 2001).

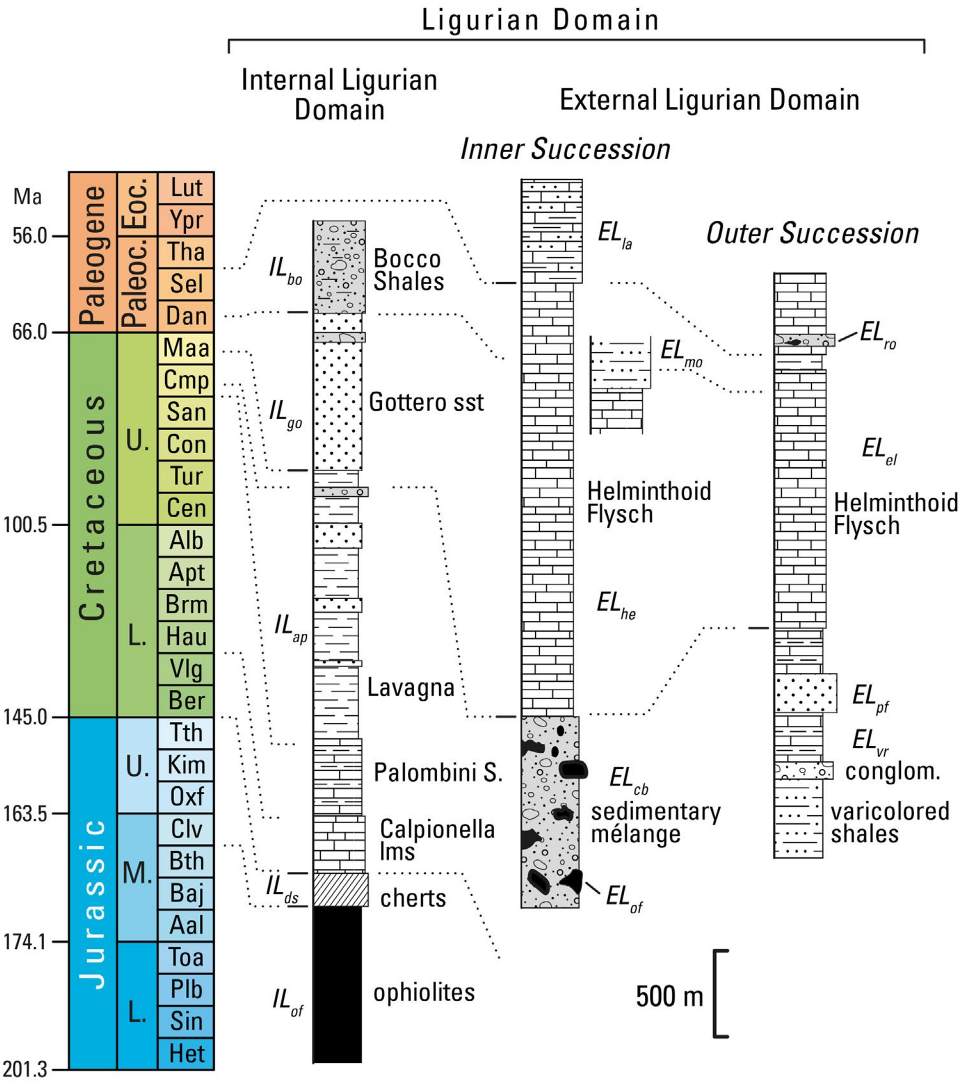

Fig. 3 - Stratigraphy of the Ligurian Domain, after Marroni *et alii* (2001, 2017), modified. Occurrence of ophiolite-bearing clastic debris is shown in grey. In italics are labels of the geological map.

Inner Succession

This succession (Fig. 3, "Western succession" of Marroni *et alii,* 2001) occurring now in tectonic units as in the Ottone Unit, Caio Unit, Bettola Unit, Monghidoro Unit, Val Baganza Unit, Groppallo Unit, etc., is characterized by Upper Cretaceous sedimentary mélanges consisting of basal breccias, conglomerates and sandstones (EL_{cb}) derived from slides, debris flows and high density turbidite currents. Common are pebbly sandstones, coarse grained sandstones and rudites. The larger, km-sized, slide blocks are mapped (EL_{of}) and consists of mantle ultramafic rocks (lherzolites, piroxenites), gabbros and blocks of basalts, locally with their preserved stratigraphic cover (cherts, etc.). The blocks represent portions of the ophiolite suite and its sedimentary cover. Continental-derived rocks are also present, as granitoids, schists, orthogneisses, paragneisses, arkoses and arenites.

Upward follows a thick succession of alternating thick calcareous turbidites with calcarenitic base, marly limestones, thin siliciclastic turbidites and hemipelagic limestones (EL_{he}, Helminthoid Flysch: Caio Fm., Ottone Fm.). Locally polygenic conglomerates and breccias (sometimes with ophiolitic clasts) with shaly matrix are present (Parea, 1961; Abbate & Sagri, 1967; Sagri & Marri, 1980; Mutti *et alii,* 1984; Fontana *et alii,* 1994). In the Emilia Apennines, the Helminthoid flysch successions pass locally to siliciclastic turbidites, with alternating arenites, sandstones and shales (EL_{mo}: Monghidoro Fm., Daniele *et alii,* 1995; Fioroni *et alii,* 1996). The succession is here more arenitic-rich at the base and more pelitic in the upper part. Intercalated are marly-calcareous turbidite beds, similar to the Helminthoid flysch succession.

In central Tuscany the calcareous Helminthoid flysch and the ophiolitic complex are locally overlain stratigraphically by a very heterogeneous succession (EL_{la}: Lanciaia Fm.) consisting of alternating marls, marly limestones, conglomerates and breccias with ophiolite clasts and blocks, calcarenites, siltstones, ophiolitic sandstones, varicolored shales, of early-middle Eocene age (Signorini *et alii,* 1963; Cerrina Feroni *et alii,* 1973; Lazzarotto & Mazzanti, 1976; Lazzarotto *et alii,* 1995, 2002). This succession is interpreted as a proximal turbidite-slope deposit, developed within thrust-top basin during the Ligurian tectonic phases.

Outer Succession

The Outer Succession is represented by different successions, now outcropping in the Antola Unit, Cassio Unit, Sporno Unit, Morello Unit, Solignano Unit, Media Val Taro Unit, Farini Unit, S. Fiora Unit, etc.. In general it is characterized by thick shaly "basal complex" with interbedded siliciclastic conglomerates and turbidite sequences, capped by a Cretaceous-Eocene Helminthoid flysch. Blocks of mafic and ultramafic rocks (ophiolites) are scarce or absent (Fig. 3).

The basal succession (EL_{vr}) is represented by thick varicolored shales alternating with siltstones, siliceous limestones, calcareous marls and carbonate sandstones (Fontana *et alii,* 1994; Vescovi *et alii,* 1999; Nirta *et alii,* 2005; Marroni *et alii,* 2015b). Shales are often affected by diffuse black manganese alterations. This succession is characterized by the occurrence of conglomerates ("Conglomerati di Salti del Diavolo", Sames, 1967; Rio & Villa, 1987) with well-rounded clasts of continental Adriatic origin (metamorphic rocks, granitoids, limestones, etc.). Based on the occurrence of these continental conglomerates early Authors postulated the presence of a continental area (ridge, "Ruga Insubrica", Baldacci *et alii,* 1972) between the Ligurian and the Tuscan Domain. Intercalated in this basal succession are siliciclastic turbidites (EL_{pf}: Arenarie di Ostia, Pietraforte) consisting of a regular alternation of medium to fine-grained quartz-feldspathic-calcareous sandstones and shales (Bortolotti, 1962a; Mezzadri, 1963; Bortolotti, 1967; Elter & Marroni, 1991; Vescovi *et alii,* 1999; Nirta *et alii,* 2005; Marroni *et alii,* 2015b). In the basal succession, clasts of ophiolite rocks are usually missing, but with some notable exceptions, as in central Tuscany and especially near Arezzo (Monti Rognosi), where ophiolite rocks outcrop (EL_{ro}) and their relationships with adjoining successions are still a matter of debate (Bortolotti, 1962b; Plesi *et alii,* 2002b).

The varicolored shales grade upward to Cretaceous-Paleocene Helminthoid flysch (EL_{el}: M. Cassio, Sporno, Solignano flysch, Papani & Zanzucchi, 1969; Daniele & Plesi, 2000), and consist of a thick succession of marly-calcareous turbidites (marly limestones, marls and limestones) with intercalated arenaceous-pelitic turbidites. Clasts within the sandstones are derived from low and medium grade metamorphic rocks, acid and basic volcanic rocks, extra basinal dolostones and limestones. We included in this succession also the Antola Fm. (Marroni *et alii,* 1992) and the younger Monte Morello Fm., an Eocene carbonate turbiditic succession consisting of alternating marly limestones, calcarenites and shales ("Alberese" *Auctt.*: Sestini, 1959; Bortolotti, 1964; Abbate & Sagri, 1970; Ponzana, 1993). Small and rare Cretaceous volcanic and subvolcanic bodies with alkaline composition (lamprophyre) occur within Cretaceous succession in southern Tuscany as intruded or interbedded bodies (Faraone & Stoppa, 1990; Brogi *et alii,* 2000).

In central-southern Tuscany the partition of the External Ligurian Domain in an Inner and an Outer succession is difficult and often problematic, due to the intense compressional and, especially, later extensional tectonics (Bettelli *et alii,* 1980; Costantini *et alii,* 1995; Bertini *et alii,* 2000; Lazzarotto *et alii,* 2002; Nirta *et alii,* 2005; Pandeli *et alii,* 2005a; Marroni *et alii,* 2015b).

Epiligurian Succession (pre-evaporitic)

The Epiligurian Succession (Fig. 5) consists of formations outcropping along the Northern Apennines, from its northwestern part in the Emilia region to the Romagna, San Marino area and the northernmost Marche. The Epiligurian Succession was sedimented within minor basins placed onto the Ligurian thrust sheets (top of the orogenic wedge) so to be configured as satellite basins (Ricci Lucchi, 1986, 1987; Argnani & Ricci Lucchi, 2001) or thrust-top, wedge-top or piggy-back basins (*sensu* Ori & Friend, 1984). This succession is not significantly deformed by the Ligurian tectonic phases.

The Epiligurian Succession spans in age from the middle Eocene to the late Miocene or the earliest Pliocene, recording the foreland allochthonous transport of the orogenic prism (Ricci Lucchi & Ori, 1985; Argnani & Ricci Lucchi, 2001). Deposits lie on top of the Ligurian units through a regional angular unconformity, middle-late Eocene in age (Bettelli *et alii,* 1987b; Remitti *et alii,*

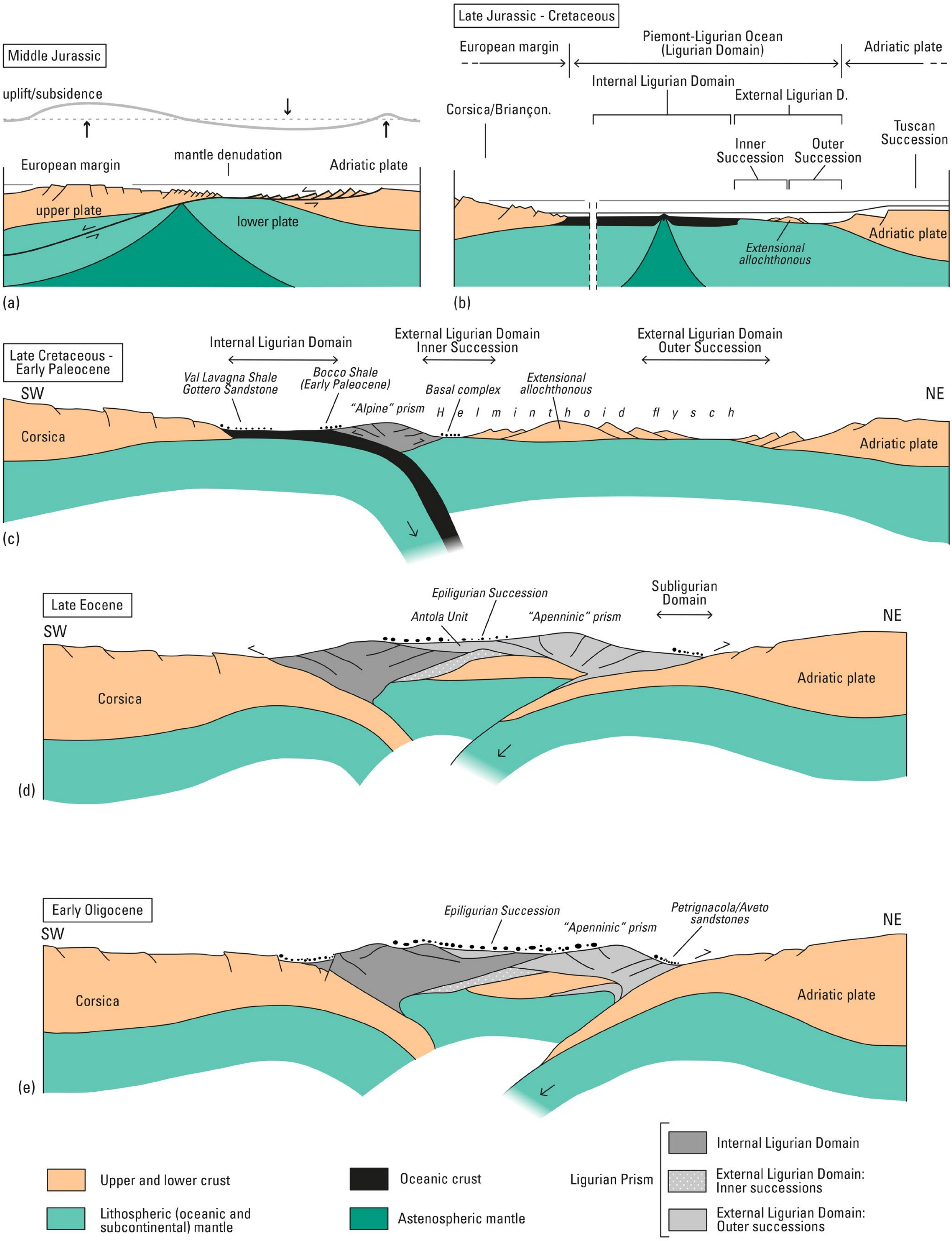

Fig. 4 - (a) Mode of asymmetrical extension of continental crust; based on Wernicke (1985) and Lemoine *et alii* (1987) models. (b) Paleogeography of the Piedmont-Ligurian ocean and adjoining areas at the Jurassic-Lower Cretaceous. (c), (d), (e) Reconstruction of the geodynamic setting and evolution for Late Cretaceous (Campanian-Maastrichtian), late Eocene and early Oligocene of the Ligurian Units of the Northern Apennines, after Marroni *et alii* (2010), modified.

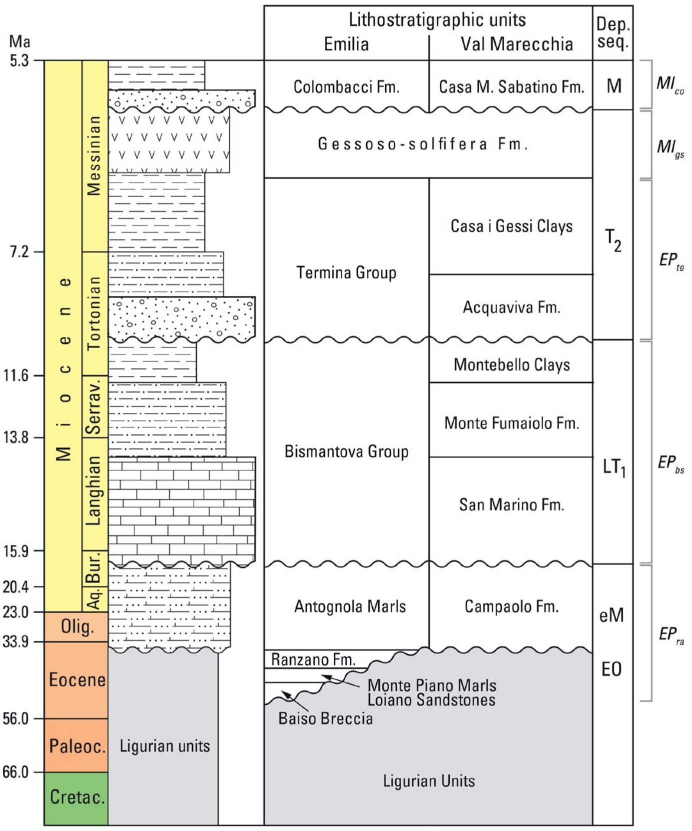

Fig. 5 - Stratigraphy of the Epiligurian Succession, after Roveri *et alii* (1999), depositional sequences from Ricci Lucchi (1986). New data and an updated overview of the Epiligurian Succession are reported in Conti *et alii* (2016) and Argentino *et alii* (2017). In italics are labels of the geological map.

2012; Piazza *et alii,* 2016). Moreover, the deposits of the Epiligurian basins are laterally connected with the deposits of the episutural Piedmont Tertiary Basin (Di Giulio, 1991; Mutti *et alii,* 1995).

The Epiligurian Succession has been here divided into three sequences delimited by stratigraphic unconformities (Ricci Lucchi, 1986).

A lower sequence (EP_{ra}), Lutetian to early Burdigalian in age (Cerrina Feroni *et alii,* 2002a; Catanzariti *et alii,* 2002; Piazza *et alii,* 2016), is formed by a great variety of lithological terms, deposited in deep marine to upper bathyal environments (Bettelli *et alii,* 1987b; Di Giulio *et alii,* 2002; Mancin *et alii,* 2006), in response to the tectono-sedimentary variability within the satellite basins. This is testified by marls and clays occurring in different stratigraphic positions (Monte Piano Marls, Antognola Marls; Contignaco Fm.), turbidite sandstones with great variability in composition and provenance (Ranzano Fm., Loiano Sandstones; Poggio Carnaio Sandstones, Lagrimone Sandstones), breccias and sedimentary melanges (Baiso Breccias, Valle del Savio Complex) (Cibin, 1993; Bettelli *et alii,* 1994; Martelli *et alii,* 1998; Cibin *et alii,* 2001, 2003). The complete stratigraphic record shows from bottom to top: Baiso Breccias and Loiano Sandstones, Monte Piano Marls, Ranzano Sandstones, Campaolo Fm., Antognola Marls, Contignaco Fm. (Catanzariti *et alii,* 2002).

An intermediate sequence (EP_{bs}) follows an important regional-scale unconformity, Burdigalian in age (Fregni & Panini, 1988; Bettelli *et alii,* 1987b; Amorosi *et alii,* 1995; Mutti *et alii,* 1995; Remitti *et alii,* 2012), and is represented by the Bismantova Group (Amorosi *et alii,* 1996a; Roveri *et alii,* 1999; Papani *et alii,* 2002). It corresponds to the LT1 sequence of Ricci Lucchi (1986), ranging in age from the Burdigalian to the early Tortonian (Catanzariti *et alii,* 2002) It is characterized by conglomerates, bioclastic calcarenites (San Marino Fm., La Verna Calcarenites, Pantano Fm. *p.p.*), marls, siliciclastic and hybrid sandstones (Bismantova Sandstones, Monte Fumaiolo Fm., Pantano Fm. *p.p.*), clays and silts (Montebello Clays; Cigarello Fm.), marls and sandstones, breccias and olistostromes, referred to shallow marine to basin slope environment (Amorosi, 1992; Amorosi *et alii,* 1996b; Roveri *et alii,* 1999; Catanzariti *et alii,* 2002; Argentino *et alii,* 2017; Conti *et alii,* 2017). The stratigraphic record of the Bismantova Group is represented, from bottom to top, by the Pantano Fm. and San Marino Fm., Monte Fumaiolo Fm., Bismantova Sandstones and Montebello Clays (Catanzariti *et alii,* 2002; Conti *et alii,* 2016). This sequence occurs widely also in the Marecchia Valley and in the easternmost Tuscany, where it occurs in large slabs lying unconformably directly on to the Ligurian Units (Conti, 2002; Conti *et alii,* 2016; Cornamusini *et alii,* 2017) as at La Verna, Mt. Fumaiolo, Sasso Simone-Simoncello, San Leo, Mt. Fotogno, Pietracuta, San Marino, Torriana (Cornamusini *et alii,* 2009a; Conti *et alii,* 2016).

The upper Epiligurian sequence (EP_{te}) is represented by the Termina Group or T2 sequence of Ricci Lucchi (1986). It lies unconformably on the Bismantova Group (Roveri *et alii,* 1999), characterizing the upper part of the Epiligurian Succession, below the upper Messinian and Pliocene deposits. This sequence consists of sediments ranging from fluvio-deltaic conglomerates and sandstones (Acquaviva Fm.), shallow marine marls and clayey marls with sandstone interbeds (Termina Fm., Sant'Agata Fossili Marls), shallow marine clays (Casa i Gessi Clays), to evaporite gypsum and bituminous muds (Gessoso-solfifera Fm., mapped as MI_{gs}).

The complete stratigraphic record of the T2 sequence is formed, from bottom to top: Acquaviva Fm. and Termina Fm., Casa i Gessi Clays, Gessoso-solfifera Fm. (Ricci Lucchi, 1986; Catanzariti *et alii,* 2002; Cornamusini *et alii,* 2009a, 2017; Conti *et alii,* 2016). The age of this sequence ranges from Tortonian to Messinian.

In the Val Marecchia area the Epiligurian Succession, part of the "Coltre della Val Marecchia", typically includes also Messinian and earliest Pliocene age deposits, as evaporites of the Gessososolfifera Fm., deltaic conglomerates and sandstones of the Casa Monte Sabatino Fm., foreshore clays and sandstones of the Monte Perticara Fm., and some basal beds of the "Argille Azzurre" Fm., that in turn are sealed by the autochthonous Pliocene deposits (De Feyter, 1991; Conti, 1994; Roveri *et alii,* 1999; Conti *et alii,* 2016; Cornamusini *et alii,* 2017). In the geological map these deposits are included in the "Messinian evaporite succession" and in the "Messinian post-evaporite succession", respectively.

