

Geological Field Trips and Maps

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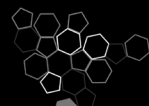
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The geological structure of the Emilia-Tuscany Northern Apennines and Alpi Apuane

**Gruppo Italiano di Geologia Strutturale – Riunione Annuale GIGS 2018, Centro di Geotecnologie,
San Giovanni Valdarno (AR), 12-14 giugno 2018**

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Cover page Figure: Panoramic view of the northern Alpi Apuane, view toward NE. Antona-Arni road, near Passo del Vestito.

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Abstract

The aim of this excursion is to give a concise but complete picture of the evolution of the Italian Northern Apennines in the Tuscany and Emilia-Romagna regions and in the Alpi Apuane area. This excursion-book includes a short outline of the stratigraphic and tectonic evolution of units cropping out in the Northern Apennines and the description of itineraries and stops.

The excursion is divided in two days:

- a) the first day is dedicated to the tectonics of the Emilia-Tuscany Northern Apennines in the area of Abetone, Pievepelago, Radici Pass, discussing the relationships between the Tuscan Nappe, the Modino unit and the Cervarola units;
- b) the second day will focus on the tectonics of the Alpi Apuane Metamorphic Complex, and in more detail structures developed in the central part of the Alpi Apuane, with examples of superposition of compressional and extensional uplift-related structures.

We wish you an interesting and enjoyable excursion!

Key words: Northern Apennines, Oligocene-Miocene, turbidite systems, foredeep, Sestola-Vidiciatico unit, structural evolution

INFORMATION

General information

Emergency contact numbers, hospitals and first-aids

112 - Carabinieri

113 - Police

115 - Fire Department

118 - First Aid

- Guardia Medica - Servizio di Continuità Assistenziale, Via Adolfo Ferrari, 22 - 41027 Pievepelago (MO), phone 0536 309800

- Hospital Pacini, Via Pacini, San Marcello Pistoiese (PT), phone 057363401
- Hospital Santa Croce, Via dell'Ospedale, 3, Castelnuovo Garfagnana (LU), phone 0583970000

Accommodation

There are several hosting structures, as hotel, guesthouse, bed and breakfast, private rooms, camping.

Field trips summary

1st day - Tectonics and stratigraphy of the sedimentary foredeep basins and units of the Emilia-Tuscany Northern Apennines.

Significance: the itinerary, subdivided in five stops (Fig. 1), allows a significant view of the relationships between the Tuscan Nappe/Cervarola unit/Modino unit, as well as to have a frame of the kinematic evolution of the involved tectonic units. The itinerary focuses on panoramic views allowing a general knowledge of the geological setting of this crucial sector of the Northern Apennines and detailed outcrop views, allowing the recognizing of important details concerning the structural and stratigraphical-sedimentological structures.

In particular:

- the Stop 1.1 shows the relationships between Tuscan Nappe and Cervarola unit, and the Libro Aperto shear zone;
- the Stop 1.2. shows the M. Modino succession, the relationships between the M. Modino sandstone and the M. Modino "basal complex", and the Tuscan Nappe and Modino unit tectonics;
- the Stop 1.3 shows the deformation of tectonic units overlying the Modino and Cervarola units, as well as of the Sestola-Vidiciatico unit;
- the Stop 1.4 shows the deformation in the Libro Aperto Shear zone, the relationships between the Modino unit/Cervarola unit/Sestola-Vidiciatico unit;
- the Stop 1.5 shows the deformation in the frontal parte of the Tuscan Nappe, the later thrusting of tectonics units, the relationships with Modino unit and Sestola-Vidiciatico unit, and finally a panoramic view of the Garfagnana graben and Alpi Apuane Metamorphic Complex.

2nd day – The Alpi Apuane geology

Significance: the itinerary, divided in eight stops (Fig. 1), runs across the southern part of the Alpi Apuane, showing panoramic view and outcrop details of the structure and tectonics of the Alpi Apuane Metamorphic Complex, the exhumation and uplift of metamorphic units, the relationships with overlying units, and finally the microfabric development in marbles.