Subligurian Domain

The Subligurian Domain is classically regarded as a domain with a paleogeographic position intermediate between the Ligurian Domain and the Tuscan Domain (Fig. 6). The stratigraphic succession of the Subligurian

Domain is characterized by the presence of a main regional unconformity, middle-late Eocene in age, separating two portions: a) a pre-middle-late Eocene succession, that ranges from early Paleocene to the lower part of the middle Eocene), and b) a post-Eocene succession (early Oligocene earliest Miocene in age) (ZANZUCCHI, 1963; ELTER *et alii*, 1964; PLESI, 1974, 1975b; MONTANARI & ROSSI, 1982; CERRINA FERONI *et alii*, 1991; CATANZARITI *et alii*, 1996; VESCOVI, 1998; BRUNI *et alii*, 2007; PERILLI *et alii*, 2009; REMITTI *et alii*, 2011; VANNUCCHI *et alii*, 2012). From this domain originated, during the Miocene tectonic phases of nappe emplacement, a series of tectonic units now outcropping in the Ligurian and in the Emilia-Tuscany Apennines, interposed between the Ligurian Units (above) and the Tuscan Units (below).

The (?upper Cretaceous) lower Paleocene-middle Eocene succession (SL_{ac}: Canetolo Shales and Limestones Fm., Groppo del Vescovo Limestones Fm.) is represented by shales, siltstones and limestones with affinity with successions of the External Ligurian units of Late Cretaceous to early Eocene in age and also, for what concerns the Groppo del Vescovo, with the limestone serie of the Scaglia Toscana of the Tuscan Domain. This succession is strongly deformed in low-temperature conditions and isoclinal folds are common in the more shaly layers; REMITTI *et alii* (2011) showed that deformation is similar to what has been described for the External Ligurian Units. Definitively, this lower portion of the Subligurian Domain Succession is therefore similar in stratigraphy to the External Ligurian Domain.

The uppermost lower Oligocene-lowermost Miocene succession is characterized by siliciclastic turbidite sandstones, with close affinities with turbidites of the Tuscan Domain, volcanic-rich sandstones and conglomerates (SL_{ar}: Petrignacola Sandstones, Aveto Sandstones, Ponte Bratica Sandstones, etc.). This succession is only slightly folded and internal thrusting shows a top-NE transport direction. All these features allow to infer for this upper succession a paleogeographic origin close to the Tuscan Domain.

Based on all the above considerations and in agreement with earlier Authors, we consider the lower Oligocene-lowermost Miocene succession of the Subligurian Domain to be deposited above the already deformed lower Paleocene-middle Eocene succession, i.e. onto the previously deformed Ligurian prism (Fig. 6). The sandstone-rich lower Oligocene-lowermost Miocene succession deposited therefore as the infill of a thrust-top type basin developed on the accretionary wedge, with close lithological affinity with the more external sandstone successions (Modino Fm., Macigno, etc.), with the main difference consisting in the great amount of volcanic clasts, probably due to a closer location to the volcanic source.

TUSCAN DOMAIN

In the Tuscan Domain we separate the Pseudoverrucano Succession, the Modino Succession, the Tuscan Succession, the Tuscan Metamorphic Succession, the more external Cervarola-Falterona Succession and the Rentella Succession (with a close affinity with the Umbria Domain).

Pseudoverrucano Succession

The Pseudoverrucano Succession is represented by small and scattered outcrops in southern Tuscany near Grosseto, with a peculiar stratigraphic succession unlike any other successions of the Tuscan Domain, so to be considered as a sort of "*incertae sedis*" in the old geological literature of the area. "Pseudoverrucano" is an informal term to indicate coarse quartz-conglomerates with a diffuse dark red color, very similar to the Lower Triassic Verrucano lithofacies of Tuscany, but that pass upsection to Liassic-Eocene successions. This succession outcrops in complex tectonic settings, in thrust sheets below the Tuscan Nappe.

The Pseudoverrucano-bearing succession of southern Tuscany represents a still uncertain, controversial and debated subject, as to its significance, stratigraphic-paleogeographic and structural position and in the past, despite the limited outcrops, has gained attention by many Authors (FAZZINI & PAREA, 1966; SIGNORINI, 1967; COSTANTINI *et alii*, 1980; DECANDIA & LAZZAROTTO, 1980b; MORETTI, 1991; CAMPETTI *et alii*, 1999; ALDINUCCI *et alii*, 2008a; MONTOMOLI *et alii*, 2009; CONTI *et alii*, 2010;

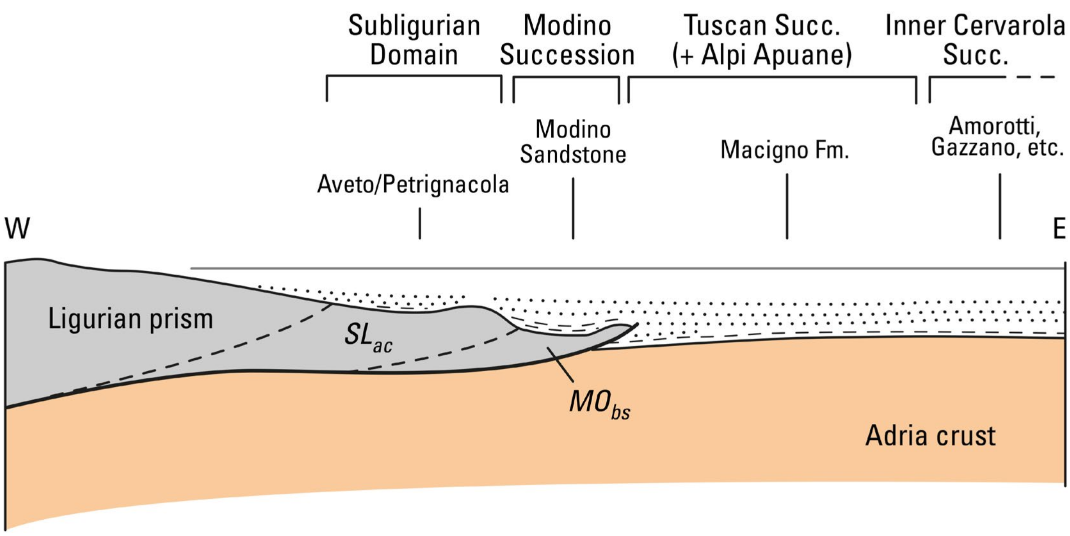

Fig. 6 - Paleogeographic reconstruction for the Subligurian-Tuscan domains at Early Oligocene-Miocene transition, before early-middle Miocene underthrusting and subduction. Grayed is the Ligurian prism/accretionary wedge, in italics are labels of the geological map.

Baldetti *et alii,* 2011; Gandin, 2012; Perrone *et alii,* 2006). We consider this succession as belonging to the westernmost part of the Adria continental paleomargin, i.e. the most internal portion of the Tuscan Domain (Conti *et alii,* 2010). In the geological map we separated the lower conglomeratic, coarse quartz-rich terrigenous and shallow-marine carbonate succession (PS_{vr}) from the uppermost limestone-rich deposits (PS_{nu}) similar to the Cretaceous-Eocene formations of the Tuscan Succession and particularly with the "nummulitic" lithofacies. The lower portion of the succession (PS_{vr}) is diachronous, but with a general age ranging from the late Triassic to the early Jurassic, whereas the upper carbonate portion (PS_{nu}) has a ?Cretaceous-Eocene age.

Modino Succession

This succession now occurs in the Modino tectonic Unit. A long-lasting debate concerned the stratigraphic and structural position of the Modino Unit, with two end-member interpretations that consider the Modino succession either (i) stratigraphically overlying the Macigno Fm. of the Tuscan Nappe (Abbate & Bortolotti, 1961; Nardi, 1965; Martini & Sagri, 1977; Abbate & Bruni, 1987; Lucente & Pini, 2008) or (ii) tectonically superposed on the Tuscan Nappe (Reutter, 1969; Plesi, 1975a; Bettelli *et alii,* 1987a; Chicchi & Plesi, 1991; Cerrina Feroni *et alii,* 2002a). In this overview we favour this second interpretation, also based on recent tectonic and biostratigraphic data (Marchi *et alii,* 2017; Cornamusini *et alii,* 2018). The Modino Unit, similar to the Subligurian Succession, can be divided into two parts: a strongly deformed Cretaceous basal complex, followed (through an unconformity, Mochi *et alii,* 1995) by a less deformed marly-shaly-sandstone succession of middle Eocene-early Miocene age.

The basal chaotic complex (MO_{bs}: Modino basal complex, Abetina Reale Fm.) consists of Cretaceous Ligurian-derived rocks as limestones, marly limestones (similar to the Helminthoid Flysch), siliceous limestones, varicolored shales and shaly-calcareous breccias with clasts of Ligurian limestones. This succession is strongly deformed and is considered a tectonic mélange belonging to the easternmost part of the Ligurian prism (Fig. 6), developed during the Paleocene-Eocene Ligurian phases (Marchi *et alii,* 2017).

Above this tectonic mélange unconformably lies a succession (MI_{fi}) of middle Eocene-late Oligocene (Bartonian-late Chattian) age made of green-reddish shales with intercalated calcarenites, marls, siltstones and sandstones (Fiumalbo Shales), passing upwards to massive marlstones (Marmoreto Marls), with subordinate siltstones, sandstones and local breccia bodies. The upper part of the unit (MO_{ar}) is represented by the Modino Sandstone Fm., some hundred meters thick, formed by siliciclastic turbidite sandstones, with thin to thick beds and a thickening- upwards trend, of late Oligocene-early Miocene age (Catanzariti & Perilli, 2009; Marchi *et alii,* 2017, with references therein).

Based on the above features we consider the Eocene-Oligocene Modino Succession deposited close to the Tuscan Succession, but in a more internal basin position located above the advancing Ligurian orogenic prism (Fig. 6).

Tuscan Succession

This succession, Triassic-early Miocene in age (Fig. 7), occurs in the Tuscan Nappe tectonic unit and outcrops extensively in Tuscany. The stratigraphy of the Tuscan Succession points to a marine shelf carbonate sedimentation starting in the Norian up to Early Jurassic (Hettangian). Since the Sinemurian extensional tectonics linked with the opening of the central Atlantic led to breakup and downthrowing of the carbonate shelf, with pelagic sedimentation below CCD which continues throughout the Jurassic. During Cretaceous and part of the Paleogene, pelagic conditions continue with ongoing lowering of the sea bottom. Starting late Oligocene the Tuscan Domain developed as a foreland basin with siliciclastic turbidite deposition. Sedimentation stops in the early Miocene (Aquitanian) because of the emplacement of the overlying Ligurian Units. The stratigraphy of this succession was investigated by many Authors; see reviews in Bortolotti *et alii* (1970), Dallan Nardi & Nardi (1972), Kälin *et alii* (1979), Fazzuoli *et alii* (1985), Ciarapica & Passeri (1994, 1998) and Cerrina Feroni *et alii* (2002a).

The bottom of this succession, Norian in age (TN_{cv}: Calcare Cavernoso Fm.), consists of alternating dolomites and anhydrites representing carbonate platform deposits with evaporites; these deposits are found in their primary position stratigraphically below the Rhaetian formations only in some scattered outcrops in southern Tuscany, but are well documented from wells (Burckhardt, 1946; Merla, 1951; Vighi, 1958; Trevisan, 1955). The presence of evaporites makes this stratigraphic level a preferential detachment level for the development of thrust and faults during underthrusting and exhumation of tectonic units, with widespread development of typical cataclasites, consisting of dolomite clasts and cavities due to hydration, de-dolomitization and subsequent dissolution of sulphates during cataclastic flow; this cataclasites now represent almost all of the outcrops for this formation (Calcare Cavernoso Fm.). The cataclasites mainly developed along thrusts during the early Miocene tectonic phase, but also along late Miocene and younger normal faults. Cataclasites along normal faults show, associated with the dolomite clasts, blocks and slivers derived from adjacent tectonic units, as slivers of metamorphic rocks occurring in the Alpi Apuane, Cerreto Pass and Soraggio area. Due to the high porosity, the cataclastic Calcare Cavernoso Fm. is frequently reworked and affected by karst phenomena in recent times (Holocene), with karst cave sedimentation.

Upsection Rhaetian deposits follow (TN_{ma}) and they sedimented in subtidal platform carbonate ramp, poorly oxygenated to anoxic, represented by well bedded limestones and marly limestones with typical dark gray color (Calcari a *Rhaetavicula contorta* Fm.). Then follows deposits of inter tidal carbonate platform as the Calcare Massiccio Fm. (Hettangian-early Sinemurian); this formation shows a lower portion with dolomitic limestones and a thicker upper part, with massive to well-bedded limestones. Heteropic with the Calcare Massiccio Fm. are the Dolomie di M. Castellana Fm. and the Calcari ad *Angulata* Fm.

The succession continues upsection (TN_{ca}) with hemipelagic and condensed deposits (Rosso Ammonitico Fm.), consisting of calcilutites and nodular marly limestones of red, pink and yellowish colors, with

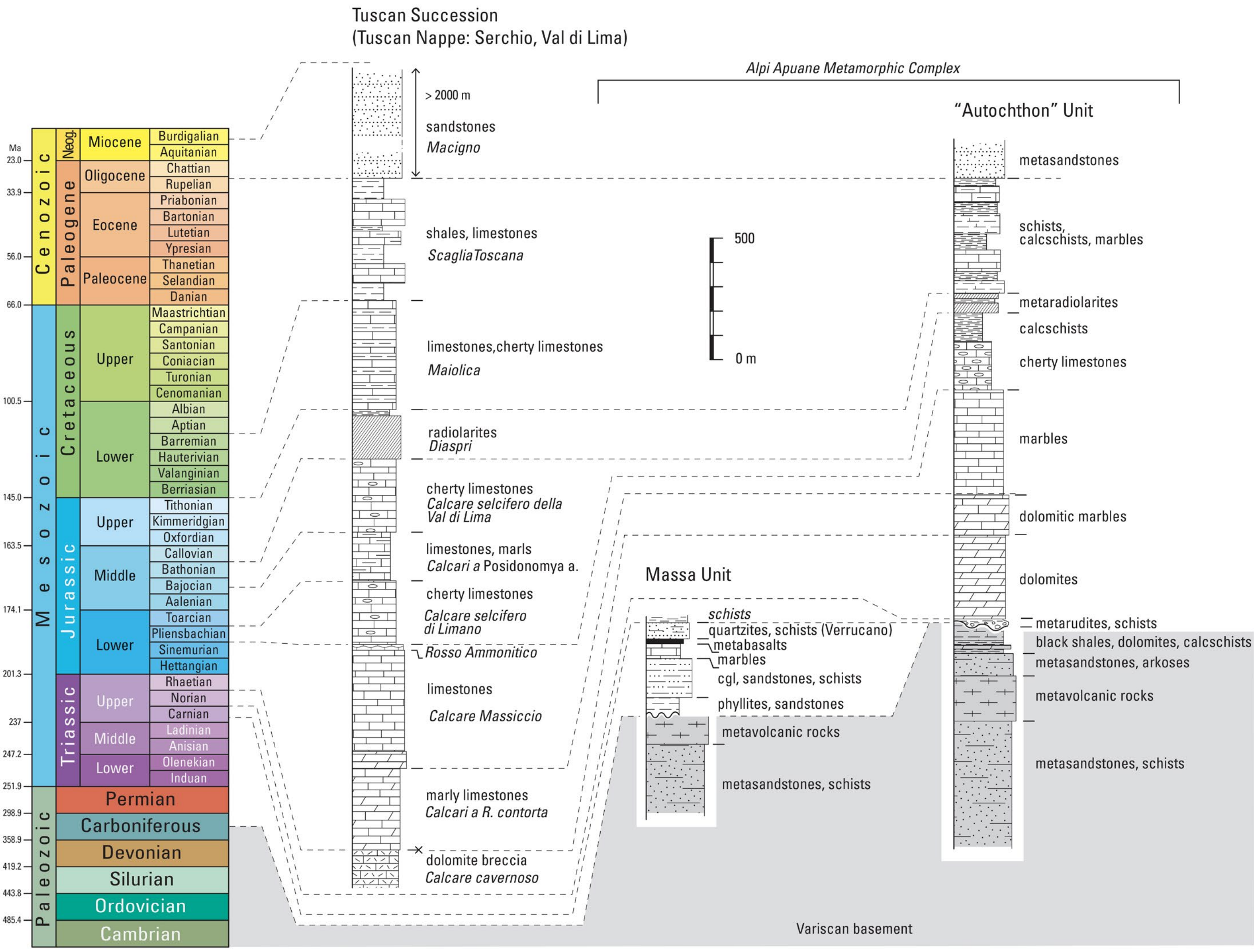

Fig. 7 - Stratigraphic logs of the Tuscan Succession (Tuscan Nappe) and Tuscan Metamorphic Successions in the Alpi Apuane area.

interbedded marls and shales; cherty nodules are present, and frequent are evidences of synsedimentary deformation (slump). Upsection follows a thick basinal succession with fine carbonate turbidites (Calcare selcifero di Limano Fm.), represented by well-bedded siliceous calcilutites with whitish chert nodules, with interbedded calcarenites, often with graded bedding, marls and shales (in some areas, i.e. near Carrara, a condensed succession of few meters of hemipelagic calcilutites outcrops). Upward again follows the pelagic sedimentation of the Calcari e marne a *Posidonomya alpina* Fm. with marls and marly limestones interbedded with calcilutites and calcarenites, locally with cherts nodules, siliceous marls and radiolarites. Pelagic turbiditic sedimentation is then testified by the Calcare selcifero della Val di Lima Fm. with graded calcarenites and silicic calcilutites with abundant black chert nodules and layers; coarse grained intraformational breccias are moreover present. Deep water deposits continues with sedimentation, below the Carbonate Compensation Depth (CCD), of well bedded siliceous radiolarites with interbedded shales (Diaspri Fm.), passing upsection to siliceous marls and limestones (Rosso ad Aptici Fm.). Later on pelagic sedimentation above the CCD is represented by the Maiolica Fm., consisting of calcilutites and intercalated calcarenites and calcirudites, with cherts layers and nodules. Calcarenites prevail in the upper part of the formation.

During the Early Cretaceous (Aptian) to the late Oligocene (Chattian) the Tuscan Domain was a wide marine basin with a thick succession of shales, siliceous shales and marlstones with reddish color, with intercalated calcilutites and turbiditic calcarenites (TN_{st}: Scaglia Toscana Fm.). The Scaglia Toscana Fm. is partitioned in several members and lithofacies; this reflects the difference of depth in different parts of the basin, the fluctuation of CCD controlled by global events, and volumes of carbonate materials resedimented by turbiditic flows. It is widely accepted that the high lithological variability of the Scaglia Toscana Fm. with its subdivision in members, reflects the complexity of the basin, in terms of structural/morphological highs and basinal lows (Fazzuoli *et alii*, 1985; Conti *et alii*, 2019), where the marlstone deposits sedimented on the highs or along deep ramps, whereas the shales and the turbidite limestones sedimented in the basin plain (Canuti *et alii*, 1965; Fazzuoli *et alii*, 1994; Ielpi & Cornamusini, 2013). Furthermore, significant stratigraphical differences have been recorded between the northern Tuscany (Fazzuoli *et alii,* 1985, 1998; Del Tredici & Perilli, 1998; Conti *et alii,* 2019) and the southern Tuscany successions (for a review see Canuti *et alii,* 1965; Fazzuoli *et alii,* 1996; Bambini *et alii,* 2009; Cornamusini *et alii,* 2012; Ielpi & Cornamusini, 2013; Pandeli *et alii,* 2018).

Starting from the late Oligocene, the Tuscan Domain represents the foredeep basin of the developing and migrating Apennine orogen (Ricci Lucchi, 1986; Argnani & Ricci Lucchi, 2001), with sedimentation of the Macigno Fm. (TN_{mg}), a thick and wide arenaceous turbidite system with significant internal bottom-to-top diachrony between northern and southern Tuscany, ranging in age overall from late Rupelian/early Chattian to Aquitanian. This formation consists of thick turbidite arenaceous sandstones and siltstones, arkose-lithic to arkose in composition, with rare thin carbonate beds and chaotic beds. In the upper part, olistostromes of Ligurian and Subligurian rocks and mudstones are present, indicating the closure of the basin due to the emplacement of the Ligurian thrust sheet (Castellucci & Cornaggia, 1980; Cornamusini, 2004a). The successions cropping out along the Tuscan coast have been indicated as "Macigno costiero" *Auctt*. and distinguished in literature by the Macigno *s.s.*, for facies, stratigraphic architecture, composition/provenance and age (Gandolfi & Paganelli, 1992; Costa *et alii,* 1997; Cornamusini, 2002, 2004b). Differently, the outcrops of Macigno along the La Spezia coast, are characterized by the dominance of the mudstone- fine arenaceous lithofacies, and named as "Arenarie zonate di Riomaggiore" (Abbate, 1969; Abbate *et alii*, 2005).

In this overview, we consider the Tuscan Succession with its classic succession, as well defined in northern Tuscany and starting with the Triassic evaporite of the Calcare Cavernoso Fm.. In southern Tuscany (Tafone Valley, Monte Bellino, etc.) the Calcare Cavernoso Fm. possibly is in stratigraphic contact with the underlying Triassic clastic formations (Tocchi Fm., "Verrucano" Group); if this is the case, the start of sedimentation in the Tuscan Succession should be brought back at least to the Carnian. As these relationships are still a matter of debate and since Triassic clastic deposits in Tuscany are usually deformed and metamorphic, we described the Tocchi Fm. and the "Verrucano" Group in the "Tuscan Metamorphic Succession" section.

Tuscan Metamorphic Succession

Metamorphic rocks outcrop only in Tuscany (Alpi Apuane, Mt. Pisano, Iano, Monticiano- Roccastrada ridge, Elba Island, Gorgona Island, Uccellina Mts., Mt. Argentario and Mt. Bellino) and represent the effects of metamorphism on successions deposited on the Tuscan margin of the Adria Plate, with a Mesozoic-Cenozoic succession similar to the Tuscan Nappe, and its underlying Paleozoic basement. The metamorphic conditions are in the greenschist facies, and high-pressure metamorphic rocks are only reported from scattered outcrops in central-southern Tuscany (see section "Units affected by HP metamorphism"). Metamorphism is related to underthrusting and deformation of the Adria- derived units during early Miocene time and is accompanied by severe internal deformation of rocks, isoclinal folding (often strongly non-cylindrical), development of widespread axial plane foliation and NE-SW directed stretching lineations, associated with top-NE tectonic transport direction. Retrograde metamorphism and low-temperature deformation occurred during late Miocene phases of exhumation and core complex formation. For more informations about metamorphism refer to the works of Franceschelli *et alii* (1986, 1997); Kligfield *et alii* (1986); Jolivet *et alii* (1998); Giorgetti *et alii* (1998); Brunet *et alii* (2000); Molli *et alii* (2000); Franceschelli *et alii* (2004); Leoni *et alii* (2009); Conti *et alii* (2019); Molli *et alii* (2018).