In particular:

- the Stop 2.1 shows the features of the Calcare Cavernoso: cataclastic rocks at the top of the metamorphic units;
- the Stop 2.2 shows the tectonic contact between the Tuscan Nappe and the "Autoctono" unit in the Eastern Alpi Apuane;
- the Stop 2.3 shows mylonitic cherty limestones;
- the Stop 2.4 shows deformation features in the Pseudomacigno;
- the Stop 2.5 shows a panoramic view toward the northern Alpi Apuane and their geological structure;
- the Stop 2.6 shows the core of the Tambura anticline;
- the Stop 2.7 shows deformed marble breccias, D1 structures and relationships with early D2 deformation; non-cylindric folds; marble meso- and microstructures, flanking-folds;
- the Stop 2.8 shows deformed marble breccia, the origin of brecciation and structures of the Cervaiole area, the Palaeozoic basement rock types and finally quarrying technology.

For people interesting in run the field trip, the following guide-books could be also of interest: Carmignani et al. (1987); Bettelli et al. (1987); Bortolotti (1992); Bruni et al. (1992); Carmignani et al. (1993); Molli G. (2002); Carmignani et al. (2004); Molli (2012); Remitti et al. (2012).

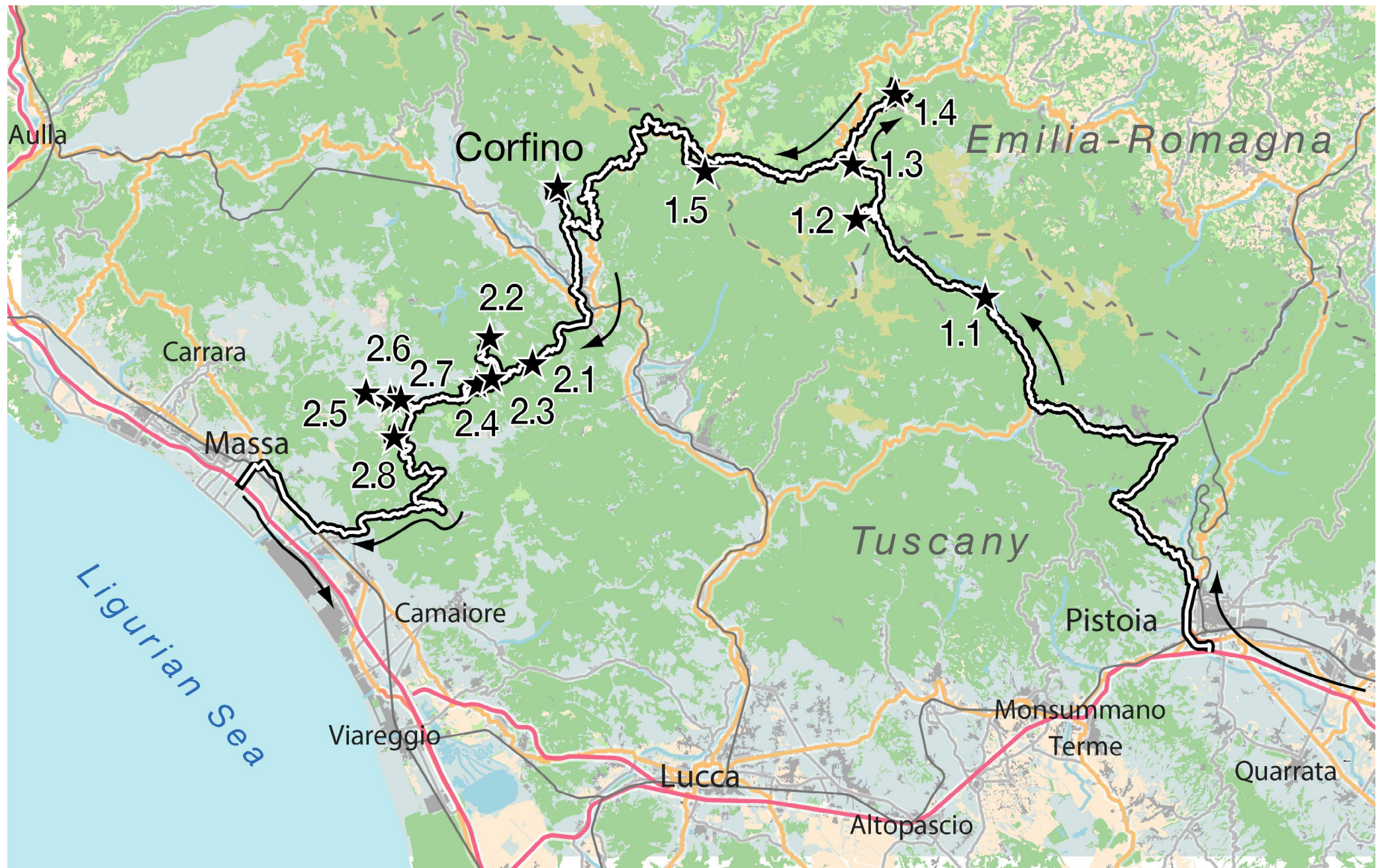


Fig. 1 – Itinerary of the field trip, with stops.

Geological setting of the Emilia-Tuscany Northern Apennines

The Northern Apennines are an orogenic belt with fold-thrust structures developed during the collisional phase, that took place from the Cenozoic, with the eastwards advancement and thrusting of the Ligurian units onto the Tuscan-Umbria units (see Figs. 2, 3 and Fig. 4).

The Ligurian units derive from the deformation of the Ligurian-Piedmont Ocean (Alpine Tethys) during the Cretaceous-Paleogene tectonic phases, well documented also in the Alps (Trümpy, 1975; Frisch, 1979, Schmid et al. 2008, Handy et al. 2010). The Tuscan-Umbria units derive from the deformation of the continental margin of the Adria (Apulia) plate, involving the Variscan basement and its Permian- to Cenozoic cover (Carmignani et al., 2004, and references therein). The progressive convergence motion between the European and Adria plates

led to the total subduction of the oceanic crust (Ligurian-Piedmont Ocean) and to the continental collision at the middle-late Eocene. The collision was followed by the thrusting eastwards of the Ligurian units on to the Tuscan-Umbria units (Elter, 1973; Vai and Martini, 2001). Starting from the middle-late Miocene, the back-arc region was involved in the rifting process, leading to the extension forming the Tyrrhenian Sea and affecting the Northern Apennines; the following processes developed, as the eastwards migration of subduction and foreland basins, the extensional tectonics forming back-arc basins (Boccaletti et al., 1971; Kligfield, 1979; Principi and