In the metamorphic units we distinguish (Fig. 7, Fig. 8): a) a Paleozoic basement affected by Variscan deformation (possibly the basement of the entire Tuscan Domain); b) a younger Paleozoic succession not affected by Variscan deformation; c) Triassic continental deposits transgressive on the Paleozoic successions, d) a Triassic-Jurassic carbonate marine platform succession, e) a Jurassic-Cretaceous basinal succession and f) Oligocene-lower Miocene flysch deposits.

The Variscan basement (TM_{bs}) outcrops extensively in the Alpi Apuane area, to a lesser extent in central and southern Tuscany, and is reached in some deep wells in northern Tuscany (Pontremoli) and in the geothermal area of southern Tuscany (Vai, 1978; Bagnoli *et alii,* 1979; Elter & Pandeli, 1990; Conti *et alii,* 1991a, 1993; Rau, 1993; Pandeli *et alii,* 1994; Franceschelli *et alii,* 2004). The Variscan basement includes rocks of Cambrian-Devonian age with strong similarities with successions outcropping in central-southern Sardinia. In southern Sardinia the Variscan orogeny (nappe emplacement, deformation and metamorphism) is considered to be of early Carboniferous (Visean) age, and the same is assumed for Tuscany (Conti *et alii,* 1991a). It is important to note that the outcropping Variscan basement in Tuscany shows greenschist facies metamorphism paragenesis, i.e. Variscan orogeny developed regional metamorphism not higher than Alpine/Apenninic deformation. Higher metamorphic conditions for the Variscan basement are only reported from deep wells (Pandeli *et alii,* 2005b). The stratigraphic succession starts with alternating quartzites and phyllites of early Cambrian age with relics of sedimentary structures (graded and cross-bedding) followed by acidic to intermediate metavolcanic rocks that are correlated with the middle Ordovician calc-alkaline continental volcanism of Sardinia. Upsection follow quartzites and phyllites regarded as continental deposits unconformably transgressive above volcanic rocks, passing to basinal deposits. Silurian black shales and radiolarites (lydian stones) are reported and the succession closes with carbonate deposits as Orthoceras-bearing dolostones, metalimestones and calcschists of Devonian age. These rocks are involved in the Variscan orogeny during early Carboniferous (Visean).

Unconformably above the deformed Variscan basement, an upper Carboniferous-Permian succession developed, outcropping mainly in central and southern Tuscany (Lazzarotto *et alii,* 2003; Aldinucci *et alii,* 2008b), with metaconglomerates, metalimestones, metasandstones metavolcanic rocks and phyllites (TM_{cp}, Fig. 8). This succession was deposited in very different environments and basins, as strike-slip basins and uplifted areas, resulting from post-collisional deformation of the Variscan orogen.

Mesozoic sedimentation started in the Tuscan Domain with a Middle Triassic (Anisian-Ladinian) succession deposited in narrow continental rift basins, as testified

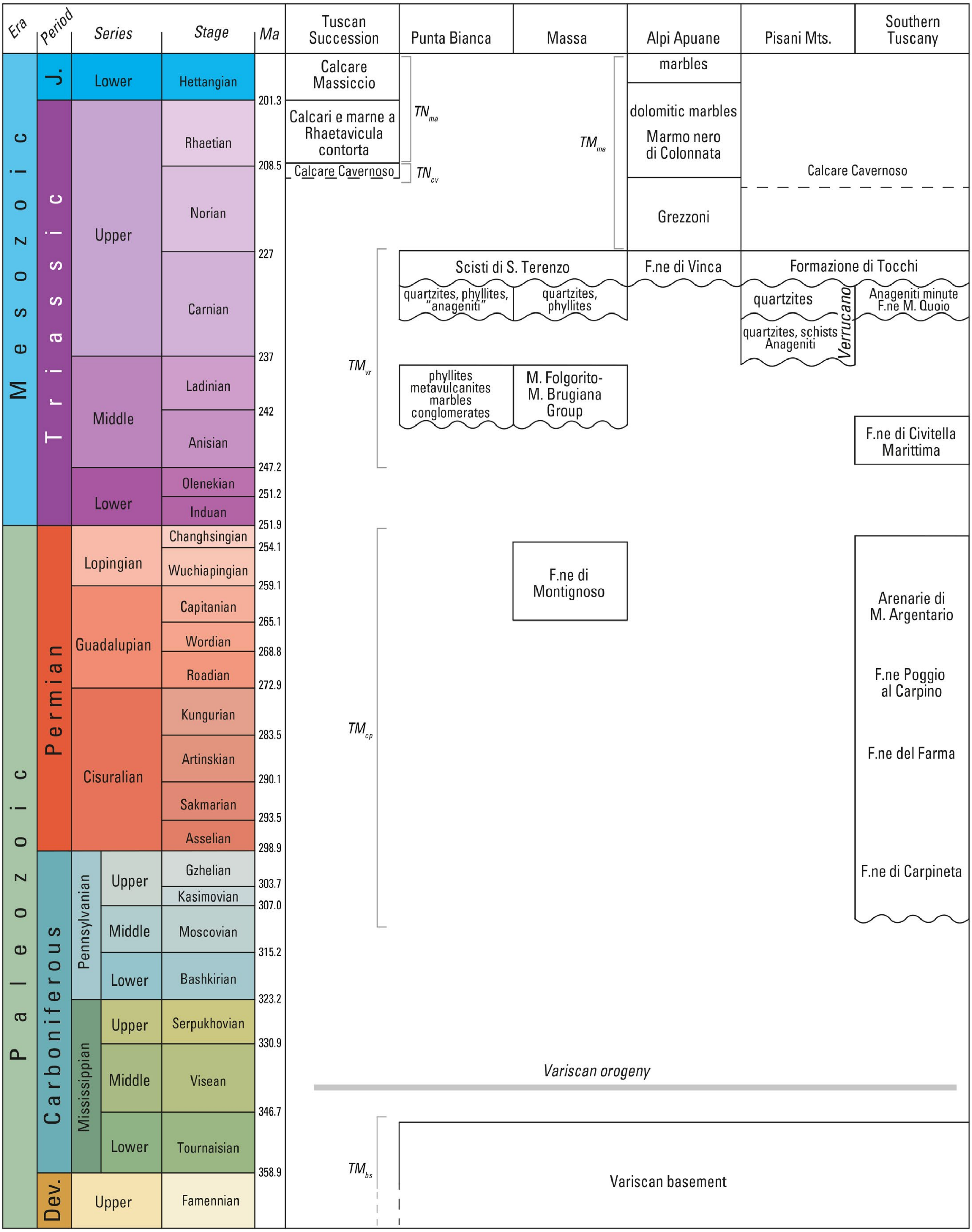

Fig. 8 - Stratigraphic relationships for the Permian-Triassic successions of the Tuscan Domain (after LAZZAROTTO *et alii*, 2003 and E. Patacca in CONTI *et alii*, 2019, modified). In italics are labels of the geological map.

by clastics, phyllites and carbonate deposits interbedded with alkaline basalts (pillow lavas) in the Massa Unit (Punta Bianca: Passeri, 1985; Rau *et alii,* 1985) and coeval deposits in southern Tuscany; elsewhere non depositional conditions continues, with subaerial exposure of the Variscan basement. During Late Triassic (Carnian) time widespread fluvial and littoral deposits unconformably covered the Variscan basement throughout the Tuscan Domain (Verrucano *Auctt.*, see Rau & Tongiorgi, 1974; Cassinis *et alii,* 1979; Perrone *et alii,* 2006 and references therein), with deposition of conglomerates, sandstones and phyllites, with very variable thickness in the area. In the map the Middle and Upper Triassic successions are mapped together (TM_{vr}).

Starting in the Norian, carbonate platform deposition occurs, now resulting in the thick dolomites, dolomitic marbles and marble successions (TM_{ma}). Local episodes of subaerial conditions of the carbonate platform are documented. These conditions persisted up to the Early Jurassic (Sinemurian).

Fragmentation of the carbonate platform since the Pliensbachian (Early Jurassic) led to the deposition of progressively deeper marine deposits (cherty limestones, calcschists) up to meta-radiolarites of Late Jurassic (Callovian-Tithonian) age. Upsection carbonate sedimentation resumed, with pelagic limestones, reworked carbonates and local neritic limestones (TM_{sc}: Scisti sericitici Fm. and Cipollino marble Fm.).

The Metamorphic Succession, similar to the Tuscan Nappe, closed with deposition of terrigenous flysch deposits, with typical alternating metasandstones and phyllites (TM_{pm}: Pseudomacigno Fm.).

Cervarola-Falterona Succession

The Cervarola-Falterona Succession was deposited in the outermost portion of the Tuscan Domain. It is composed of lower marlstones, shales and limestones referred to the pre-foredeep phase, a thick sandstone turbidite complex referred to the foredeep sedimentation, and the upper marlstones and shales referred to the basin closure phase (Ricci Lucchi, 1986; Argnani & Ricci Lucchi, 2001). This succession occurs in the Cervarola-Falterona tectonic Unit.

The paleogeographic and structural position of the Cervarola-Falterona Unit has been the object of a long scientific debate which has not yet generated a unique accepted view (see the several hypotheses in Chicchi & Plesi, 1991 and in Bettelli *et alii,* 2002a). Some authors infer that the Monte Cervarola Sandstones and the Monte Falterona Sandstones are in stratigraphic lateral-vertical relationships (Bruni & Pandeli, 1980; Günther & Reutter, 1985; Abbate & Bruni, 1987; Bettelli *et alii,* 2002b), whilst other authors suggest a tectonic independence between the Falterona Unit and the Cervarola Unit, derived from different stratigraphic and paleogeographic settings (Cerrina Feroni *et alii,* 2001, 2002b; Plesi *et alii,* 2002a; Benini *et alii,* 2014).

We adopt here the comprehensive term "Cervarola-Falterona Succession" and we group together two similar stratigraphic successions now outcropping in two distinct tectonic units: the Cervarola Unit *s.s.* outcropping west of the Futa Pass - Collina Pass (Pistoia area) and the Falterona Unit *s.s.* outcropping east of the Futa Pass - Collina Pass, both with a tectonic position between the Tuscan Nappe (above), and the Marnoso-arenacea Fm. of the Umbria-Marche Domain (below) (Cornamusini *et alii,* 2018; Conti *et alii,* 2019). Paleogeographically the Falterona Unit seems to have a more internal origin with respect to the Cervarola Unit.

In the Falterona Succession the base is represented by the Villore Fm. (CF_{vl}), passing upwards to the Monte Falterona Sandstones (CF_{fa}), up to the Vicchio Marls (CF_{vc}). In the Cervarola Succession the bottom is represented by the Villore Fm. or Civago Marls (CF_{vl}), passing upwards to the Monte Cervarola Sandstones (CF_{ce}).

The Monte Falterona Sandstones, ranging in age from the Chattian to the early-middle Burdigalian, include the Acquerino Fm., the Pratomagno Sandstones (Abbate & Bruni, 1987; Bruni & Pandeli, 1980), the Trasimeno Sandstones (Bigi *et alii,* 1990) and extend for a wide and long belt, from the Pistoia Apennines to south of the Trasimeno Lake (Aruta & Pandeli, 1995; Aruta *et alii,* 1998; Bortolotti *et alii,* 2008). They are turbidite sandstones, siliciclastic in composition, subdivided in some members on the base of the sand/mud ratio. The Monte Falterona Sandstones lie above the marls and shaly marls of the Villore Fm. for the northern area, while in the southernmost Umbria area, the Monte Falterona Sandstones lie conformably above marlstones, shales and limestones that we correlate with the Villore Fm. Such differences, as well as other features involving the sandstone succession, allowed some Authors (Martelli, 2002; Brozzetti, 2007; Pialli *et alii,* 2009; Plesi, 2010; Barchi & Marroni, 2014) to correlate the Monte Falterona Sandstones of the Umbria area with the Macigno Fm. and the underlying Villore Fm. with the Scaglia Toscana Fm. of the Tuscan Nappe.

The Monte Cervarola Sandstones, outcropping extensively in the Emilia Apennines, are referred to a complex and confined foredeep basin (Tinterri & Piazza, 2019), subdivided in an inner and in an outer part (Andreozzi, 1991). The inner part includes the Torre degli Amorotti, Gazzano, Gova, Ozola, Cerreto systems, the outer part includes the Fellicarolo-Dardagna, Stagno, Torrente Carigiola, Castiglion dei Pepoli systems, which are respectively late Chattian-Aquitanian (Cornamusini *et alii,* 2018), or Aquitanian-Burdigalian (Andreozzi *et alii,* 1991; Plesi, 2002b) the former, Burdigalian-Langhian in age (Botti *et alii,* 2002, 2017; Bettelli *et alii,* 2002b) the latter.

The whole Monte Cervarola Sandstones are turbidite sandstones and siltstones forming a thick succession, siliciclastic in composition, with different sand/mud ratio, so to identify different lithostratigraphic members (Botti *et alii,* 2002; Bettelli *et alii,* 2002a; Cornamusini *et alii,* 2018; Tinterri & Piazza, 2019). The upper and younger parts of this unit show an increase in carbonate sandstone composition.

In the more external areas (i.e. Scoltenna and Fellicarolo systems of Andreozzi, 1991) stratigraphic above and locally lateral of the sandstones, a thick marlstone succession is preserved (CF_{vc}). This marlstone succession is related to the closure of the turbidite basin (Ricci Lucchi, 1986), as the San Michele Marls for the Monte Cervarola Sandstones of the Emilia Apennines and the Vicchio Marls for the Monte Falterona Sandstones. These are marlstones and silty/shaly marlstones with minor thin-bedded-turbidites, Aquitanian to Langhian in age (Catanzariti *et alii,* 2002). Differently, for the internal areas (i.e. Torre Amorotti system) these sandstones are for some authors (Andreozzi, 1991; Tinterri & Piazza, 2019) stratigraphically overlain by chaotic deposits with Ligurian affinity, the Sestola-Vidiciatico Fm., and lie stratigraphically onto the Civago Marls, a chaotic formation with Ligurian affinity, and a marly complex with high grade of internal deformation (Pievepelago Fm.), which in turn lies stratigraphically on to the Mt. Modino Succession (see also in Gunther & Reutter, 1985, Plesi, 2002b and Tinterri & Piazza, 2019).

Rentella Succession

South of the Trasimeno Lake a stratigraphic succession is recognized, now occurring in the Rentella Unit (Fig. 1). Its stratigraphic features are intermediate between the Tuscan and the Umbria-Marche successions (Signorini & Alimenti, 1968; Brozzetti *et alii,* 2000). Tectonically the Rentella Unit is interposed between the Tuscan units and the Umbria-Marche-Romagna Unit.

The basal succession (RE_{st}) consists of varicolored marlstones, marly limestones and siltstones with a thickness of about 250 m Rupelian-Aquitanian in age (M. Rentella Fm. of Barchi & Marroni, 2014). These rocks represent pelagic to hemipelagic sedimentation, with thin turbiditic carbonate levels to testify a progressive change of the sea level. Upsection follow turbiditic marls and silty-marls with silica-rich levels Aquitanian to Burdigalian in age (RE_{ar}, Montagnaccia Fm. of Barchi & Marroni, 2014), with typical graded bedding and $T_{c\text{-}d}$ interval of the Bouma sequence, that testify turbiditic foredeep deposition in this area. Thickness is about 700 m. Based on composition of lithic fragments (richer in clasts of sedimentary origin) is possible to differentiate this succession respect to the siliciclastic turbidites of the Tuscan Domain (Barchi & Marroni, 2014).

Umbria-Marche-Romagna Domain

In the Umbria-Marche-Romagna Apennines crops out extensively a thick and articulated sedimentary main succession deposited onto the more external sector of the Adria plate, subdivided in some minor successions. We first illustrate here the Triassic-Miocene Succession, then we describe the siliciclastic successions outcropping in the more internal areas, then the siliciclastic succession outcropping in the more external areas and in the "intra-Apenninic minor basins". Successions have been distinguished on the base of age, basin size and lateral-vertical relationships. Comprehensive overviews of the stratigraphic evolution of this sector of the Northern Apennines can be found in Centamore *et alii* (1971, 1986); Cresta *et alii* (1989); Boccaletti *et alii* (1990b); Centamore & Micarelli (1991); Ciarapica & Passeri (1998); Barchi *et alii* (2001); Pierantoni *et alii* (2013); Barchi & Marroni (2014) and more detailed informations in Selli (1954); Crescenti *et alii* (1969); Colacicchi *et alii* (1970); Capuano *et alii* (1986); De Donatis (1993); Santantonio (1993). A schematic lithostratigraphic log is in Fig. 9.

Triassic-Lower Jurassic succession

Pre-Triassic rocks are not exposed in this external part of the Northern Apennines, but are only reached by some deep wells (Martinis & Pieri, 1964; Anelli *et alii,* 1994; Barchi *et alii,* 1998c), as Permian sandstones and phyllites. The Triassic starts with alternating anhydrites, dolomites and subordinate limestones and marls, only outcropping at the core of main anticlines in Umbria (UM_{cv}, Anidriti di Burano Fm., Martinis & Pieri, 1964; Ciarapica & Passeri, 1976). The widespread occurrence of evaporites at the base of the Umbria-Marche Succession is documented by well data, with thickness of a few hundred meters and a maximum of about 2500 m in the S. Donato 1 well (Anelli *et alii,* 1994). The fossil content is poor (gastropods, echinoids, sponges fragments, etc) and only a generic Early Triassic age can be inferred. These rocks document deposition in a widespread platform margin, with coastal basins, lagoon and sabkhas (Centamore *et alii,* 1986). The evaporitic succession passes upsection to alternating blackish limestones and marls (UM_{rt}) similar to the Rhaetian deposits of the Tuscan Domain (Calcari a *Rhaetavicula contorta* Fm.).

During the early Liassic (Hettangian) a carbonate platform developed, with oolitic bar, lagoonal and tidal facies. Later, in the Sinemurian, the carbonate platform broke up developing a series of intrabasinal highs and low, producing diversity of depositional environments, that persisted throughout the Jurassic. In the Map we distinguish the condensed succession deposited on top of seamounts and the more complete basinal successions (Fig. 9).

The complete succession represents sedimentation in basins experiencing subsidence during this time span, with development of massive carbonate platform limestones (UM_{ms}, Calcare Massiccio del Burano).

Jurassic condensed succession

The Jurassic condensed succession (UM_{bg}), Sinemurian-Tithonian in age, is deposited on structural highs and is represented by tidal massive limestones followed by detritic facies (Calcare Massiccio del M. Nerone) that testify to the inception of fragmentation of the carbonate platform, upsection follow well-bedded nodular limestones and marly limestones with hard-grounds, unconformities and syn-sedimentary dykes (Bugarone Fm.).

Jurassic complete succession

Carbonate sedimentation continues with micritic pelagic limestones with cherty nodules and layers (UM_{co}, Corniola). Upsection follow limestones, marly limestones and marls, with nodular limestones and marls (UM_{po}; Rosso Ammonitico, Marne a Posidonia) and then more siliceous sedimentation with micritic limestones with cherts and calcarenites (UM_{di}; Calcari diasprini).

Cretaceous-Miocene calcareous-marly succession

The Maiolica Fm. (UM_{mi}) closes the mainly carbonate sedimentation in the Umbria-Marche Domain, the extensional events that affected the carbonate platform

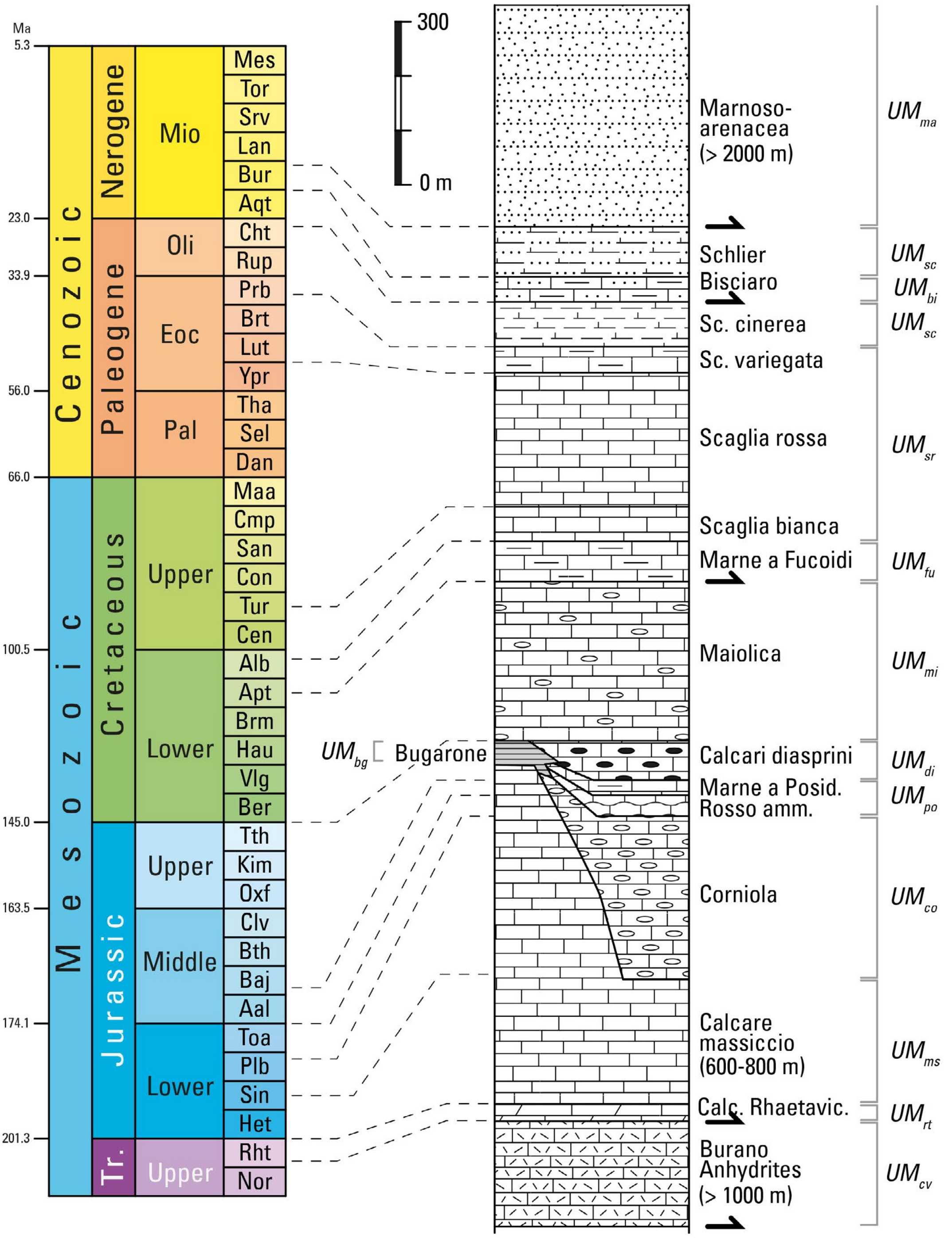

Fig. 9 - Lithostratigraphic log of the Umbria-Marche succession. Arrows indicate the main rheological discontinuities, where thrust and detachment nucleate during compressional tectonics. After Barchi (2015) and Cipriani (2016). In italics are labels of the geological map.

come to end and uniform sedimentation conditions developed throughout the basin (Barchi *et alii*, 2001). This is associated with a progressive deepening of the whole area with deposition of well bedded micritic limestones with black chert layers and interbedded black pelites.