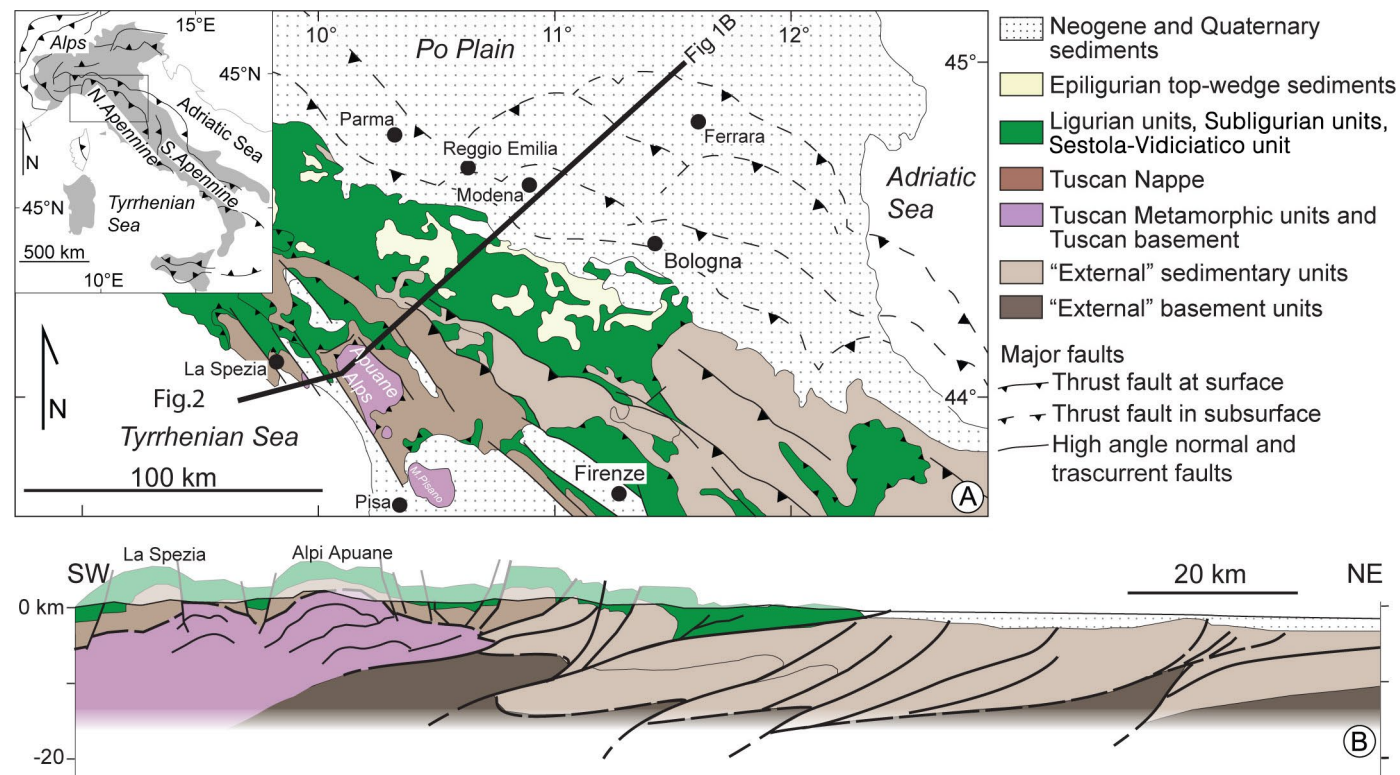


Fig. 2 - Tectonic map of the Northern Apennines, with schematic cross section. After Molli (2008).

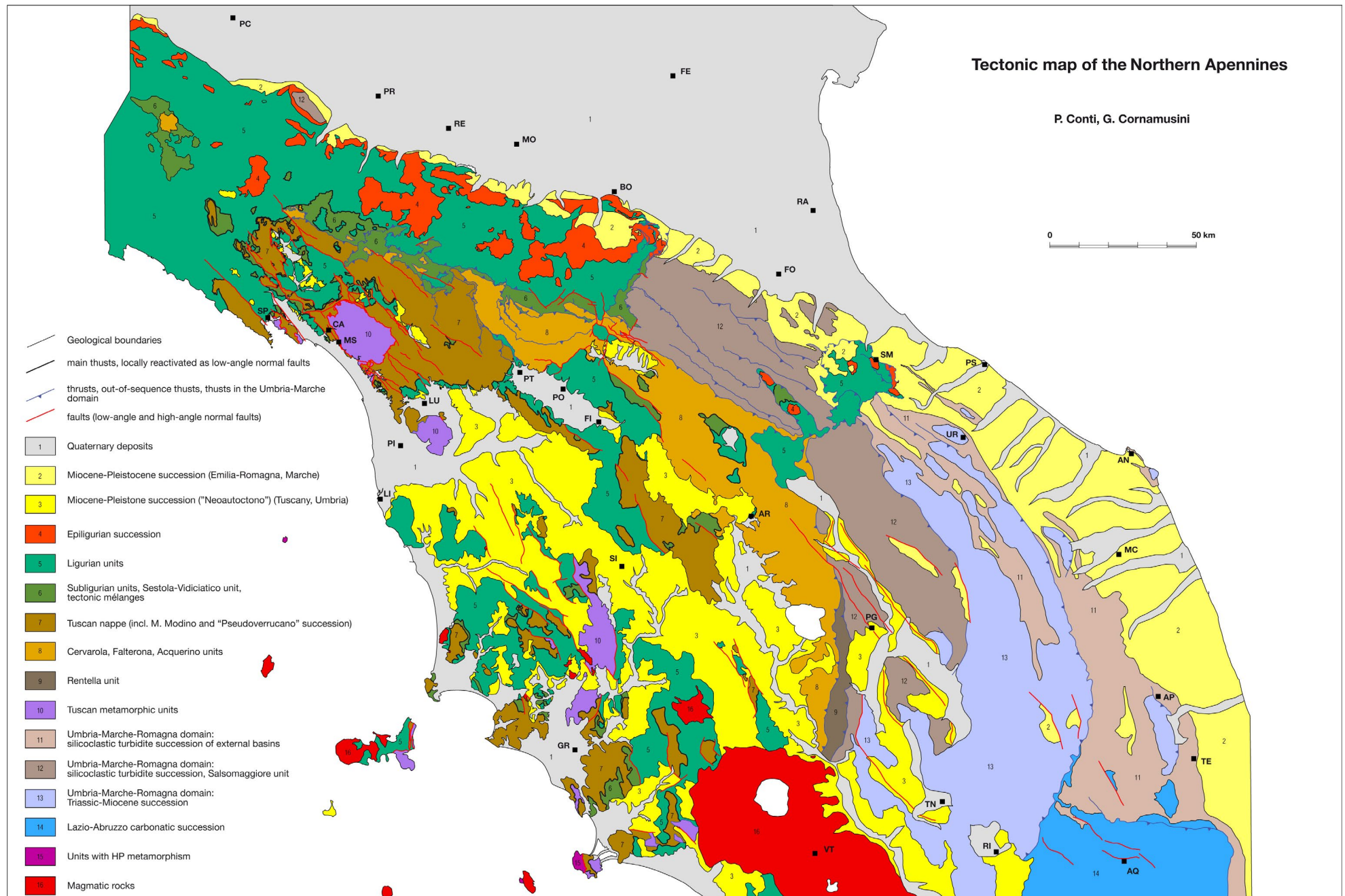


Fig. 3 - Tectonic map of the Northern Apennines.