The deposition of the Marne a Fucoidi Fm. (UM_{fu}) marks the end of the mainly calcareous sedimentation and the inception of marly sedimentation throughout, with local anoxic deposits (i.e. Livello Selli, Livello Bonarelli). Marly sedimentation continues during Cretaceous to Eocene, with deposition of Scaglia Bianca, Scaglia Rossa and Scaglia Variegata fms. (UM_{sr}), together with development of local basins and high zone. This is testified by deposition of micritic limestones with cherts, interbedded with detritic levels, passing to marly limestones and limestones; calcarenites and slumpings are common. The pelagic calcareous sedimentation in the area ends with the deposition of the Scaglia Cinerea Fm. (UM_{sc}: late Eocene-early Miocene), consisting of alternating limestones, marly limestones and marls.

Starting in the Miocene, the Umbria-Marche Domain is affected by shortening and gradually evolved in a turbiditic foredeep. But, before of the turbiditic sedimentation, hemipelagic deposits developed, as the Bisciaro Fm. (UM_{bi}: Aquitanian p.p.-Burdigalian p.p.) consisting of alternating marly limestones, marls, clays with volcanoclastic levels and the following upwards Schlier, Marne con Cerrogna and Marne a Pteropodi fms. (UM_{sh}), consisting of alternating marls and clays, with locally marly limestones and calcarenites. Linked with eastward migration of compression, age of the top of the Schlier Fm. is younger toward the East (late Burdigalian in the more internal areas, early Messinian in the more external areas).

Ongoing deformation led to development of basins where siliciclastic turbiditic deposition occurred (BARCHI *et alii,* 2001). We differentiate in the geological map the siliciclastic successions of the major and more internal area/basin and the siliciclastic successions of the more external areas and "intra-Apenninic" minor basins.

Siliciclastic succession of the inner basin

The Siliciclastic Succession of the inner basin (also called Umbria-Romagna subdomain succession) is mainly represented by the Marnoso-arenacea Fm. s.s. (UM_{ma}), that consists of a very thick turbidite complex extending from the Emilia Apennines to the Umbria-Marche Apennines, forming a belt some hundreds of km long. The Marnoso-arenacea Fm. is subdivided in several members, on the base of the age, sand/mud ratio, stratigraphic, paleogeographic and basinal position, as well as sedimentological and structural features. The Marnoso-arenacea Fm. represents the infilling of the main foredeep basin of the Northern Apennines, from the late Burdigalian to the earliest Messinian, recording an articulated foreland migration of the basin depocentres, accompanied by a structural basin fragmentation (RICCI LUCCHI, 1986; ARGNANI & RICCI LUCCHI, 2001; TAGLIAFERRI & TINTERRI, 2016, with references therein). The Marnoso-arenacea Fm. lies conformably on to the Schlier Fm. representing the uppermost marly deposits of the Cretaceous-Miocene calcareous-marly succession of the Umbria-Marche-Romagna Domain, whilst it is overlain conformably by marly deposits marking the foredeep basin closure (RICCI LUCCHI, 1986; ARGNANI & RICCI LUCCHI, 2001). These closure deposits (UM_{gh}) are progressively younger eastwards the foreland: the Verghereto Marls and the San Paolo Marls, the Ghioli di letto Fm. and Campo Marls (respectively late Tortonian – to earliest Messinian in age) (DE FEYTER, 1991; CONTI, 1994; ROVERI *et alii,* 1999; ARGNANI & RICCI LUCCHI, 2001; CORNAMUSINI *et alii,* 2009b; PIALLI *et alii,* 2009).

The Marnoso-arenacea Fm. consists of turbidite sandstones and siltstones with high variability in facies and bed thickness, siliciclastic in composition, interlayered with marlstones. Several turbidite key-beds occur within it, formed of siliciclastic meter-thick sandstone beds, thick hybrid beds (*sensu* ZUFFA, 1980) (i.e. Contessa bed) and calcarenite beds (called "colombine", RICCI LUCCHI & VALMORI, 1980). Some internal unconformities have been recorded within the formation, due to synsedimentary tectonics, as well as slumps, olistostromes and chaotic complexes, to document a complicated evolution of the foredeep basin (TINTERRI & TAGLIAFERRI, 2015; TAGLIAFERRI & TINTERRI, 2016; TINTERRI & MAGALHAES, 2011).

Some other sandstone successions show peculiar relationships with the Marnoso-arenacea Fm. and have been grouped with it in the map, as the Monte S. Maria Tiberina Fm. and the Monte Vicino Sandstones. The Monte S. Maria Tiberina Fm. is considered by BROZZETTI (2007) a succession deposited between the Tuscan and the Umbria domains, lying unconformably on to the Falterona Succession and conformably on to the Marnoso-arenacea Fm. The Monte Vicino Sandstones could represent the turbidite deposits of the innermost of the Marche minor basins (CENTAMORE *et alii,* 1977, 1978; CANTALAMESSA *et alii,* 1986b). But due to their stratigraphic relationships and analogies, they have been grouped with the Marnoso-arenacea Fm. in the Map. These successions and relationships could represent evidence of a segmentation of the foredeep during late Tortonian-early Messinian, that led some authors to subdivide the Umbria-Marche-Domain in Umbria-Romagna and Marchean-Adriatic subdomains.

The Verghereto Marls and the San Paolo Marls (UM_{gh}) consist of marl and clay deposits with occasional interbeds of thin-bedded turbidite sandstones, at the top of the inner Marnoso-arenacea Fm. The Ghioli di letto Fm. (UM_{gh}) is represented by clays and marly clays with lenticular interlayers of coarse sandstones, slumps and Ligurian-derived olistoliths in the upper part; it is placed at the top of the outer Marnoso-arenacea Fm., and it is in turn overlain by the euxinic clays of the Tripoli Fm. or unconformably by the resedimented evaporites of the Sapigno Fm. belonging to the Evaporitic Messinian Succession and to the Post-evaporitic Messinian Succession, respectively (CONTI, 1994; ROVERI *et alii,* 1999; CORNAMUSINI *et alii,* 2017).

Siliciclastic succession of the intra-Apennine minor basins and outer basins

This succession crops out in the Adriatic foreland, extensively in the Marche Region (also called Marchean-Adriatic subdomain succession) and are sedimented in foreland basins, simple foredeep or complex foredeep basins *sensu* ARGNANI & RICCI LUCCHI (2001). Most of these successions are represented by turbidite systems, with minor starved euxinic shales and resedimented evaporites. They consist of pre-evaporite turbidite deposits of the Marchean Marnoso-arenacea Fm. (UM_{am}) and of the pre-, syn- and post-evaporite turbidite deposits of the Laga Fm. (UM_{la1}, UM_{la2} and UM_{la3}).

The oldest and inner deposits belong to the the Marchean Marnoso-arenacea Fm. (UM_{am} in the Marche region; CAPUANO, 2009; CORNAMUSINI *et alii,* 2009b), Tortonian – early Messinian in age, which represent the turbidite basinal sediments of the Umbria-Marche Succession and also corresponds to the "minor Marche basins" or molasse basins of CENTAMORE *et alii* (1978) and of CANTALAMESSA *et alii* (1986b). These basins were located in a complex foredeep system, with syntectonic activity and complicated tectonics vs. sedimentary relationships, with sharp lateral discontinuity, facies change and diachrony (RICCI LUCCHI, 1975; CENTAMORE *et alii,* 1978). The Marchean Marnoso-arenacea Fm. is characterized by a 1000 m thick turbidite sandstones with minor conglomerates and mudstones, with high-grade interfingering, so to determine a subdivision in several members and lithofacies (CAPUANO, 2009). It lies conformably on to the marly Schlier Fm. and it is overlain by the bituminous clays and marls, sandstones, diatomites and dolomitic limestones of the Tripoli Fm. belonging to the Messinian Evaporite Succession, passing unconformably upwards, to the resedimented gypsum of the Sapigno Fm., belonging to the Messinian Post-Evaporite Succession (CREMONINI & FARABEGOLI, 1978). These deposits are in turn unconformably overlain by post-evaporite continental deposits of the Po Plain-Adriatic Margin Mio-Pleistocene Succession with the continental Colombacci Fm. and the Pliocene marine deposits.

Furthermore, Cantalamessa *et alii* (1986b) separate the whole siliciclastic successions of the minor basins in an inner and older Marche Basin system and in an outer and younger Marche Basin system. These turbidite systems are many and known in literature with different names (i.e. Urbania Sandstones, Urbino Sandstones, Sant'Angelo in Vado Sandstones for the Marchean Marnoso-arenacea Fm., Serraspinosa Sandstones, Matelica Sandstones, Collamato Sandstones, San Donato-Cantia Sandstones, Camerino Sandstones for the inner system, the Laga Fm. for the outer system), outlining the complexity of the basinal fragmentation, confinement and depocentre migration (Centamore *et alii,* 1978; Cantalamessa *et alii,* 1986b; Ricci Lucchi, 1986; De Feyter, 1991; Argnani & Ricci Lucchi, 2001).

The Laga Fm. is an important and thick turbidite complex deposited within the outermost and southern minor Marche basin (Centamore *et alii,* 1990, 1991, 1993; Cantalamessa *et alii,* 1986b; Bigi *et alii,* 1995; Milli *et alii,* 2007). It has been ascribed to the Messinian p.p. and across the Messinian Salinity Crisis, so to recognize a Pre-evaporite Member (UM_{la1}), an Evaporite Member (UM_{la2}) and a Post-evaporite Member (UM_{la3}) (Cantalamessa *et alii,* 1982, 1986b; Micarelli & Cantalamessa, 2006; Cello, 2009). The UM_{la1} member lies onto the Schlier Fm. or the Pteropods Marls, and consists of turbidite sandstones and mudstones. The UM_{la2} member, laterally corresponding to the Gessoso-solfifera Fm. following the early authors, but overall to the Sapigno Fm. of the minor basins, consists of turbidite sandstones and mudstones with thin interlayers of euxinic bituminous clays and recrystallized gypsum and gypso-arenites. The above UM_{la3} consists of turbidite sandstones and mudstones, and conglomerates, with a volcanoclastic interlayered level. Recently, some authors (Roveri *et alii,* 2003; Manzi *et alii,* 2005; Roveri & Manzi, 2006) through a review of the Messinian Salinity Crisis stratigraphic record along the Peri-Adriatic Basin, established that the primary gypsum due to the evaporite phase, is restricted to the Gessoso-solfifera Fm. of the marginal setting of the Vena del Gesso, whereas the gypsum settled in deeper basins, as the Laga Basin or the other minor Marche and Romagna basins, should be considered as resedimented, both as slide blocks, and as gypso-arenites (Fig. 10). In such case, the gypsum-bearing deposits of the Laga Fm., particularly of the Evaporite Member UM_{la2}, corresponds to the basinal p-ev$_1$ sequence of Roveri *et alii* (2003), to be correlated with the Sapigno Fm. or "Formazione di tetto". Consequently, the post-evaporite Member of the Laga Fm. (UM_{la3}) can be considered subdivided in two successions: the lower, corresponding upbasin to the San Donato Fm. (upper part of the sequence p-ev$_1$ of Roveri *et alii,* 2003) and the upper, separated by a correlative conformity surface, corresponding upbasin to the Colombacci Fm. (sequence p-ev$_2$ of Roveri *et alii,* 2003). Following this view, the resedimented deposits of the Gessoso-solfifera Fm., should be considered as post-evaporite deposits, whereas the euxinic clays represent the basinal record of the evaporite phase, time-equivalent to the Gessoso-solfifera Fm. of the Vena del Gesso.

Miocene-Pleistocene syn-and post-evaporite succession of the Po Plain and Adriatic margin

This succession consists of a complex system of depositional units at the front of the chain recording the late foredeep deposits of the late orogenic phases. It has been subdivided by Ghielmi *et alii* (2013) into four allogroups on the base major unconformities: EM-early Messinian allogroup; LM-late Messinian-early Pliocene

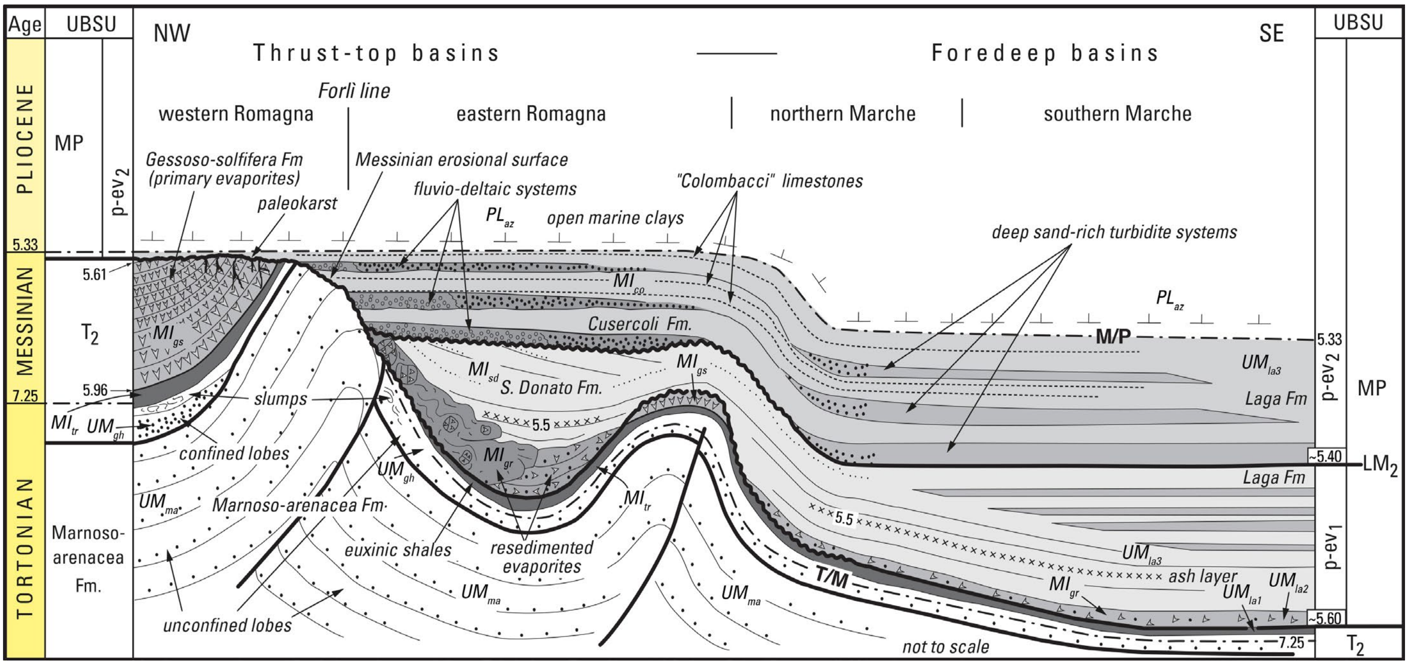

Fig. 10 - Schematic cross-section of the Adriatic foredeep representing the upper Tortonian - lower Pliocene stratigraphic relationships, after Roveri & Manzi (2006). T/M and LM2 are intra- Messinian unconformities. In italics are labels of the geological map, for other labels see text.

allogroup; EP-early-late Pliocene allogroup; LP-late Pliocene-Pleistocene allogroup; in turn subdivided in lower rank unconformity bounded units, defined as Large-Scale Sequences. The deposits crop out extensively from Piacenza to San Benedetto del Tronto and also occur in the Po Plain subsurface. Geographically the succession can be divided into two lateral successions: the Po Plain-Apenninic Margin Succession to northwest (Emilia-Romagna Region) (Ricci Lucchi *et alii,* 1982; Roveri *et alii,* 2004) and the Adriatic-Apenninic Margin Succession to southeast (Marche Region) (Savelli & Wezel, 1978; Barchi *et alii,* 2001; Roveri *et alii,* 2005; Artoni, 2013). The two successions are similar and laterally correlated but showing some differences in the stratigraphic architecture (Fig. 10).

In the whole, this succession is comprehensive of the Messinian evaporite succession, the Messinian post-evaporite succession and the Pliocene-middle Pleistocene marine succession. The Messinian evaporite succession and the Messinian post-evaporite succession are separated by the intra-Messinian unconformity. The whole succession is classically subdivided in sedimentary cycles by Ricci Lucchi *et alii* (1982): cycle T2 *p.p.* early-middle Messinian in age containing the euxinic pre-evaporite and the gypsum and clay syn-evaporite deposits; cycle M late Messinian in age, of continental to shallow marine environment; cycle P1 early Pliocene in age, of marine environment; cycle P2 late Pliocene in age, of marine environment; cycle Qm early Pleistocene in age, of marine environment; above the cycle Qm, there is the cycle Qc middle-late Pleistocene in age, of continental environment, lying through a disconformity (Di Celma *et alii,* 2015). The deposits related to this last cycle (Qc) are discussed in the section "Quaternary ("post-Villafranchian") continental and coastal deposits".

These "cycles" consist of different successions as they deposited in different position, in the basin margin or in the deep-sea basin depocenter and are separated by unconformities for the former case and by correlative conformities for the latter case (Ricci Lucchi *et alii,* 1982; Cantalamessa *et alii,* 1986a). The Laga Fm., although belonging to the T2, M and P sequences or "cycles", is discussed in the section dedicated to the "Siliciclastic succession of the intra-Apennine minor basins and outer basins". The Central Periadriatic Basin in southern Marche, including the Laga Fm. up to Pleistocene foredeep deposits, has been subdivided into eight large-scale stratigraphic units (UBSU *sensu* Salvador, 1987) showing a progressive infilling of the basin and a shallowing-regressive upwards trend (Artoni, 2013; Ghielmi *et alii,* 2019).

Messinian evaporite succession

This succession consists of pre- and syn-evaporite deposits (Tripoli Fm. and Gessoso-solfifera Fm. p.p. respectively) early-middle Messinian in age, relative to the Messinian Salinity Crisis of the paleo-Mediterranean Sea (Hsü *et alii,* 1973, 1977; Krijgsman *et alii,* 1999; Roveri *et alii,* 2001, 2014). It occurs in different settings: a) conformably on to the Ghioli di letto and Marnoso-arenacea fms. of the inner main foredeep basin of the Umbro- Marche-Romagna Domain; b) conformably on to the Marnoso-arenacea Fm. of the outer minor basins, and; c) conformably on to the Schlier Fm. in the structural highs of the outer minor basins. Furthermore, evaporites occur also within the outer and southern minor basin (as in the Laga Fm.) and at the top of the Epiligurian Succession.

Case a) corresponds to the most complete and thick evaporite succession, like at the Vena del Gesso (Roveri *et alii,* 2003), where the Gessoso-solfifera Fm. is mainly formed by primary gypsum, deposited on a morpho-structural and basin-margin setting. Case b) corresponds to the occurrence of pre-evaporitic euxinic clays and diatomites of the Tripoli Fm. following the foredeep turbidite sedimentation, whereas the primary evaporites are lacking. Case c) corresponds to euxinic clays of the Tripoli Fm. and gypsum of the Gessoso-solfifera Fm. deposited on top of structural anticline high as in the Montefiore-Montescudo Ridge, where these deposits sedimented directly on to the Schlier Fm., lacking the basinal turbidite deposits.

The Tripoli Fm. (MI_{tr}) consists of euxinic and bituminous clays, marly clays, thin-bedded sandstones and siltstones, diatomites, limestones and tripolaceous marls, to represent the basin starvation anticipating the salinity crisis. The evaporites of the Gessoso-solfifera Fm. (MI_{gs}) are particularly well-developed at Vena del Gesso, a shallow water thrust-top basin linked with the Riolo anticline (Roveri *et alii,* 2003), and consist of a wide variety of gypsum, mainly selenitic, and minor intrabasinal reworked gypsum, like gypsarenite and gypsum rudite.

Messinian post-evaporite succession

It represents the post "intra-Messinian tectonic phase" succession, linked with the sedimentation recovery after the evaporite Messinian crisis, i.e. the post-evaporite and "lago-mare" facies (Selli, 1973; Ricci Lucchi *et alii,* 1982; Roveri *et alii,* 1998, 2003, 2004; Gennari *et alii,* 2013). It corresponds to the "cycle" M of Ricci Lucchi *et alii* (1982) and to the Unit MP *p.p.* (UBSU) of Roveri *et alii* (2004), divided into two subunits by an unconformity (Fig. 10): the "p-ev_1" formed by resedimented evaporites and siliciclastic deposits, occurring particularly in the deep basins, and the "p-ev_2" occurring both in deep and marginal settings (Roveri *et alii,* 1998; Ricci Lucchi *et alii,* 2002).

This succession lies unconformably on the Messinian evaporite succession, which is represented by evaporite deposits for the marginal areas and by the pre-evaporite euxinic shales or siliciclastic turbidites for the basinal areas (Roveri *et alii,* 1998), and locally, where the latter is lacking, directly onlaps the topmost units of the Umbria-Marche-Romagna Succession, such as the Ghioli di letto Fm.

In more detail, the deposits of the the "p-ev_1" subunit consists of resedimented gypsum bodies from the Gessoso-solfifera Fm., known as Sapigno Fm., "Formazione di tetto", or Gessoso-solfifera Fm. *p.p.*, associated with bituminous and organic-rich clays, dolomitic limestones, gypsarenites (MI_{gr}), that grade laterally basinward and upwards, to alternations of turbidite sandstones and clays (San Donato Fm., MI_{sd}) of continental to shallow marine environment and more basinward to the Laga Fm. (Bassetti *et alii,* 1994; Invernizzi *et alii,* 1995). These deposits occur both in the inner main foredeep basin and in the outer "minor Marche basins" of Cantalamessa *et alii* (1986b).

The "p-ev_2" subunit, separated by the lower succession through another Messinian unconformity (LM2 of Roveri *et alii,* 1998), is represented by continental clays, sandstones, conglomerates and limestones, known as Colombacci Fm.

(MI_{co}) or Cusercoli Fm., or Pietrarubbia Conglomerates and turbidites of the Turrino Sandstones (Centamore *et alii,* 1978; Cantalamessa *et alii,* 1986b; Bassetti, 1994, 2000). This subunit, relative to the "lago-mare" facies, occurs both in the basinal and in the marginal areas, or structural highs (as the Montefiore-Montescudo Ridge), where it lies unconformably onto the evaporites of the Gessoso-solfifera Fm. and the euxinic shales of the Tripoli Fm., belonging to the messinian evaporitic succession. In the deeper areas of the "minor Marche basins", it lies unconformably on to the San Donato Fm. In the Marche area, thhese subunits have been defined as M2b and M3 sequences by Guerrera & Tramontana (2011).

The two subunits grade basinward (southern Marche) and laterally to the Laga Fm. (Roveri & Manzi, 2006), which has been here assigned to the Messinian siliciclastic succession of the outer basins, representing the most recent post-evaporite turbidite unit of the Umbria-Marche-Romagna Domain (Cantalamessa *et alii,* 1986b; Barchi *et alii,* 2001).

Pliocene-Pleistocene marine succession

The bottom of this succession marks the marine transgression after the "lago-mare" phase and the subsequent filling of the Adriatic foredeep (Ricci Lucchi *et alii,* 1982). Four main sequences have been identified (P1, P2, Qm, Qm1) based on significant environmental changes, sea-level rise-and-fall and tectonic settings (Colalongo *et alii,* 1982; Ricci Lucchi *et alii,* 1982; Cantalamessa *et alii,* 1986a), and correspond to the MP Unit *p.p.* and particularly to the upper part of the "p-ev_2" of Bassetti *et alii* (1994). The subdivision in sequences, especially for the Periadriatic Basin, is discussed in Cantalamessa *et alii* (2002) and in Bigi *et alii* (1995).

The marine deposits of the P1 sequence, early Pliocene in age, consist of fossiliferous marls, clays, minor sandstones and conglomerates of shallow marine environment. They are known in the literature as Cella Marls, "Argille Azzurre inferiori", Santerno Clays *p.p.*, Borello Sandstones, Porto Corsini Fm. (Fig. 11). They lie paraconformably on to the Colombacci Clays of the p-ev_2 subunit or unconformably on to other units. This sequence or cycle (*sensu* Ricci Lucchi *et alii,* 1982), has been locally divided into two subsequences by Ricci Lucchi *et alii* (1982) for the Emilia-Romagna area and by Cantalamessa *et alii* (1986a, 2002) for the Marche area: the "P1a" and "P1b" both of early Pliocene age, separated by unconformity or correlative conformity surface.

It is worth to note that in the northern Marche - southeastern Romagna, between the two subsequences and marking the unconformity, is comprised the "Coltre della Val Marecchia". It represents for some Authors huge submarine complexes emplaced in the Messinian and in the early Pliocene, formed of Ligurian and Epiligurian gravitational slivers triggered by tectonic pulses (Ricci Lucchi, 1986; Veneri, 1986; De Feyter, 1991; Lucente *et alii,* 2002; Lucente & Pini, 2008; Cornamusini *et alii,* 2009a, 2017), whereas for other Authors is considered not gravitational, but linked to pure tectonic activity and advancement of thrust sheets (Conti, 1994; Conti & Tosatti, 1996; Cerrina Feroni *et alii,* 2002a; Conti, 2002, *cum biblio*).

The deposits of the P2 sequence are marine too, but late Pliocene/early Pleistocene in age, and are separated from the P1 sequence through a complex surface, varying from unconformable to conformable, depending by the basin position (Ricci Lucchi *et alii,* 1982). It consists of fossiliferous clays, alternations of clays and sandstones, minor conglomerates, known as "Argille Azzurre superiori", Santerno Clays *p.p.*, Montecalvo in Foglia Mb. *p.p.*, Porto Garibaldi Fm. *p.p.*. In the southern Marche an unconformity subdividing the P2 sequence into two subsequences P2a (Spungone Mb. or Montefalcone Mb. of the "Argille Azzurre" Fm.) and P2b (Monte Ascensione Mb. of the "Argille Azzurre" Fm.), has been recorded (Cantalamessa *et alii,* 2002; Micarelli & Cantalamessa, 2006). In particular, the P2a has been referred to the Piacenzian and the P2b to the Gelasian (Cantalamessa *et alii,*

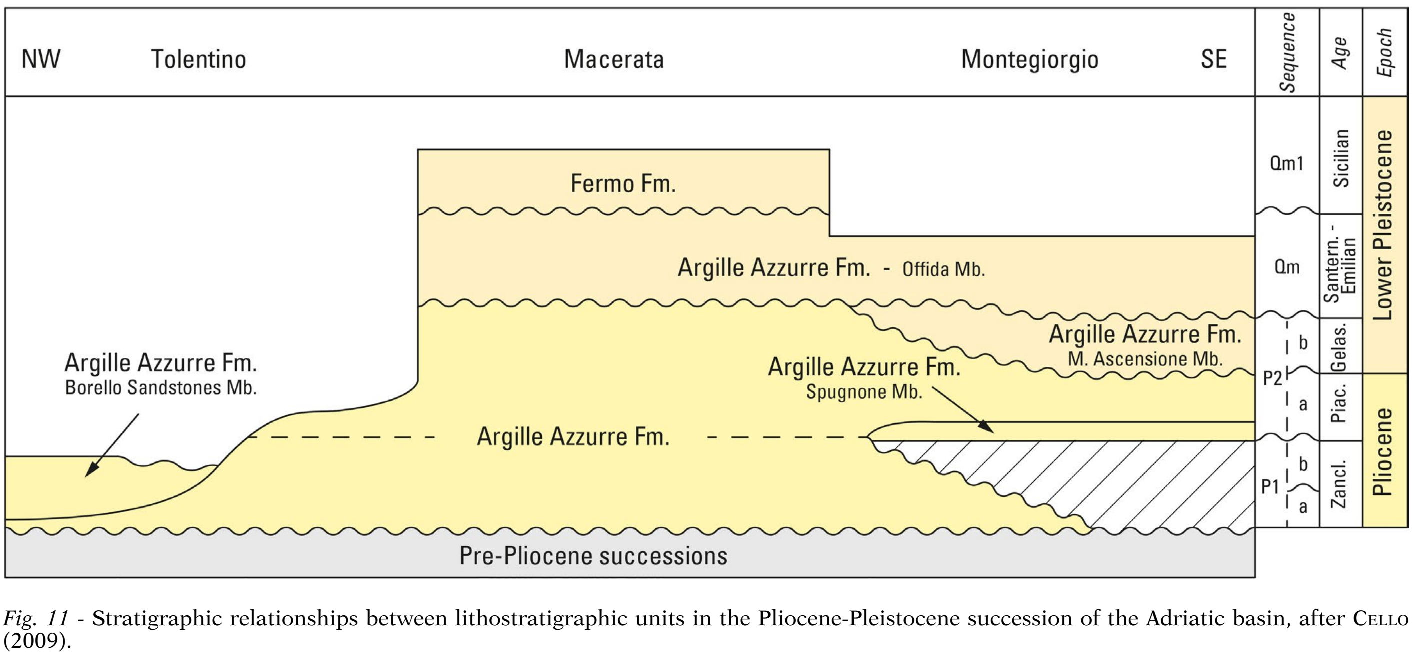

Fig. 11 - Stratigraphic relationships between lithostratigraphic units in the Pliocene-Pleistocene succession of the Adriatic basin, after Cello (2009).

2002). Pliocene lower Pleistocene marine conglomerates and sandstones have been mapped as PL_{ar}, whereas the lithostratigraphic units showing an increase in the clay content, as fossiliferous clays, silty clays, with interlayers of sandstones and conglomerates, have been grouped as PL_{az} in the geological map.

The deposits of the Qm sequence are marine in environment, early Pleistocene (post-Gelasian) in age, and consists of fossiliferous clays, sandstone and conglomerates, analogously to the P2 sequence, with conformable to disconformable stratigraphic relationships. The Qm sequence, with respect to the below P2 sequence, represents a regressive cycle (Ricci Lucchi *et alii,* 1982). Furthermore, Cantalamessa *et alii* (2002) recognize a Qm sequence (Santernian-Emilian early Pleistocene) and an unconformable above lying Qm1 sequence (Sicilian; early Pleistocene) formed of littoral sands and conglomerates. Sandstones and clays of the Qm sequence are indicated as PE_{im} in the geological map (i.e. Imola Sands), whereas the coarser units with sandstones and conglomerates have been grouped as PE_{fe} (i.e. Fermo Fm.). The subdivision of the Pliocene-Pleistocene marine deposits in sequences have been also adopted by the CARG Project cartography (Cello, 2009; Deiana, 2009; Guerrera & Tramontana, 2011, 2012). Other stratigraphic subdivisions, using UBSU, particularly for the Periadriatic Basin are in Artoni (2007) and Ghielmi *et alii* (2019). The Fermo Fm. (PE_{fe}) represents the main marine regressive sequence of the whole succession (Cantalamessa & Di Celma, 2004; Cello, 2009; Sarti & Coltorti, 2010).

Miocene-Pleistocene succession of the Tyrrhenian margin and intermontane basins

This succession (Fig. 12) is composite and strongly heterogeneous, mainly clastic and with very subordinate carbonates and evaporites, linked with the post-orogenic depositional phases that took place in the Northern Apennines back-arc, since the middle-late Miocene (Martini & Sagri, 1993; Carmignani *et alii,* 1995b; Bossio *et alii,* 1998; Jolivet *et alii,* 1998; Martini *et alii,* 2001; Sartori, 2001; Carmignani *et alii,* 2004). The deposition developed from the western and deeper Corsica Basin to the Tuscan Shelf, to the inland Tuscany basins, through different paleoenvironmental shifting (Bossio *et alii,* 2000; Pascucci *et alii,* 1999; Mauffret & Contrucci, 1999; Cornamusini *et alii,* 2002; Cornamusini & Pascucci, 2014). The geodynamic context of such basins is nowadays debated, with a vision privileging an extensional basin system (Martini & Sagri, 1993; Carmignani *et alii,* 1994, 1995a; Bossio *et alii,* 1998; Jolivet *et alii,* 1998; Pascucci *et alii,* 1999; Martini *et alii,* 2001; Carmignani *et alii,* 2004; Bonciani *et alii,* 2005; Brogi & Liotta, 2008), and an alternative hypothesis which states that most of the basins were formed within a compressional setting generating significant stratigraphic unconformities (Bernini *et alii,* 1990; Boccaletti & Sani, 1998; Finetti *et alii,* 2001; Bonini & Sani, 2002; Bonini *et alii,* 2014; Benvenuti *et alii,* 2015).

The Miocene-Pleistocene Succession of the Tyrrhenian margin has been classically named "Neoautochthonous" *Auctt.*, as it lies unconformably onto the orogenic unit stack, and it has been subdivided in some minor successions or stratigraphic-depositional units, through unconformable and disconformable boundaries, which can be locally erosional, changing in extension, significance and importance from basin to basin (Bossio *et alii,* 1993, 1998, 2000). Each minor succession represents a different depositional cycle due to the relative sea-level changes induced by post-collisional tectonics, magmatic and climate events, which determined different paleoenvironmental and basinal conditions through time (Pasquarè *et alii,* 1983; Martini & Sagri, 1993; Bossio *et alii,* 1993; Carmignani *et alii,* 1995b; Bossio *et alii,* 1998; Carmignani *et alii,* 2004; Pandeli *et alii,* 2010; Cornamusini *et alii,* 2011).

Middle Burdigalian - lower Tortonian marine deposits (Tyrrhenian Epiligurides Auctt.)

The succession lie unconformable only onto the deformed Ligurian Units, and upsection passes to the Upper Miocene continental deposits of the Neoautochthonous Succession *s.s.*, through a transition variable from angular unconformity, to disconformity, to conformity (Foresi *et alii,* 1997a; Cornamusini *et alii,* 2011; Ielpi & Cornamusini,

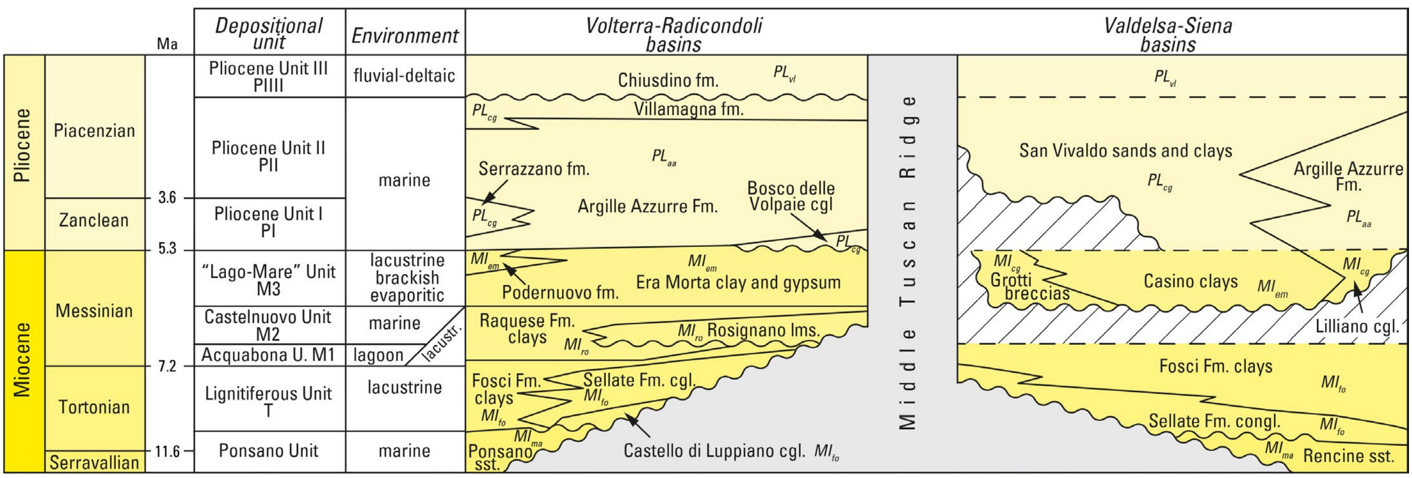

Fig. 12 - Miocene-Pliocene stratigraphic sketch for the central and southern Tuscany; modified after Costantini *et alii* (2009). In italics are labels of the geological map.

2016), showing relationships coherent with a regional progressive unconformity (Ielpi & Cornamusini, 2012).

These deposits (MI_{ma}) are represented by minor outcrops scattered within the inner Tuscany- northern Latium, of shallow marine sandstones with subordinate conglomerates and marlstones. Sandstones are fossiliferous, bioturbated and characterized by cross-bedding and sandy bedforms, together with other sedimentary structures typical of shoreface-deltaic environment. The rocks have different ages. The oldest and westernmost are represented by the Marina del Marchese Fm. in the Pianosa Island, middle Burdigalian in age, which has partially different lithological association formed by shallow marine turbidite calcarenites and marlstones (Colantoni & Borsetti, 1973; Cornamusini *et alii,* 2014). In southern Tuscany-northern Latium the Manciano Sandstones are recognized, ascribed to an unspecified middle Miocene (Giannini, 1957), or to an not well constrained Miocene age (Barbieri *et alii,* 2003), and the Ponsano Sandstones of southern Tuscany of late Serravallian-early Tortonian age (Mazzanti *et alii,* 1981; Foresi *et alii,* 1997a, b). These deposits are here considered as the base of the Miocene-Pleistocene Succession of the Tyrrhenian Margin and thus included in the post-collisional succession, but this is a matter of discussion. Classically, these deposits have been considered "Epiligurian" thrust-top basins with respect to the latest collisional phases (Martini *et alii,* 1995), or relative to a not well-defined geodynamic setting (Bossio *et alii,* 1998). Recently some evidence, both stratigraphic (Foresi *et alii,* 1997a, b; Cornamusini *et alii,* 2011, 2014; Ielpi & Cornamusini, 2012, 2016) and structural (Brogi, 2004; Bonciani *et alii,* 2005; Brogi & Liotta, 2008), suggests to consider them (at least the Manciano Sandstones and Ponsano Sandstones) as the lower part of the "Neoautochthonous" Succession, developed during the first rifting phase of the inner Northern Apennines.

Lower Turolian (upper Tortonian) fluvio-lacustrine succession

This succession is classically known as "Serie Lignitifera" (Lazzarotto & Mazzanti, 1976) and comprises many formational lithostratigraphic units (as Golfo della Botte Fm. for the Pianosa Island, Luppiano Castle Conglomerates, Fosci Creek Clays, Bithynia Marls, Sellate Creek Fm., Ribolla Clays, Collacchia Conglomerates, Casino Clays, etc.). This succession lies unconformable to conformable onto the middle-upper Miocene marine deposits (Ielpi & Cornamusini, 2012, 2016), or where these are lacking, directly on to the Ligurian units through a marked angular unconformity. Upwards it passes to the Messinian Pre-evaporite marine succession, through a conformable surface (correlative conformity), which locally could become an unconformable transition at the basin margin (Bossio *et alii,* 1993, 1998; Cornamusini *et alii,* 2011). These deposits represent the widespread lowest portion of the "Neoautochthonous" Succession (Bossio *et alii,* 1993, 1994, 1998; Martini & Sagri, 1993; Rook & Ghetti, 1997; Foresi *et alii,* 2000; Benvenuti *et alii,* 2001; Costantini *et alii*, 2002a; Lazzarotto *et alii*, 2002; Costantini *et alii,* 2009; Cornamusini *et alii,* 2011; Rook *et alii,* 2011), occurring within the western Neogene post-rift basins of the hinterland of the chain (e.g. Fine, Volterra, Radicondoli, Cornia, Ribolla, Casino, Baccinello, Albegna, Tafone, Fiora basins), and representing its base when the MI_{ma} deposits are lacking. They have been indicated as MI_{fo} in the geological map, Tortonian in age, but they are very heterogeneous in association, with conglomerates, sandstones, siltstones, clays and marly limestones with complex relationships, interfingering, internal erosional surfaces and disconformities. The facies are relative to alluvial systems, formed by alluvial fans, fluvial, lacustrine and palustrine systems (Martini & Sagri, 1993; Bossio *et alii,* 1998, 2000; Benvenuti *et alii,* 1999, 2001; Ielpi & Cornamusini, 2012). Ielpi (2013) revealed some evidences suggesting lacustrine-paralic setting interplays and the formation of subaerial unconformities within the middle part of the succession for the eastern part of the Volterra Basin. Brackish water clays have been well recorded by many authors (Bossio *et alii,* 1996, 1998; Lazzarotto *et alii,* 2002) for the upper part of the Fosci Fm. (only for the basins west to the Middle Tuscan Ridge, see Fig. 12), relative to a lagoonal-brackish environment, earliest Messinian in age, outlining a gradual environmental change to the upper succession. The former, of fresh water, has been ascribed to the depositional-stratigraphic Unit T "Lignitiferous Unit", the latter of brackish water, to the lower part of the Unit M1 "Acquabona-Spicchiaiola Unit" (Bossio *et alii,* 1998; Costantini *et alii,* 2002a, 2009; Lazzarotto *et alii,* 2002). Unit T is also important for its lignitiferous seams, particularly in the southern Tuscany basins of Baccinello and Cinigiano, and for significant mammal and hominoid remnants as *Oreopithecus bambolii* (Benvenuti *et alii,* 2001; Rook *et alii,* 2011). It is worth to note that the presence of pre-Messinian late Miocene land mammals, documents different bioprovinces with endemic features and peculiar paleogeography (Rook *et alii,* 2006).

Messinian pre-evaporite marine succession

This succession (MI_{ro}) represents the post-orogenic late Miocene marine transgression in the back-arc of the chain. It developed during the early Messinian for the western Tuscany basins (Riforgiato *et alii,* 2008), whereas in the same time continental settings persisted in the eastern basins (Bossio *et alii,* 1978, 1981, 1993, 1998, 2000). Indeed, two different successions have been recorded, a marine one west of an important morpho-structural high which is the Middle Tuscan Ridge, and a lacustrine/alluvial one east of it (Bossio *et alii,* 1993, 1998; Costantini *et alii,* 2009). The western succession occurs particularly in the Volterra, Radicondoli and Fine basins and also in the southernmost Tafone Basin, delineating a complex marine transgression in basins west to the Middle Tuscan Ridge, but also affecting southeastern areas linked with the Latium-Tarquinia Basin (Bossio *et alii,* 1993; Cornamusini *et alii,* 2011).

The succession is made up by the upper part of the Unit M1 "Acquabona-Spicchiaiola Unit", of brackish water and by the Unit M2 "Castelnuovo Unit" of shallow marine water environment (Bossio *et alii,* 1998; Costantini *et alii,* 2009). This succession comprises the *Pycnodonta* Clays, the Raquese Fm., the Rosignano Limestones, etc. These units lie on brackish water deposits of the top part of the lower Turolian (upper Tortonian) fluvio-lacustrine succession (Bossio *et alii,* 1997, 1998; Ielpi & Cornamusini, 2016), and pass upsection through an unconformity (or correlative conformity) to the above succession (Messinian syn- and post-evaporite succession, in Bossio *et alii,* 1997, 1998), as shown by seismic lines in the Tuscan Shelf (Pascucci *et alii,* 1999; Cornamusini *et alii,* 2002), in the offshore Corsica Basin and onshore Corsica (Mauffret *et alii,* 1999; Bossio *et alii,* 2000).