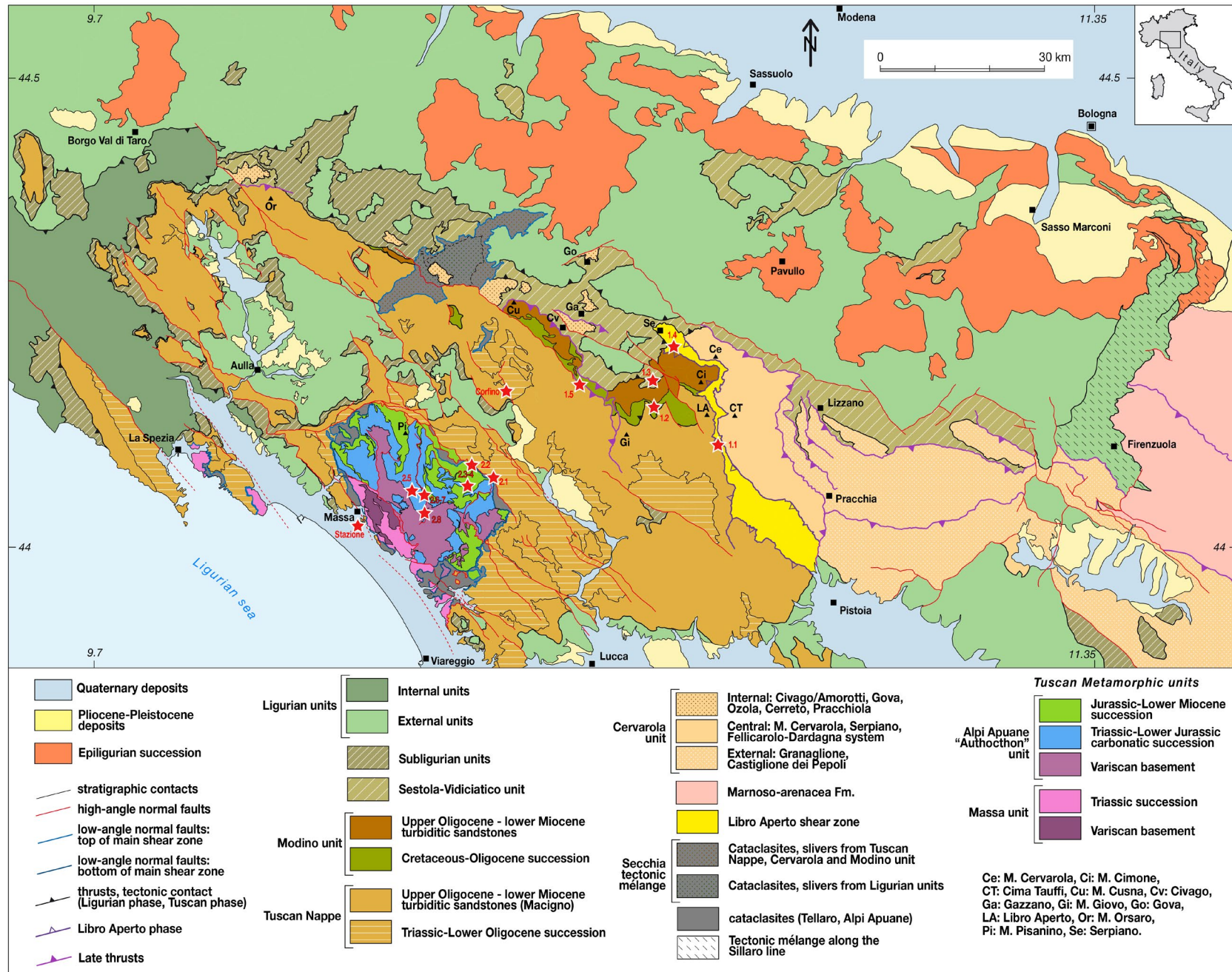


Fig. 4 - Sketch map of the Emilia-Tuscany Northern Apennines, with stops (in red).



Treves, 1984; Jolivet et al., 1998; Carmignani et al., 2001, 2004; Vai and Martini, 2001; Argnani, 2002; Molli, 2008; Marroni et al., 2010; Molli and Malavieille, 2011; Cornamusini and Pascucci, 2014, and references therein). The general tectonic stacking pattern for the study area is formed by some main tectonic units as follows (from top to bottom):

- a) the Ligurian units;
- b) the Sestola-Vidiciatico and Subligurian units;
- c) the Modino unit;
- d) the Tuscan Nappe;
- e) the Cervarola unit;
- f) the Tuscan metamorphic units (Alpi Apuane).

The relative position of tectonic units is shown in Fig. 5. The Ligurian units cropping out in the study area (not investigated here) are represented by highly deformed sedimentary successions, consisting of Helminthoid flysch deposits and sedimentary mélanges with blocks of ophiolite rocks belonging to the External Ligurian Domain (Marroni et al., 2001; Argnani et al., 2006).

The Sestola-Vidiciatico unit represents a complex and highly deformed unit, about 500 m thick, well described in Remitti et al. (2007) and in Vannucchi et al. (2008), that interpret it as a main regional shear zone developed in the Miocene during the continental collision between the European and Adria plates. The Sestola-Vidiciatico unit consists of a tectonic melange, formed by deformed tectonic slivers, and derived by the detachment and incorporation into the shear zones. Such tectonic slivers were from the overriding Ligurian units and underlying tectonic units, as the Modino unit, Subligurian units, Tuscan Nappe and inner Cervarola unit). The Sestola-Vidiciatico unit is laterally replaced towards northwest, along a belt from Alpe di Cerreto to Pracchiola, by the Subligurian unit (Elter et al., 2003; Vannucchi et al., 2012). The Subligurian unit represents a high deformed unit, formed by Upper Cretaceous to Eocene limestones and shales, and by Oligocene sandstones (Plesi et al., 1998; Catanzariti et al., 2002), deposited within a transitional paleogeographic setting, intermediate between the Adria Plate and the oceanic crust (Elter et al., 1964; Boccaletti et al., 1980).

The Modino unit represents a highly discussed unit, due to its unclear relationships with other units, both in stratigraphic and tectonic features (see in Chicchi and Plesi, 1991). The basal and lower part of the unit consists of a strongly deformed complex of Cretaceous Helminthoid Flysch (with Ligurian affinity), unconformably overlain by: Eocene- Oligocene shales, marls and marly limestones (Fiumalbo shale and Marmoreto marl), in turn overlaid by and arenaceous turbidite deposits of Mt. Modino sandstone. The Modino unit results to be now

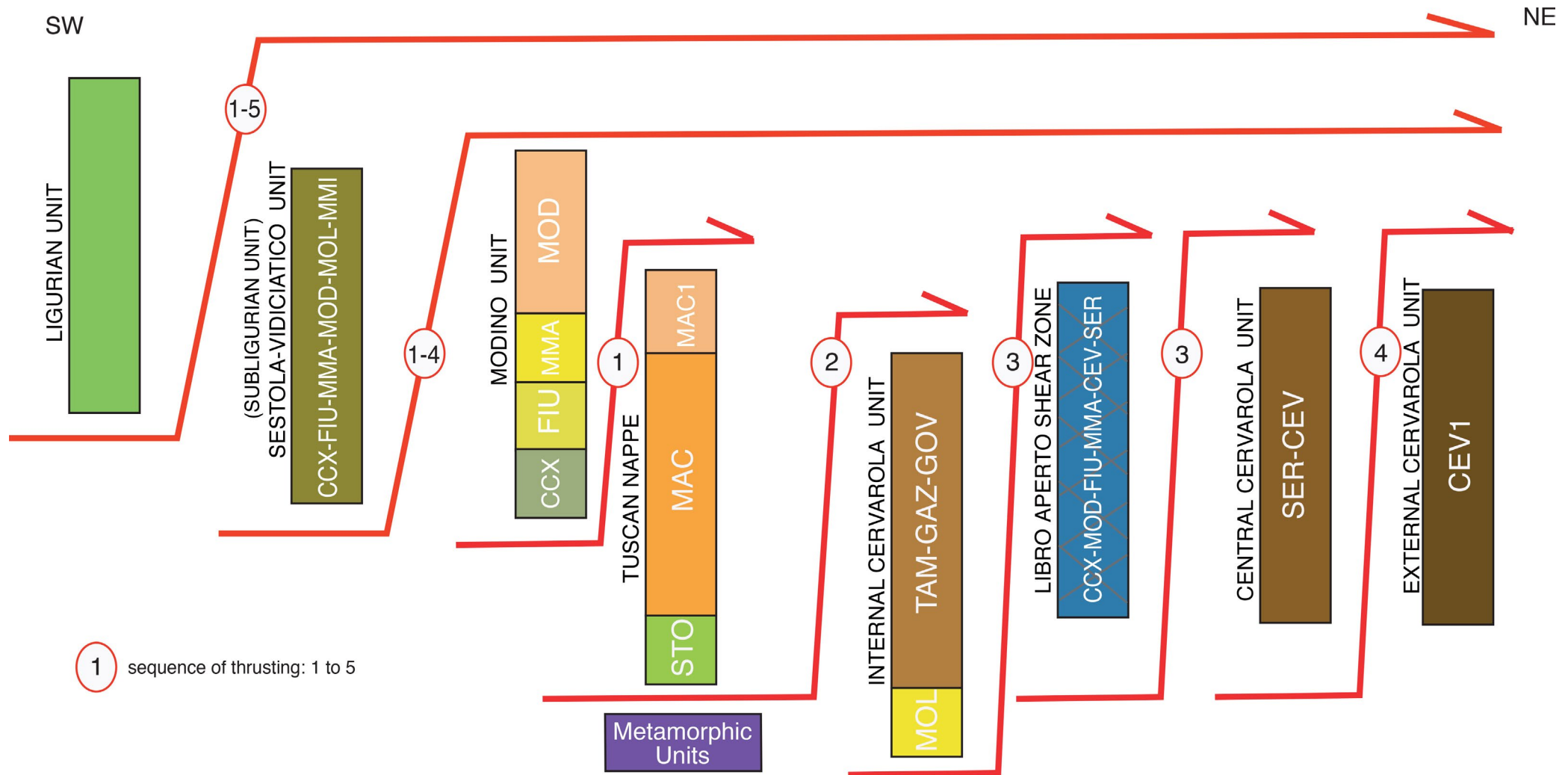


Fig. 5 - Tectonic units in Emilia-Tuscany Northern Apennines and their relative relationships. CCX-Chaotic Complex (Cretaceous); FIU-Fiumalbo shale (Bartonian-Rupelian); MMA-Marmoreto marl (Rupelian-Chattian); MOD-Modino Sandstone (Chattian-Aquitainian); MOL-Oligocene marlstones (Rupelian-Chattian); MMI-Lower Miocene marlstones - Civago Marl (Aquitainian); STO-Scaglia Toscana (Paleocene-Oligocene); MAC-Macigno sandstone (late Rupelian-Aquitainian); MAC1-Macigno thin-bedded sandstones (Chattian-Aquitainian); TAM-Torre Amorotti Sandstone-GAZ-Gazzano Sandstone-GOV-Gova Sandstone (Chattian-Aquitainian); SER-Serpiano sandstone (Aquitainian); CEV-Mt. Cervarola Sandstone (Chattian-Burdigalian); CEV1-Mt. Cervarola Sandstone - Granaglione-Castiglione dei Pepoli system (Burdigalian-Langhian).

overthrust above the Tuscan Nappe tectonic unit.