West of the Middle Tuscan Ridge deposits are characterized by clays, marls, silty clays, sandstones, conglomerates, gypsum-arenites and bioclastic reef limestones, organized in a complex architectural system, characterized by lateral facies transitions. More in detail, the lower part of the succession shows brackish water clays, with sandstone and thin gypsum-arenite interlayers (this last for the Volterra Basin only), indicating a lagoonal environment, with intrabasinal reworking of evaporite deposits (Bossio *et alii,* 1978; Lazzarotto & Mazzanti, 1976; Bossio *et alii,* 1996; Costantini *et alii,* 2009). The middle-upper part of the succession is characterized by marine water clays, rich in *Pycnodonta navicularis* with sandstone interlayers and lateral relationships with bioclastic limestones and conglomerates. They record a marine transgression replacing the lagoonal environment, leading to a shallow water environment with shoal, interacting reef complex and fan-delta at the basin margin (Bossio *et alii,* 1978, 1993; Costantini *et alii,* 2009).

To the east of the Middle Tuscan Ridge, the lagoonal and marine deposits are lacking, as in the Casino-Val d'Elsa, Siena, Radicofani and Ombrone basins, resulting in a lacuna involving the whole early Messinian, or with the sedimentation of the lacustrine clays comparable to those of the previous cycle (MI_{fo}) (Bossio *et alii,* 1981, 1993, 1996, 1998; Lazzarotto *et alii,* 2002; Costantini *et alii,* 2009).

Messinian syn- and post-evaporite succession

This succession records the depositional systems developed during the Messinian evaporite crisis affecting the whole Mediterranean Sea (Hsü *et alii,* 1977; Cita, 1982; Krijgsman *et alii,* 1999; Manzi *et alii,* 2013) and the subsequent inception of brackish to freshwater environments, particularly lacustrine to lagoonal or salmastrine (Bossio *et alii,* 1998, 2000; Aldinucci *et alii,* 2005; Carnevale *et alii,* 2006; Orszag-Sperber, 2006). It corresponds to the Unit M3 "Lago-Mare Unit" and has a late Messinian age (Bossio *et alii,* 1978, 1993, 1998). It is widespread both west and east of the Middle Tuscan Ridge, but with different stratigraphic relationships with the underlying successions. In the western basins (i.e. Volterra, Tora, Radicondoli), the succession (i.e. Era Morta River Clays and Gypsum Fm.) lies disconformable to conformable basinward above the Messinian pre-evaporite marine succession, with a gradual transition, whereas in the eastern basins (i.e. Casino, Ombrone) the succession (i.e. Casino Clays, Lilliano Conglomerates, Grotti Breccia; Montebamboli Conglomerate fms.) lies unconformable onto fluvial-lacustrine deposits (Fosci Creek Clays) of the previous older successions, lacking the brackish-marine deposits, or directly onto the Ligurian Units of the bedrock (Lazzarotto & Sandrelli, 1979; Bossio *et alii,* 1993, 1998, 2002). In such case, as evident in the Casino Basin, two lacustrine cycles overlap directly through an angular unconformity, the "lower lacustrine" and the "upper lacustrine" cycles (Bossio *et alii,* 2002; Abbazzi *et alii,* 2008; Costantini *et alii,* 2009).

This succession has different stacking patterns, depending on the depositional basins, if west or east of the Middle Tuscan Ridge. The western succession shows clays, sandstones, with interbedded lens of reworked gypsum, thin-bedded limestones and conglomerates (MI_{en}) conformable lying onto the marine clays. They are referable to a fresh to slight brackish water depositional system with paralic lakes, playas and fan deltas of late Messinian age, defining the so-called "lago-mare facies" (Bossio *et alii,* 1978, 1981, 1993, 1998, 2000). Conversely, the gypsum level occurring at the base of the succession is due to a coastal marine/lagoon evaporite phase with supersaturated water (alabastrine and laminated facies) (Bossio *et alii,* 1978, 1981; Lazzarotto *et alii,* 2002). The successions east of the Middle Tuscan Ridge show lignite-bearing clays, sandstones, conglomerates and breccias (MI_{cg}) of freshwater environment or with "lago- mare" Paratethyan affinity as for the Valdelsa Basin (Abbazzi *et alii,* 2008; Benvenuti *et alii,* 2014), late Messinian in age, lacking evaporites (Bossio *et alii,* 1978, 1993, 1998, 2000). The environmental setting is relative to shallow water lakes interacting with fan-deltas to alluvial fan system, changing to swamps depending by the oscillation of the base water level (Bossio *et alii,* 1998; Costantini *et alii,* 2009).

Pliocene-Pleistocene marine succession

The Pliocene marine deposits mark an important phase linked with the marine ingression from the Gibraltar Strait, connecting again, after the Messinian crisis, the Mediterranean Sea with the Atlantic Ocean. Ingression was very fast or catastrophic (Garcia-Castellanos *et alii,* 2009), as demonstrated by the transgressive marine basal Pliocene clay deposits occurring in the back-arc of the Northern Apennines and elsewhere in the Mediterranean area (Bossio *et alii,* 1978, 1998, 2000; Riforgiato *et alii,* 2011, with references therein). The Pliocene marine succession locally shows disconformable fresh/brackish water deposits, with two or more Pliocene marine cycles, as recorded for the Volterra Basin (Bossio *et alii,* 1994; Costantini *et alii,* 2002b; Lazzarotto *et alii,* 2002; Riforgiato *et alii,* 2005). The successions of southern Tuscany, up to the Chianti-Cetona Ridge to east, show regressive trends during the late Pliocene, up to continental deposits for the Pleistocene (Bossio *et alii,* 1993, 1998). Differently, the northern Tuscany and the eastern basins (Upper Valdarno, Mugello), do not record lower Pliocene marine deposits (Bossio *et alii,* 1993, 2010). In particular, the Val di Chiana and the Val Tiberina basins show Pliocene-Pleistocene marine deposits, to outline a paleogeographic articulated scenario for the Pliocene marine transgression (Ambrosetti *et alii,* 1978, 1987; Bossio *et alii,* 1993, 1998). The lower Pliocene marine deposits lie on to the Messinian "Lago-Mare" Unit in different settings: a) through a conformable boundary, as in depocentral part of basins, marking a water salinity change, from fresh/brackish to marine as for the basins west to the Middle Tuscan Ridge (i.e. Volterra Basin, Lazzarotto *et alii,* 2002); b) through an erosional disconformity; c) through angular unconformities, as for the basins east to the Middle Tuscan Ridge (Bossio *et alii,* 1993, 1998), especially along the basin margins, that can be variable from low- to high-angle. In these last cases particularly, the Pliocene deposits onlap unconformably also directly onto the orogenic unit stack, sealing the Ligurian and the Tuscan tectonic units (Bonciani *et alii,* 2005; Costantini *et alii,* 2009; Carmignani *et alii,* 2013).

The Pliocene marine deposits belong to two depositional units (Bossio *et alii,* 1998): the Pliocene I Unit and the Pliocene II Unit, respectively early and late Pliocene in age, in conformable or unconformable stratigraphic relationships, depending by the shape and size of the basin and by their position respect to the depocenter or basin margin; for these last cases, the boundary is often unconformable. The Pliocene I Unit marine deposits extend both west and east of the Middle Tuscan Ridge (i.e. Elsa, Siena, Radicofani, Chiana-Tevere basins for the latter), mainly formed by fossiliferous clays, silt and sand interbeds (PL_{aa}) of outer shelf environment (Bossio *et alii,* 1993; Barberi *et alii,* 1994; Bossio *et alii,* 1998). Minor occurrence of conglomerates and sandstones (PL_{cg}), locally marking internal minor unconformities, occur in the marginal portion of the major basins or within minor basins (Bossio *et alii,* 1998; Benvenuti & Degli Innocenti, 2001; Lazzarotto *et alii,* 2002; Pascucci *et alii,* 2006; Aldinucci *et alii,* 2007). The Pliocene II Unit marine deposits occur both west and east of the Middle Tuscan Ridge, locally marking an unconformity with the below Pliocene Unit I or directly on to the older units or the bedrock. It is formed of fossiliferous clays (PL_{aa}) of outer shelf environment and in the upper part of biocalcarenites and sandstones (PL_{cg}) of inner shelf environment (Bossio *et alii,* 1998; Nalin *et alii,* 2016). The above and younger Chiani-Tevere-Montescudaio Unit (Unit Q1) consists also of lower Pleistocene shallow marine to brackish water deposits (PE_{ag}), cropping out in the homonym eastern basins and along the Tuscan-upper Latium coast (Mazzanti, 1983; Ambrosetti *et alii,* 1987; Bossio *et alii,* 1993, 1998). They are represented by fossiliferous silty clays, sandstones and arenaceous limestones.

Ruscinian and "Villafranchian" non-marine succession

This succession includes the "Villafranchian" *Auctt*. deposits, here considered as continental freshwater deposits of Ruscinian, Villafranchian and Galerian ages, until 0.37 Ma. The successions are extremely articulated and they occur in southern and northern Tuscany, Umbria and Marche. They consist of Plio-Pleistocene units of Bossio *et alii* (1998), and in more detail, continental deposits are interlayered within the Unit Pliocene I (i.e. Ruscinian deposits of the Volterra Basin), as well as within and at the top of the Unit Pliocene II (Villafranchian deposits) of southern Tuscany basins (Bossio *et alii,* 1998). But overall, they form the whole Unit Pliocene III and the continental portion of the Chiani-Tevere-Montescudaio Unit, where deposits are Villafranchian in age (Bossio *et alii,* 1993, 1998). These deposits occur in northwestern Tuscany basins (Aulla-Olivola, Pontremoli, Garfagnana, Altopascio, Tuscan coast), where they are the only Neoautochthonous deposits lying unconformably onto the bedrock (Bossio *et alii,* 1993, 1998; Bernini & Papani, 2002). In southern Tuscany they lie unconformably or disconformably onto the marine Pliocene deposits or directly onto the orogenic bedrock or Miocene deposits (Fine, Valdera-Volterra, Elsa, Montescudaio-Guardistallo, Pesa, Pomarance-Chiusdino, Albegna, Tafone, Ombrone, Roccastrada and Valdichiana basins) (Ambrosetti *et alii,* 1978, 1987; Galiberti *et alii,* 1982; Bossio *et alii,* 1993, 1998). The eastern intermontane basins are filled only by Villafranchian continental deposits, as the Mugello Basin (Martini *et alii,* 2001; Benvenuti, 2003), the Upper Valdarno Basin (Fidolini *et alii,* 2013; Ghinassi *et alii,* 2013, *cum biblio*), southern part of the Florence Basin, Upper Chiana Basin, Casentino Basin and Tiber Basin, Gubbio, Gualdo Tadino, southern Umbria basins (Ambrosetti *et alii,* 1978; Boccaletti & Coli, 1982; Bossio *et alii,* 1993, 1998; Barchi, 2010). The deposits of the Tiberino and Valdichiana basins have been subdivided using UBSU (*sensu* Salvador, 1987) in Chiana Valley Supersynthem passing upwards to Tiberino Supersynthem, late Pliocene to Pleistocene in age (Barchi & Marroni, 2014). The main UBSU for these intermontane basins of the Umbria, are the Colfiorito, the Umbra Valley *p.p.*, the Morgnano *p.p.*, the Perugia *p.p.*, the Sanfatucchio, the Nestore, the Fighille synthems (Plesi, 2010; Damiani, 2011; Barchi & Marroni, 2014). The internal disconformities allowed also to subdivide other basin fillings in synthems, as the Valdelsa Basin (Benvenuti & Degli Innocenti, 2001; Aldinucci *et alii,* 2007), the Mugello Basin (Benvenuti, 2003), the Upper Valdarno Basin (Fidolini *et alii,* 2013), and others.

These deposits (PL_{vl}) are represented by conglomerates, sands, silts, clays, lignite and carbonates of alluvial environment, ranging from alluvial fan, fluvial to lacustrine environments, characterizing later phases of the Neogene-Quaternary depositional systems. They can contain rich vegetal and mammal fauna (Ambrosetti *et alii,* 1987). Carbonate fluvial-lacustrine deposits, as well as travertine and calcareous tufa, interlayered with conglomerates and clays, have been recorded extensively in the Upper Valdelsa Basin (Colle di Val d'Elsa area), where they have been subdivided into synthems (Capezzuoli & Sandrelli, 2004).

Quaternary ("post-Villafranchian") continental and coastal deposits

Quaternary deposits (gravels, conglomerates, sands, silts, clays), ranging in age from the late middle Pleistocene (Aurelian, 0.37 Ma) to the Holocene, are here indicated as "post-Villafranchian" *Auctt*. deposits and are ubiquitous along the Tyrrhenian and the Adriatic coastal plains, as well as along rivers, and in particular the Po Plain. These deposits have been usually mapped and stratigraphically subdivided using UBSU (*sensu* Salvador, 1987), in order to recognize synthems and subsynthems, as in many maps produced within the CARG Project of the Italian Geological Survey.

We mapped also main bodies of travertines and other continental carbonates as calcareous tufa with few organic-rich clay layers (Q_{tv}), linked with hydrothermal or cold freshwater, respectively (Ford & Pedley, 1996; Capezzuoli *et alii,* 2014). Areas where these deposits crop out extensively are the surroundings of Colle di Val d'Elsa, Rapolano Terme, Saturnia, Sarteano and Magliano in southern Tuscany.

The alluvial/fluvial and coastal deposits, late middle Pleistocene (Aurelian) to Holocene in age, of the Tyrrhenian side and of the inner hydrographic pattern (inner Tuscany and Umbria), including the intermontane basins, have been indicated as Q_t in the geological map. They are comprehensive of the terraced and thalweg fluvial deposits, of the alluvial fans, of the lacustrine/palustrine deposits, as well as of coastal, lagoonal and deltaic deposits (Bellotti *et alii,* 2004; Biserni & van Geel, 2005; Barchi & Marroni, 2014; Ghinassi, 2011; Rossi *et alii,* 2011; Amorosi *et alii,* 2013). They consist of gravels, sands, silts and clays, more or less organic-rich. Usually, they are uncemented, but some terraced deposits, particularly the gravel beds, can show a good cementation grade. Some of these deposits have been distinguished using synthems in the recent literature and geological maps. In particular, for the inner areas of the Umbria Region, the synthems here included, belong to the Tiberino Supersynthem, as the Citerna, Pian di Nese and upper part of the Perugia synthems (PLESI, 2010), or to the Chiana Valley Supersynthem, as the Trasimeno Synthem (BARCHI & MARRONI, 2014), or the innermost Umbra Valley Synthem *p.p.* and Morgnano Synthem *p.p.* (DAMIANI, 2011).

These deposits occur extensively also along the main Tyrrhenian side valleys (Arno, Serchio, Tevere, Ombrone rivers), in the intermontane basins (i.e. Pistoia-Florence, Mugello Basin, the Lucca Plain, the Lower Chiana Valley, the Lower Tiber Valley and Trasimeno Lake, the Casentino, the Upper Valdarno Basin, the Perugia-Terni Basin). The littoral/lagoonal deposits occur along the coastal and delta plains (from Carrara to Livorno, from Rosignano to Follonica, the Grosseto Plain, from Talamone to the Latium border).

The alluvial fan and fluvial deposits of the Po Plain and Adriatic side are indicated as Q_{a1} in the geological map. They correspond to the alluvial fan, thalweg and terraced deposits of the hydrographic pattern draining towards the Po Plain and the Adriatic Sea. They consist of gravel, sand, silt and clay sediments, that in some cases have been subdivided in UBSU, as for example the Emilia-Romagna Upper Synthem (AMOROSI *et alii*, 1996c; BOCCALETTI *et alii*, 2004; GASPERI *et alii*, 2005; BENINI *et alii*, 2009), including the Ravenna, Villa Verucchio and Bazzano subsynthems for the Emilia-Romagna side and the Musone, Matelica, Colle Ulivo, Colonia Montani and Urbisaglia *p.p.* synthems for the Marche side (CELLO, 2009; CORNAMUSINI *et alii*, 2009a; SARTI & COLTORTI, 2010; GUERRERA & TRAMONTANA, 2012).

The deposits of the Po Plain are distinguished on the base of lithological, facies, stratigraphical and environmental features (REGIONE EMILIA-ROMAGNA & ENI-AGIP, 1998), in the geological map the limits are taken from the map of PRETI (1999). The mapped lithostratigraphic units are alluvial fan and fluvial terraced deposits (Q_{a1}), fluvial channel and proximal channel levee deposits (Q_{a2}), fluvial channel and distal channel levee, interchannel and palustrine deposits (Q_{a3}), meandering fluvial plain deposits (Q_{a4}), delta plain deposits as channel, levee and swamp (Q_{a5}), delta plain deposits as interdistributary bay (Q_{a6}), littoral bar deposits as eolian dune and brackish-water swamp (Q_{a7}).

UNITS AFFECTED BY HP METAMORPHISM

Some Ligurian and Tuscan rocks are affected by high-pressure low-temperature metamorphism as evidenced in scattered outcrops in southern Tuscany, at Mt. Argentario, Giglio and Gorgona islands, in the Grosseto area. Glaucophane schists were reported in these areas by MAZZONCINI (1965), LAZZAROTTO *et alii* (1964) and RICCI (1972), but only more recently constraints for a HP-LT evolution for these rocks are set by the occurrence of magnesio-carpholite (THEYE *et alii*, 1997; GIORGETTI *et alii*, 1998; JOLIVET *et alii*, 1998; ROSSETTI *et alii*, 2002), with conditions of 0.8-1 GPa and 350-380 °C at Mt. Leoni and of 1-1.2 GPa and 350-420 °C at Mt. Argentario. HP-LT conditions are also reported for the Elba Island by BIANCO *et alii* (2015, 2019). HP metamorphism is dated as late Oligocene-early Miocene (BRUNET *et alii*, 2000). These metamorphic rocks occur as slivers in complicate tectonic settings in thrust sheets, shear zones, mylonites, developed during underthrusting and shortening phases of nappe emplacement. For more details for the Gorgona Island see the works of MAZZONCINI (1965); CAPPONI *et alii* (1990); ROSSETTI *et alii* (2001), for the Mt. Argentario and Giglio Island the works of LAZZAROTTO *et alii* (1964), CAPPONI *et alii* (1997) and ROSSETTI *et alii* (1999a,b) and BROGI & GIORGETTI (2012) for the outcrops in the Grosseto coastal area (Mt. Leoni, etc.).

In the geological map we grouped these rocks in two units, the first formed by rocks of Tuscan continental crust origin (HP_{tu}, Cala Piatti Unit of DECANDIA & LAZZAROTTO, 1980a) and the second formed by rocks of Ligurian oceanic origin (HP_{li}, Cala Grande Unit of DECANDIA & LAZZAROTTO, 1980a).

TECTONIC MÉLANGES AND SHEAR ZONES

In this section, we discuss tectonic complexes cropping out extensively and represented at the 1:250,000 map scale. These tectonic complexes incorporate rocks derived from different tectonic units and domains, so their position in the geological map legend cannot be ascribed to a definite paleogeographic domain or stratigraphic succession.

Sestola-Vidiciatico Unit

The Sestola-Vidiciatico Unit is here meant in its modern significance (REMITTI *et alii*, 2007, 2011; VANNUCCHI *et alii*, 2008, 2012), a thick (up to 500 m) tectonic mélange made of highly sheared rocks interpreted as remnants of the “subduction channel” between the Ligurian prism and the Adriatic Plate, developed during the early-middle Miocene. This tectonic unit is composed of juxtaposed tectonic slivers of different rock types detached from both the overriding Ligurian Units and the underlying Tuscan tectonic units and incorporated into the shear zones. In the geological map we distinguish main bodies of rocks of “Ligurian” origin (SV_{li}: limestones, shales, etc.), main bodies of shales and marls of probable Tuscan Domain origin, mainly from the Modino Unit (SV_{tu}: Marmoreto Marls, Fiumalbo Shales, etc.), and main slivers of turbiditic sandstones of Tuscan origin (SV_{ar}: Monte Cervarola Sandstones, Monte Modino Sandstones, etc.). This tectonic unit occurs above the Modino Unit and the Cervarola Unit in the Tuscan-Emilia Apennines.

Shear zones

During Miocene time, the Tuscan Domain experienced underthrusting, emplacement of tectonic units, with development of shear zones along tectonic contacts and later, during the late Miocene-Pliocene, it experienced exhumation and tectonic denudation. Usually, fault rocks along these shear zones are cataclasites or greenschist facies mylonites. At the scale of the geological map these shear zones usually cannot be mapped, notable exceptions being the shear zones in the Cerreto-Secchia Valley area and the Libro Aperto shear zone, in the Emilia-Tuscany Apennines.

The Cerreto Pass - high Secchia Valley area attracted the attention of many Authors during the years because it is the only area in the Northern Apennines where scattered slivers of highly deformed medium grade metamorphic rocks outcrop closely juxtaposed with non metamorphic rocks of the Tuscan Succession (Calcare Cavernoso with anhydrite levels, Oligocene-Miocene sandstones, etc.) and shales and limestones of Ligurian origin (Baldacci *et alii,* 1967a; Krampe, 1969; Di Sabatino *et alii,* 1979; Andreozzi *et alii,* 1987; Chicchi *et alii,* 2002; Costa *et alii,* 2002; Leoni & Pertusati, 2003; Lugli *et alii,* 2002; Molli *et alii,* 2002; Bonini *et alii,* 2013a; Lo Pò *et alii,* 2018). We interpret this area as an outcrop, in the form of an antiformal tectonic window, of a thick shear zone. It developed along a regional low-angle normal fault during the final stages of exhumation and core complex formation in this part of the Northern Apennines, during late Miocene-early Pliocene. The normal fault cuts the Ligurian and Tuscan units, so slivers of rocks of different paleogeographic origin are now found side by side.

Sheared rocks outcrops moreover along the Libro Aperto shear zone (Cornamusini *et alii,* 2018; Conti *et alii,* 2019), a main shear zone along the Cervarola Unit/Tuscan Nappe thrust between M. Cimone and Pistoia, probably active during early-middle Miocene (Burdigalian-Langhian).

In these shear zones rocks of different ages and origin are juxtaposed, we mapped: rocks derived from Ligurian formations (SE_{li}), main slivers of Monte Modino Sandstones and Monte Cervarola Sandstones (SE_{ar}), main slivers of Fiumalbo Shales and Marmoreto Marls (SE_{fi}), main outcrops of cataclasites with dolomite and limestone clasts ("Calcare Cavernoso") and slivers of metamorphic rocks (SE_{cv}).

Magmatic rocks

In the Northern Apennines magmatic rocks of different ages are present in various tectonic units and in different tectonic or stratigraphic settings: Ordovician magmatic rocks are present in the Variscan basement of the Tuscan Metamorphic Unit, Triassic pillow lavas in the Middle Triassic succession of the Tuscan Domain, ultramafic rocks, gabbros and basalts of Jurassic age are present in the Ligurian Units, Neogene-Quaternary intrusive and effusive rocks occur in the hinterland of the chain (Tuscany, Latium and small outcrops in Umbria). All the Paleozoic-Mesozoic magmatic rocks have been described in the sequences where they are incorporated and are discussed in the framework of the geodynamic evolution of the relative domains, in this section we discuss only the Neogene-Quaternary magmatic rocks.

After tectonic phases of shortening and nappe emplacement, and contemporaneous with regional extension, magmatic activity took place in the Tyrrhenian side of the Apennine orogen. This resulted during Neogene and Quaternary in the emplacement of plutonic, volcanic and pyroclastic rocks now outcropping in the Tuscan Archipelago, central and southern Tuscany, and northern Latium (Fig. 13). These magmatic rocks will be illustrated in this section, for an in-depth discussion refer to the exhaustive review works of Serri *et alii* (1991); Innocenti *et alii* (1992); Serri *et alii* (2001); Peccerillo (2002); Conticelli *et alii* (2004); Poli (2004); Peccerillo & Frezzotti (2015); Marroni *et alii* (2015a) and Peccerillo (2017). Tuscany hosts moreover an important metallogenic province that is related to magmatism, with mineralization at Elba, in southwestern Tuscany (Colline Metallifere), and at Monte Amiata. Important quantities of iron, lead, copper, zinc, silver, antimony, mercury, and gold, have been extracted until a few decades ago (Tanelli & Lattanzi, 1986; Dini, 2003).

Most of the magmatic rocks belong to the "Tuscan Magmatic Province", that extends from the Tuscan Archipelago to the Tuscan mainland and northern Latium (Tolfa-Manziana area). The Tuscany Magmatic Province consists of various intrusive and extrusive bodies ranging from mafic to felsic in composition and from calcalkaline to ultrapotassic lamproitic. Ages range from about 8.5 Ma (Elba Island) to 0.3 Ma (Monte Amiata), and decreases eastward from the Tuscan Archipelago to the southern Tuscany mainland as a result of eastward migration of backarc crustal extension. Silicic magmas are polygenetic and have been formed by crustal melting, mixing between crustal anatectic and minor amounts of mafic melts, and fractional crystallization. Mafic melts originated in the mantle but resemble closely some upper crustal rocks (trace elements, radiogenic isotope signatures). The particular composition of these magmas reveals sources consisting of upper mantle rocks that underwent contamination by subducted upper crustal rocks, such as metapelites during Tertiary "Alpine" and "Apenninic" subduction processes.

Plutonic rocks (γ) outcrop in the Elba Island (monzogranite stock with aplites and pegmatites), Montecristo Island (monzogranite stock with aplites), Giglio Island (multiple monzogranite intrusions, aplites and pegmatites), Campiglia Marittima (monzogranite to alkali-feldspar granite, mostly beneath surface), Gavorrano (monzogranite to alkali feldspar granite) and in some hidden intrusion below surface (monzogranites, syenogranites, granodiorites: Larderello, Campiglia, Gavorrano).

Volcanic and subvolcanic rocks (β) are present as silicic and mafic volcanic centres. Silicic volcanic centres are present at San Vincenzo (lava flows and domes with calcalkaline peraluminous rhyolites), Roccastrada (dome and pyroclastic deposits with trachydacites to high-silica rhyolites), Monte Amiata (silicic lava flows and domes with trachydacites and minor olivine-latites and shoshonites). Mafic volcanic and subvolcanic centres are present at Capraia Island (remnants of a large stratovolcano formed mainly of calcalkaline andesites and dacites lavas, with final shoshonitic basalts), Montecatini Val di Cecina (phlogopite-rich plug with high-silica lamproites), Orciatico (mafic hypabyssal body, with high-silica lamproites), Radicofani (mafic neck and remnants of lava flows with basaltic andesites to shoshonites), Torre Alfina (mafic necks and lava flows with high-silica lamproites).

In the southernmost part of the geological map volcanic rocks belonging to the Roman Province occur. This part of the Roman Province consists of two large volcanic complexes, the Vico and Monti Vulsini volcanic complex. In the Monti Vulsini volcanic complex some minor complexes can be distinguished: the Latera,

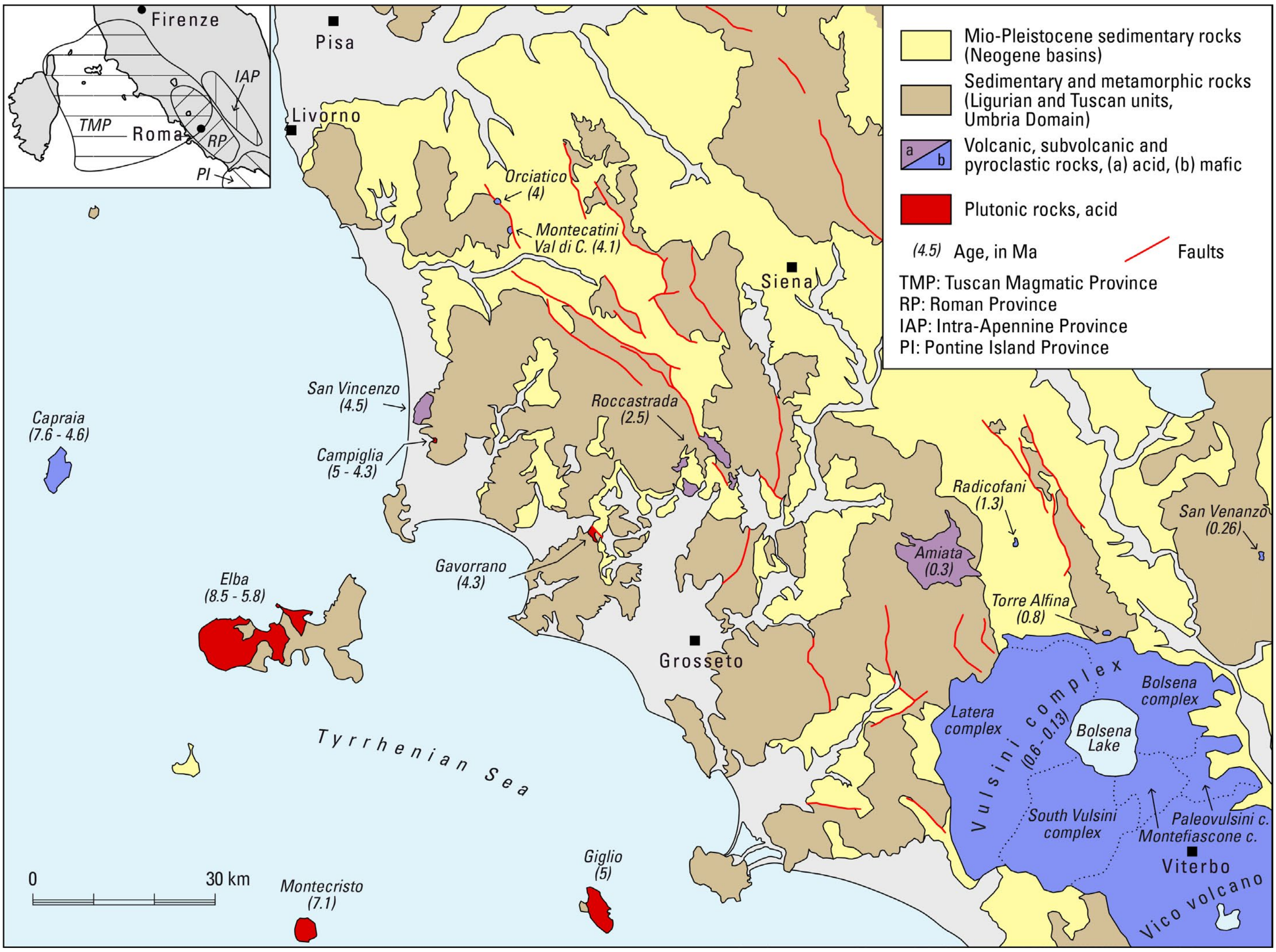

Fig. 13 - Magmatic provinces and distribution of Neogene-Quaternary magmatic rocks in Tuscany and Northern Latium. Ages after Peccerillo (2017), volcanic complexes in the Roman Province after Vezzoli *et alii* (1987), modified.

Bolsena, Paleovulsini, Montefiascone and South Vulsini complexes (Fig. 13), with preserved calderas and cones. In the Vulsini complex (0.6 - 0.13 Ma) prevailing rocks are pyroclastic (fall deposits, ignimbrites, surges) and minor lavas with potassic to ultrapotassic affinity, undersaturated in silica (trachybasalt to trachyte, leucitite and leucite tephrite to phonolite). Major and trace element variations for the Vulsini rocks point to an evolution dominated by fractional crystallization starting from different types of parental melts.

The Intra-Apennine Province is only represented in the geological map by the small outcrops of San Venanzo and surroundings in Umbria (San Venanzo, 0,26 Ma, Polino 0,25 Ma, Acquasparta 0,39 Ma and Colle Fabbri 0,8 Ma). The San Venanzo volcanic field includes three distinct eruptive vents: San Venanzo (maar), Pian di Celle (tuff-ring) and Celli (tuff cone) (Zanon, 2005). Pyroclastic rocks predominate (fall, flow and surge deposits), with olivine-melilitite lava flows. A complex mechanism of compression, mantle eviction and normal faulting could be responsible for the San Venanzo magmatism (Peccerillo, 2017).

SYNTHESIS OF THE TECTONIC EVOLUTION

The successions outcropping in the Northern Apennines experienced the following tectonic phases, from the oldest:

1) Variscan phases, related to the building of the Variscan chain during the Carboniferous;
2) Jurassic extension related to the opening of the Piedmont-Ligurian ocean;
3) Ligurian phases (Late Cretaceous-Paleogene) that led to the formation of the Ligurian prism;
4) Tuscan phases (early Miocene), that led to metamorphism and nappe emplacement in the Tuscan Domain;
5) Miocene-Quaternary tectonics of the Tyrrhenian margin;
6) Miocene-Recent tectonics in the Umbria-Marche-Romagna Apennines.

Variscan phases

Rocks of Paleozoic age are documented in the Tuscan Domain and outcrop at Punta Bianca, the Alpi Apuane, Pisani Mountains, Monticiano-Roccastrada Ridge, eastern Elba Island, Romani Mountains and also in the subsurface of the Larderello-Travale geothermal area and in the Pontremoli area. Due to the bad quality of the outcrops, their limited extensions and the overprint of the Alpine deformations, regional correlations are problematic and the Variscan tectonic evolution it is still a matter of debate.

The Alpi Apuane area shows the best mappable outcrops of Paleozoic rocks and tectonic structures related to the Variscan orogeny (CONTI *et alii,* 1991b), with synclines with Devonian rocks at the core. No absolute age dating is available for Variscan deformation in this area, but based on correlation with the Sardinia Variscan basement, an early Carboniferous (Visean) age is assumed. This is also supported by the presence of non-conformable non-metamorphic successions of Carboniferous age in southern Tuscany (LAZZAROTTO *et alii,* 2003).

In the other areas of Tuscany where Paleozoic rocks crop out shear zones, regional-scale schistosity, mylonitic foliation, tectonic mélanges, etc. have been studied (CONTI *et alii,* 1991a; BERTINI *et alii,* 1994; PANDELI *et alii,* 1994; BATINI *et alii,* 2003; FRANCESCHELLI *et alii,* 2004; PANDELI *et alii,* 2005b; LO PÒ *et alii,* 2016a, b, 2018). The Variscan age for these features is documented by isotopic dating (BORSI *et alii,* 1967; DEL MORO *et alii,* 1982; MOLLI *et alii*, 2002; MUSUMECI *et alii,* 2011), but their regional correlations are difficult.

JURASSIC EXTENSION

Extension related to the rifting phase that will lead to the opening of the Piedmont-Ligurian Ocean started affecting the Adria continental margin in the Early Jurassic (Sinemurian), as results of first opening stages of the central Atlantic. This is documented by dismembered carbonate platform sequences of the Tuscan Domain and in the Umbria-Marche Succession (BERNOULLI & JENKYNS, 1974; BERNOULLI *et alii,* 1979; CENTAMORE *et alii,* 1986; CIARAPICA & PASSERI, 1998; BOSELLINI, 2004, and references therein).

In the Middle Jurassic ongoing rifting led to the formation of the Adria and Europe passive continental margins. Rifting was probably asymmetric, with simple shear kinematics along a major detachment dipping below the European margin (LEMOINE *et alii,* 1987; STAMPFLI *et alii,* 1991; MARRONI *et alii,* 1998; MANATSCHAL & BERNOULLI, 1999; MANATSCHAL, 2004). This led to the formation of the two continental margins (Europe: upper plate, Adria lower plate) that had two very different stratigraphic evolution during the Jurassic (Fig. 4a).

At the end of Middle Jurassic rifting evolved into spreading, with formation of the Piedmont-Ligurian oceanic basin (Fig. 4b), a slow-spreading mid-ocean ridge system with oceanic lithosphere of reduced thickness, serpentinized mantle peridotites, gabbro bodies, basalts with intercalated sedimentary ophiolitic breccias (monogenic, polygenic and ophicalcites, DECANDIA & ELTER, 1972; ABBATE *et alii,* 1980; BORTOLOTTI *et alii,* 2001).

No oceanic crust younger than Late Jurassic is found in the Northern Apennines, and no volcanic activity or syn-sedimentary deformation is testified in Lower Cretaceous-Santonian rocks. The Late Jurassic marks, therefore, the end of spreading in the Piedmont-Ligurian Ocean (MARRONI *et alii,* 1992; PRINCIPI *et alii,* 2004).

It is worth mention finally that earlier rifting phases of Middle Triassic (Ladinian) age are proposed to have affected the Tuscan Domain with development of continental-shallow marine basins with alkaline basalts (“aborted rift” of Punta Bianca, Massa: PASSERI, 1985; RAU *et alii,* 1985; STOPPA, 1985; MARTINI *et alii,* 1986). This interpretation is still a matter of debate as in the southern Alps Ladinian basins with volcanic rocks (pillow lava basalts, etc.) are instead interpreted to be related with regional strike-slip tectonics (DOGLIONI, 1984; BLENDINGER, 1985; MASSARI, 1986). Probably similar process affected the External Ligurian Domain of southern Tuscany, with the occurrence of Lower Cretaceous alkaline basalts (BRUNACCI *et alii,* 1983; FARAONE & STOPPA, 1990; BROGI *et alii,* 2000).

LIGURIAN PHASES

The term “Ligurian phases” (ELTER, 1973) is often used with different meanings in the geological literature of the Northern Apennines. It is here used with its original meaning, i.e. a comprehensive term to indicate all the tectonic phases affecting the Ligurian Units from the Late Cretaceous to the middle Eocene, when closure of the Piedmont-Ligurian Ocean and complete subduction of oceanic crust occurred. The complicated internal structure of the Ligurian Units led to the development of many different reconstructions during the years to explain their tectonic evolution, often with very contrasting views. It is now widely accepted that deformation of the Ligurian Units is linked first with a Late Cretaceous-middle Eocene “Alpine” east dipping oceanic subduction (Fig. 4c) and then with a late Eocene-Quaternary west dipping “Apenninic” subduction (Fig. 4d, BOCCALETTI *et alii,* 1971; ELTER & PERTUSATI, 1973; DOGLIONI, 1991; MARRONI *et alii,* 2010; MOLLI & MALAVIEILLE, 2011; MARRONI *et alii,* 2017).

The presence of a tectonically active “double-vergent” accretionary wedge in the Late Cretaceous is testified by debris with ophiolite blocks in the Internal Ligurian Domain and in the External Ligurian Domain (Inner Succession) (Fig. 4b). This elevated area that separated the Internal and External successions was postulated since the first studies in the Ligurian Apennines (“Ruga del Bracco” of ELTER & RAGGI, 1965). The accretionary wedge incorporated during this stage mainly material of the Piedmont-Ligurian oceanic domain (mantle, oceanic crust and oceanic sedimentary cover).

Ongoing subduction led to thickening of the accretionary wedge through continuing incorporation of oceanic crust. As no sedimentary rock of age younger than middle Eocene is documented in the Internal Ligurian units incorporated in the Ligurian prism, middle Eocene is usually regarded as the age of the closure of the Piedmont-Ligurian Ocean. Deformation did not stop at this stage and continuing convergence between Europe and Adria caused the deformation of the Outer Succession of the External Ligurian Domain (Fig. 4d). During this stage portion of the External Ligurian Domain (Antola Unit) are emplaced above Internal Ligurian units.

End of oceanic crust subduction, closure of Piedmont-Ligurian Domain and inclusion in the accretionary wedge are marked by deposition of the Epiligurian Succession started at the middle-late Eocene. Close to the continental collision, the deformation is at this time transferred eastward producing an early Apennine orogenic prism with foredeep deposits (Fig. 4d). The sedimentation developed at this time therefore in two different settings: a) over the Ligurian units in wedge-top basins (Epiligurian Succession); b) at the front of the Ligurian prism, within a migrating foredeep basin.

Tuscan phases

During Oligocene-Aquitanian time ongoing convergence and W-dipping subduction caused foredeep development to affect more external areas of the Adria continental margin, with siliciclastic turbidite deposits of the Monte Modino Sandstones (outcropping in the Modino Unit), of the Macigno Fm. (belonging to the Tuscan Nappe) and of the Pseudomacigno Fm. (now part of the Tuscan Metamorphic Unit), and following Cornamusini *et alii* (2018), also of the innermost part of the Mt. Cervarola Sandstones (Torre Amorotti System, Fig. 14). According to the above authors, turbiditic sedimentation stopped in all these basins in the late Aquitanian. Based on this evidence, the Burdigalian is considered to mark the inception of the "Tuscan phase", during which the Ligurian prism was emplaced onto the turbidite basins of the Tuscan Domain, leading to the end of sedimentation. Several different models have been proposed over the years concerning the paleogeographic position of successions, the kinematics and the timing of their tectonic evolution, specially concerning the original position of the Monte Cervarola Succession, in some reconstruction placed in a more internal position, next to the advancing Ligurian orogenic front (Andreozzi, 1991; Chicchi & Plesi, 1991; Plesi *et alii*, 2000; Plesi, 2002a; Tinterri & Piazza, 2019).

During the Tuscan Phase is documented emplacement and deformation of the Ligurian and Subligurian units, the Modino Unit, the Tuscan Nappe and the Internal Cervarola Unit (Fig. 14b), all with top-NE tectonic transport direction. Along the boundary between the Ligurian prism and the Adria margin a thick shear zone developed, which corresponds to the Sestola-Vidiciatico Unit (Remitti *et alii*, 2007; Vannucchi *et alii*, 2008), active until the early Serravallian. However, it is important to point out that extensive and often contrasting literature exists about timing of deposition and deformation for the successions outcropping in the Emilia-Tuscany Northern Apennines, as well as different interpretations for the origin and emplacement (tectonic vs. sedimentary) of the Ligurian complexes interposed with turbidite systems in this area. This led over the years to various paleogeographic reconstructions, basin evolution and tectonic settings for the Tuscan successions of the area (Dallan Nardi & Nardi, 1972; Plesi, 1975a; Sagri, 1975; Martini & Sagri,

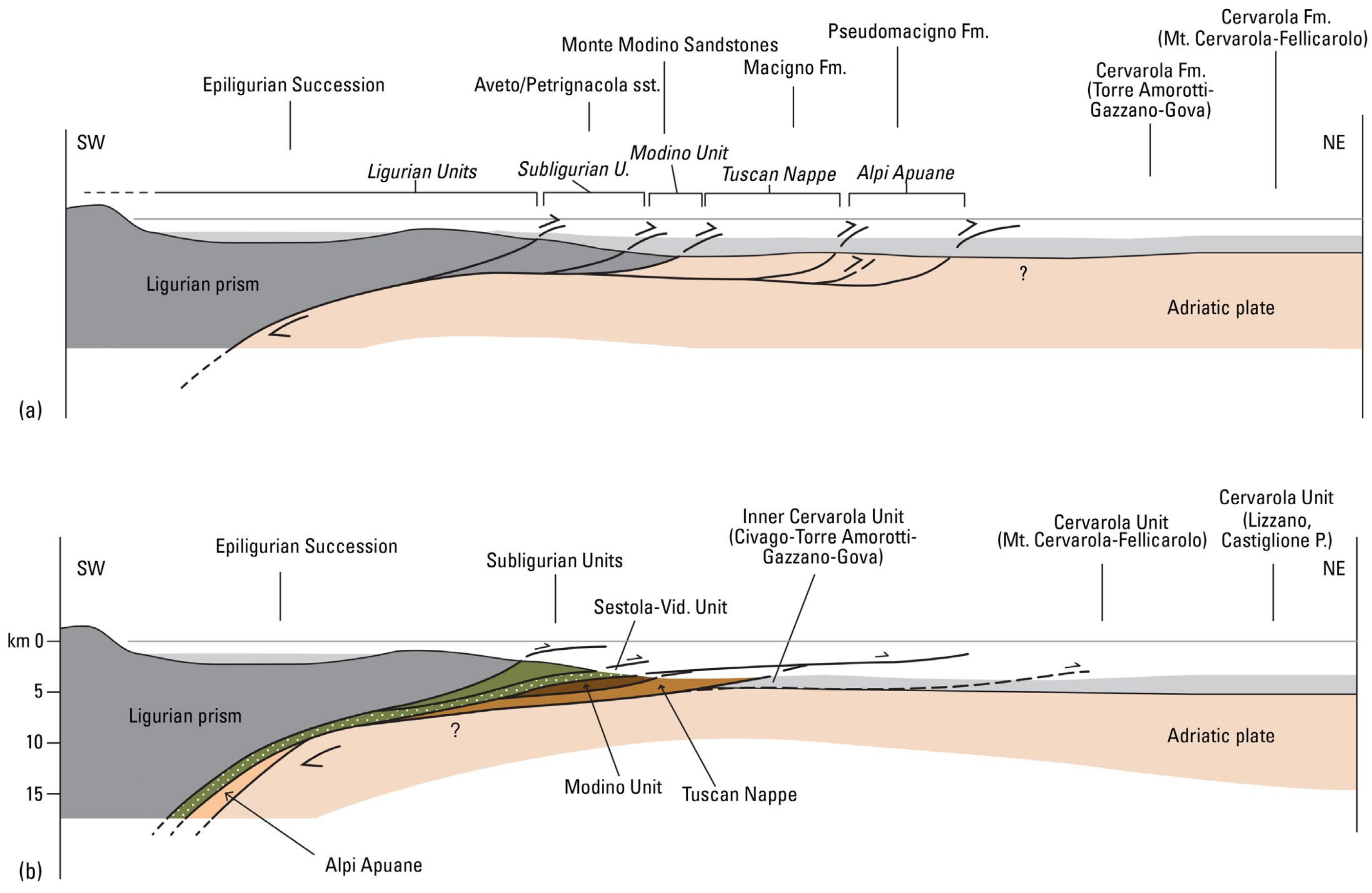

Fig. 14 - (a) Paleogeographic reconstruction for Subligurian and Tuscan units of the Tuscan-Emilia Northern Apennines during flysch deposition (Chattian-Aquitanian). (b) Tectonic units develop- ment during the Tuscan phase (Burdigalian). The Sestola-Vidiciatico Unit developed as a shear zone between the Ligurian prism and the Adria Plate, incorporating rocks of "Ligurian" and "Tuscan" origin.

1977; Abbate & Bruni, 1987; Bettelli *et alii,* 1987a; Martini & Plesi, 1988; Chicchi & Plesi, 1991; Bruni *et alii,* 1994; Bettelli *et alii,* 2002b; Botti *et alii,* 2002; Cerrina Feroni *et alii,* 2002b; Plesi *et alii,* 2002a; Vescovi, 2005; Lucente & Pini, 2008; Cornamusini *et alii,* 2018; Conti *et alii,* 2020; Tinterri & Piazza, 2019).

Moreover, during this phase, the subducted portion of the Adria crust experienced high-pressure metamorphism (HP units in central-southern Tuscany) and greenschist facies metamorphism (Tuscan Metamorphic Unit: Alpi Apuane, etc.), with development of km-scale folding, regional foliation, and NE-SW oriented stretching lineation (Carmignani *et alii,* 1978; Carmignani & Kligfield, 1990; Jolivet *et alii,* 1998). In the Modino Unit, Tuscan Nappe and Cervarola Unit, metamorphism is much lower than in the Tuscan Metamorphic Unit (sub-greenschist facies, anchizone facies), as internal deformation and strain, and all primary features of rocks are preserved. Antiforms and synforms are however developed in the Modino Unit, Tuscan Nappe and Cervarola Unit, with locally overturned limbs. During the late Burdigalian probably later stages of shortening led to the final emplacement of the Tuscan Nappe above the central part of the Cervarola Unit (Libro Aperto shear zone) and to the development of km-scale open folds in the frontal part of the Tuscan Nappe (Conti *et alii,* 2019, with references therein). For more information about the tectonics of the Tuscan Domain refer also to the works of Trevisan (1962); Baldacci *et alii* (1967b); Boccaletti *et alii* (1980); Cerrina Feroni *et alii* (1983); Reutter *et alii* (1983); Bettelli & Panini (1991); Decandia *et alii* (1993); Elter & Sandrelli (1994); Boccaletti & Sani (1998); Bernini & Papani (2002); Zattin *et alii* (2002); Liotta *et alii* (2015).

Miocene-Quaternary tectonics in the Tyrrhenian margin

Starting from the early-middle Miocene, due to slab retreat, the Apennine compressional front migrated eastward, so the tectonic regime progressively changed in the hinterland (northern Tyrrhenian Sea and Tuscany) from compressional to extensional, with termination of thrusting and tectonic units emplacement (Jolivet *et alii,* 1990, 1998; Carmignani *et alii,* 1995a; Brunet *et alii,* 2000). This phase produced in the inner Northern Apennines widespread extensional tectonics and exhumation (Carmignani *et alii,* 1994, 2001, 2004; Doglioni *et alii,* 1999; Brogi, 2004; Brogi & Liotta, 2008) with core complex formation as in the Alpi Apuane area. Extension was also accompanied by widespread late Miocene-Quaternary magmatism deriving from mixing of crustal and mantle sources. Shortening was transferred to more external areas (Umbria-Marche-Romagna Apennines).

In the Alpi Apuane the earlier compressional (D1) structures and tectonic contacts are overprinted by different generations of later structures (D2). The D2 structures are represented by syn-metamorphic, high strain shear zones and well-developed fold systems mainly associated with a sub-horizontal axial planar foliation (S2) of crenulation type, associated with different generations of brittle faults as in Carmignani & Giglia (1979) and Carmignani & Kligfield (1990). Younger late Tortonian-Quaternary evolution produced in the area NW-SE striking normal faulting, which developed graben structure (Garfagnana, Lunigiana) and played a key role in the development of the NW-SE oriented Tyrrhenian coast.

Southern Tuscany, south of the Arno Valley, is characterized by high rates of extension, with the development of structural highs and basins, to be defined as a basin-and-range structural setting (Carmignani *et alii,* 1994; Brogi, 2003; Pauselli *et alii,* 2006; Barchi, 2010). The structural highs are characterized by outcrops of Paleozoic-lower Miocene rocks deformed and metamorphosed during collisional phases, whereas the basins ("Neoautochthonous" basins) are characterized by the infilling of sediments, ranging from Miocene to Pleistocene (Martini & Sagri, 1993; Martini *et alii,* 2001). Central-southern Tuscany shows tectonic features linked to rifting and crustal thinning processes, with a lithosphere thickness estimated to be about 30 km, very high heat flow values and positive Bouguer anomalies (Calcagnile & Panza, 1981; Decandia *et alii,* 1998; Della Vedova *et alii,* 2001).

In southern Tuscany, a first extensional event during middle-late Miocene time developed low-angle normal faults and it was responsible of strong tectonic elision and crustal thinning, forming the so-called "serie ridotta" (Trevisan, 1955; Giannini *et alii,* 1971; Bertini *et alii,* 1991). Starting from late Miocene until Pleistocene time, listric high-angle normal faults cross-cut the previous structures and bounded highly subsiding basins (Baldi *et alii,* 1994; Dallmeyer & Liotta, 1998; Bonciani *et alii,* 2005; Brogi & Liotta, 2008; Barchi, 2010). These basins were also affected by transverse tectonic lineaments, determining the discontinuity of such basins and acting as controlling structures of magmatic activity (Liotta, 1991; Acocella & Funiciello, 2002; Pascucci *et alii,* 2007; Brogi *et alii,* 2010).

A different tectonic framework for the Neogene inner Northern Apennines has been developed by some Authors (Bernini *et alii,* 1990; Bonini & Sani, 2002; Boccaletti *et alii,* 1995, 1999; Sani *et alii,* 2009; Bonini *et alii,* 2013b, 2014), which infer a main compressional tectonics acting in such area. On the base of structural and geophysical data, these Authors consider the role of compressional tectonics as controlling the basin development, as thrust-top basins instead of rift basins, until the late Pliocene-early Pleistocene, when started the extensional tectonics. This different tectonic scenario represents a strongly debated topic that still needs to be definitively resolved.

For more informations about the tectonics of this portion of the Northern Apennines refer also to the works of Decandia (1982); Lavecchia *et alii* (1983); Lavecchia (1985); De Feyter *et alii* (1986); Menichetti & Pialli (1986); Barchi *et alii* (1988); Lavecchia *et alii* (1988); Boccaletti *et alii* (1990a); Calamita (1990); Calamita *et alii* (1991); Bertotti *et alii* (1997); Tavarnelli (1997); Barchi *et alii* (1998b); Pialli *et alii* (1998); Calamita *et alii* (1999); Boncio *et alii* (2000); Lavecchia *et alii* (2003); Picotti & Pazzaglia (2008).

Miocene-Quaternary tectonics in the Umbria-Marche-Romagna Apennines

Evidence from the Tiberina Valley, Casentino, Mugello and Marecchia Valley allow to infer that the Ligurian Units covered almost completely the Northern Apennines, and that their emplacement progressively interrupted the sedimentation of the foredeep successions: in the Serravallian for the Marnoso-arenacea Fm. of the western

Romagna Apennines and in the Tortonian for the eastern Romagna Apennines (Menichetti *et alii,* 1991; Pizziolo & Ricci Lucchi, 1991; Conti, 1994; Landuzzi, 1994; Cerrina Feroni *et alii,* 1997; Barchi *et alii,* 2001). Advancing of Ligurian Units is associated with precursor olistostromes sliding in the foredeep basins.

As recorded in the Marecchia Valley area, emplacement of Ligurian complexes occurred in this portion of the Northern Apennines in the late Messinian and in the early Pliocene, above mainly already deformed successions (Fig. 15). This is evidence for the important tectonic event in the area in the late Messinian, as emphasized by the "intra-Messinian" regional unconformity. The large outcrop of the "Coltre della Val Marecchia" *Auctt.* in the Romagna Apennines was in details investigated over the years and different modes of final emplacement, tectonics vs. gravitational, or mixed, were proposed (Ricci Lucchi & Ori, 1985; Veneri, 1986; De Feyter, 1991; Conti, 1994; Bettelli *et alii,* 1994; Conti & Tosatti, 1996; Lucente *et alii,* 2002; Lucente & Pini, 2008; Cornamusini *et alii,* 2017).

In the westernmost portion of the Umbria-Romagna Apennines the overthrust of the Tuscan Nappe onto the Cervarola-Falterona Unit along top-NE directed thrust planes has been documented, with repeated imbricates of Macigno and Scaglia Toscana fms.

In the Umbria-Romagna-inner Marche area tectonics is characterized by multiple thrust planes developing a complicate imbricate structure involving the Mesozoic cover and the basement (Fig. 16). Thrusts usually developed along the main rheological discontinuities in

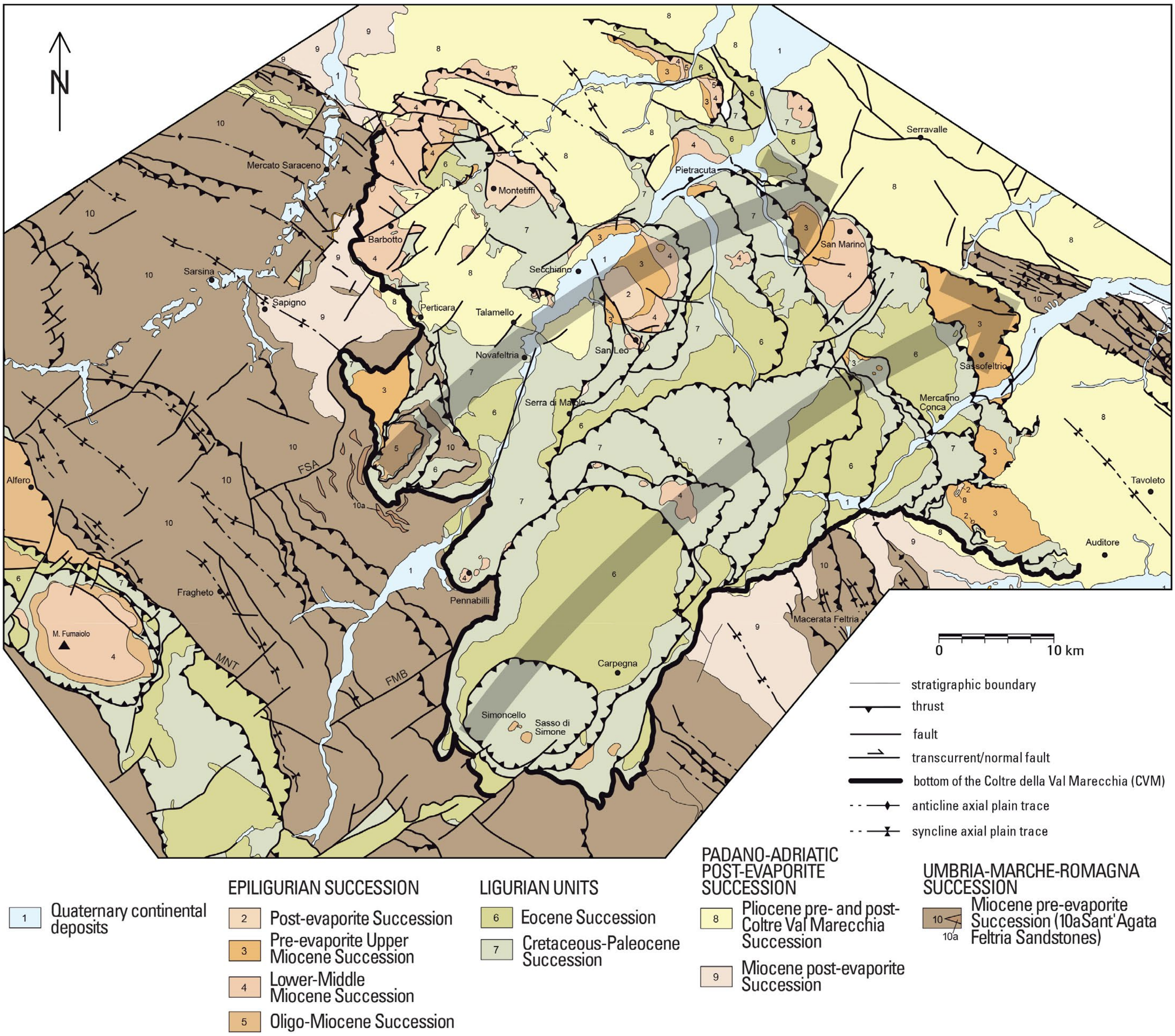

Fig. 15 - Tectonic map of the Val Marecchia area, with evidenced the "Coltre della Val Marecchia" formed by stacked slivers of Ligurian and Epiligurian units. The main tectonic structures as well as the main sedimentary successions are indicated. FSA: Sant'Agata Feltria fault; FMB: Molino di Bascio fault. The gray arrows indicate the two inferred emplacement trajectories. After Cornamusini *et alii* (2017).

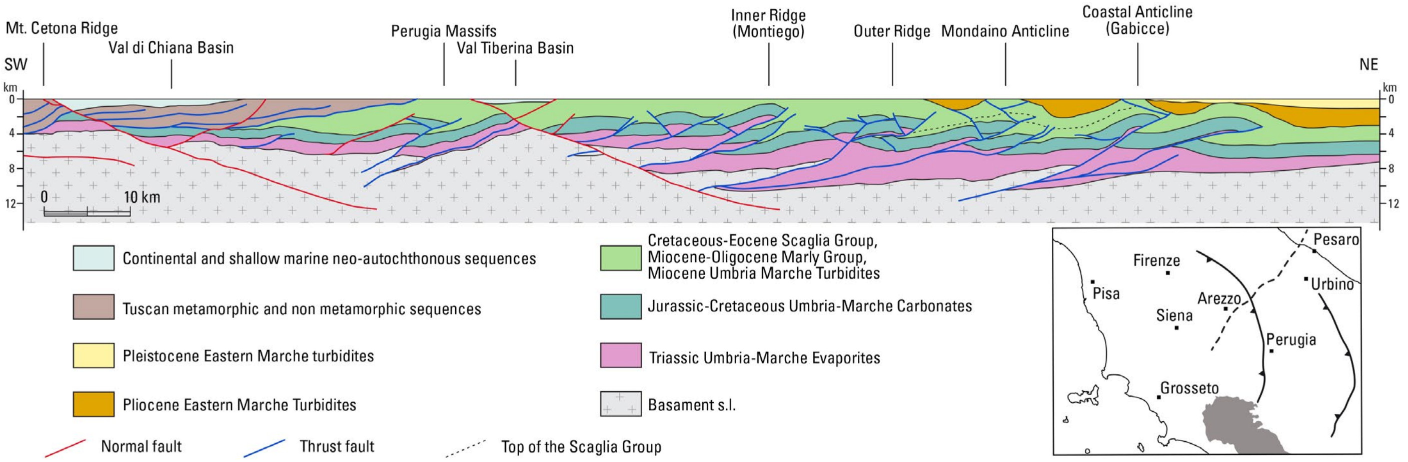

Fig. 16 - Geological cross section from the Mt. Cetona ridge (Tuscany) to the Adriatic Sea, based on interpretation of the seismic reflection line CROP 03; inset: location of the CROP03 section (dashed line), after BARCHI *et alii* (1998a).

the stratigraphic succession, i.e. top of basement, top of the evaporites, within the Marne a Fucoidi Fm., top of the Scaglia Fm. and top of the Schlier Fm. (Fig. 9) and nucleate typical compressional structures (BARCHI *et alii,* 2001; DEIANA & PIALLI, 1994): a) imbricate thrusts and shallow folds detached within the Marne a Fucoidi, Scaglia or Schlier fms; b) box fold anticlines (“carbonate folds” *Auctt.*) and tight synclines nucleating from the Triassic evaporites and affecting the whole Jurassic- Cretaceous carbonate succession, developing the main Umbria-Marche ridges; c) major thrust sheets involving the upper part of the metamorphic basement (basement wedges), with regional longitudinal continuity and that can be responsible for development of major antiformal structures of the area (Inner Ridge and Outer Ridge of Fig. 16).

In the outer Marche, different fold-and-thrust structures can be recognized nucleating within the Triassic evaporites or Messinian deposits, producing main antiformal structures as the Acquasanta Terme-Cingoli-Cesana antiforms, Montagna dei Fiori antiform, Teramo-Bellante-Ortezzano-Montescudo antiforms, Mt. Conero antiform (CENTAMORE *et alii,* 1972; BALLY *et alii,* 1986; ORI *et alii,* 1986; DE FEYTER, 1991; CALAMITA *et alii,* 1995; ORI *et alii,* 1993; DEIANA & PIALLI, 1994; CAPOZZI *et alii,* 1998; DE DONATIS *et alii,* 1998). Similar structures are documented also in the Po Plain area (Monferrato, Emilia and Ferrara folds: PIERI & GROPPI, 1981; CASTELLARIN, 2001) and in the Adriatic offshore (ARGNANI *et alii,* 1991; ORI *et alii,* 1993; ARGNANI & GAMBERI, 1995).

A peculiar tectonic feature of the Northern Apennines is the “Sillaro Line” in the Romagna Apennines, an important transverse lineament whose kinematic significance is still debated, as testified by the large number of works and interpretations. In the years it was interpreted as: a) the original floor thrust of the Ligurian Units onto the Marche Units; b) a right lateral strike-slip zone; c) a shear zone belonging to the Sestola-Vidiciatico tectonic Unit; d) a tear fault developed in response to along-strike variations in the rates of slab rollback (BORTOLOTTI, 1966; DE JAGER, 1979; PATACCA & SCANDONE, 1985; TEN HAAF, 1985; CASTELLARIN & PINI, 1987; BETTELLI & PANINI, 1991; NIRTA *et alii,* 2007; BETTELLI *et alii,* 2012; VANNUCCHI *et alii,* 2012; ROSENBAUM & PIANA AGOSTINETTI, 2015).

Chronology of all these deformation events is constrained by stratigraphic data and allows to recognize (BARCHI *et alii,* 2001) a late Burdigalian age for the emplacement of the Tuscan Nappe onto the inner Umbria-Romagna Succession, whereas a late Serravallian-early Tortonian age is documented for the development of the carbonate folds in the Mt. Martani, Assisi, Gubbio and Verghereto folds, crosscut by later thrusts during early Messinian. The carbonate folds of the outer Umbria developed during early Tortonian-early Messinian time, while those in the inner Marche started developing in the early Messinian. At the same time deformation started in the Laga Basin and the Ferrara folds in the Po Plain subsurface. Acquasanta, Montagna dei Fiori, Cingoli and Monti della Cesana carbonate folds developed in the late Messinian and were cut by thrusts in the early Pliocene. Compression and tectonic activity in the external Adriatic offshore areas started in the Pliocene and continues until present times, as in the Ferrara folds.

The Umbria-Marche area was then affected by extensional tectonics since the late Pliocene, developing continental and shallow marine basins, like the Val Tiberina Basin (Fig. 16). The Val Tiberina Basin is the more important basin of this portion of the Northern Apennines and is related to activity along a NE-dipping low-angle normal fault (BONCIO *et alii,* 1998), which reach a depth of about 12 km. Eastern basins (Colfiorito, Norcia, etc.) have minor extension and younger ages, as witnessed by present-day seismic activity, documented to occur along normal faults bordering the basins (BONCIO & LAVECCHIA, 2000; BROZZETTI *et alii,* 2009; CHIARALUCE *et alii,* 2005; BARCHI, 2010).

FINAL REMARKS

We present here an overview of the geology of the Northern Apennines and a new geological map (scale 1:250,000) based on geological maps at 1:10,000 scale produced by Geological Services of the Emilia-Romagna, Marche, Tuscany and Umbria. This map represents the first product of a larger project aimed to produce a common geological map at 1:10,000 scale for all the above regions. The map (GIS vector data and raster) is freely available from: https://www.geological-map.it.

For the compilation of the map we employed the most consolidated and shared geological interpretations for the different paleogeographic domains and tectonic units of the Northern Apennines. The Ligurian Domain is divided in Internal and External domains; the External Domain is further divided in two successions, an Inner Succession and an Outer Succession. All these units and successions represent different paleogeographic domains in the Jurassic-Cretaceous paleogeography of the Tethys Ocean and adjoining area.

The Subligurian Domain is considered a paleogeographic domain which can be identified from the Paleocene until the middle Eocene, with an Oligocene earliest Miocene succession deposited on the deformed accretion prism. The Subligurian Units, together with the Sestola-Vidiciatico Unit represent the main zones where subduction of Adriatic crust occur, with development of a "subduction channel" now evidenced by thick shear zones.

The successions of the Tuscan Domain were deformed in different tectonic units, originating from different portion of the Adria plate: a) the Pseudoverrucano Unit (regarded as the paleogeographically more internal unit); b) the Modino Unit (tectonically placed above the Tuscan Nappe); c) the Tuscan Nappe; d) the Tuscan Metamorphic Unit; e) The Cervarola-Falterona Unit; f) the Rentella Unit (a transitional unit between the Tuscan Domain and the Umbria-Marche Domain). Rocks derived from the Tuscan and the Ligurian domains were offscraped during subduction and locally experienced HP metamorphism.

The Umbria-Marche Domain is the more external domain of the Adria plate and shows a complete Triassic-Miocene Succession. The upper part of the succession shows different age in the inception of turbidite deposition and we distinguish a Siliciclastic succession of the inner basin and a Siliciclastic succession of the intra-Apennine minor basins and outer basins.

The top of the deformed Ligurian Units was covered by the Epiligurian Succession (Eocene-Miocene) that in the Po Plain Adriatic margin stratigraphically passes to the Messinian evaporite, post-evaporite and Plio-Pleistocene successions. In the Tyrrhenian margin a succession of Miocene-Pleistocene age developed, testifying extension and basin infilling in central-southern Tuscany, accompanied by magmatic processes.

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