The Tuscan Nappe unit crops out extensively in the Northern Apennines, forming a long belt from the Ligurian Apennines to the Tiberina Valley. It consists of a thick sedimentary succession, which shows great variability in thickness and facies, depending by the regional areas, due to its strong synsedimentary tectonics relationships (Fazzuoli et al., 1985; Cornamusini et al., 2012; Conti et al., 2019). The Tuscan Nappe succession ranges in age from Triassic to early Miocene, with an evaporite-calcareous-shaly succession and a thick turbidite sandstone succession (Macigno) at the top.

The Cervarola unit, consisting of a thick arenaceous turbidite succession (Mt. Cervarola Sandstone), crops out for a wide areas along the Northern Apennines, from the studied area to the Trasimeno Lake in Umbria. Moreover, the Civago Marl of the study area, is considered to be the unit's stratigraphic base (Ghelardoni et al., 1962); outside the study area, the Villore Shale fm. (varicoloured shale) is regarded as the base of the Mt. Cervarola Sandstone.

The metamorphic units outcrop in the Alpi Apuane area and consist of a Cambrian to lower Miocene succession, deformed in greenschist facies metamorphism. The succession is similar to the Tuscan Nappe succession.

Previous works and interpretations

As previously introduced, this sector of the Northern Apennines represents a crucial sector for to understand the framework and the evolution of the orogen. It is due to the complex relationships among the several units and to their relatively good outcrops, so to stimulate intense and long time debate within the geological literature. The main debated points are respect to: the palinspastic position of the Modino and Tuscan Nappe - Cervarola units and their relative locations; the nature of their boundaries (tectonic vs. stratigraphic), as well shown by the comprehensive overview of the different interpretations by Chicchi and Plesi (1991).

The first paper, showing a modern and total geological model of the Northern Apennines framework is represented by the fundamental paper of Merla (1951). To follow, several investigations were performed along the Emilia-Tuscany Northern Apennines, as Nardi (1965) and Baldacci et al. (1967), and than by geologists from Berlin University (Günther and Rentz, 1968; Reutter, 1969; Günther and Reutter, 1985). They thought a single, albeit complicated, stratigraphic succession for the Modino-Cervarola succession.

To resume, the intense literature debate concerning the stratigraphic and structural relationships of the Modino unit, has produced two main end-member different interpretations, that are current still today. They can be



shortly explained as follow:

- a) the Mt. Modino sandstone lies stratigraphically on to the Macigno of the Tuscan Nappe, through the interposition of a thick gravitational chaotic complex called "Monte Modino Olistostrome" (Abbate and Bortolotti, 1961; Nardi, 1965; Baldacci et al., 1967; Martini and Sagri, 1977; Boccaletti et al., 1980; Abbate and Bruni, 1987; Lucente and Pini, 2008);
- b) the Mt. Modino sandstone lies tectonically on to the underlying Macigno, through the interposition of a tectonic basal complex formed by tectonic slices of Ligurian l.s. terms (Reutter, 1969; Plesi, 1975; Martini and Plesi, 1988; Bettelli et al., 1987; Chicchi and Plesi, 1991; Cerrina Feroni et al., 2002; Plesi, 2002).

Recent investigations in the Emilia-Tuscany Northern Apennines (Cornamusini et al., 2018) reveal a complex setting of stacked units, where the arenaceous-marly successions are part of different tectonic units. In particular, whereas the Macigno belongs to the Tuscan Nappe, the Mt. Modino sandstone, the Marmoreto marlstone and the Fiumalbo shale belong to the Modino unit or occur as tectonic slices incorporated within the Sestola-Vidiciatico unit or the Libro Aperto Shear Zone (Fig. 6).

Differently, the marly-arenaceous successions of the Torre Amorotti system (Torre Amorotti, Gazzano, Ozola, Cerreto), the Gova system (Gova Sandstone and Pracchiola Sandstone), and the Fellicarolo-Dardagna system (Mt. Cervarola Sandstone), as well as the lower Miocene marlstones (i.e. Civago Marl), are all part of the Cervarola unit. Tectonic slices of Mt. Cervarola Sandstone and of marlstones have been recognized within the Libro Aperto Shear Zone and in the Sestola-Vidiciatico unit.

Geometrical and age relationships of all these successions allow us to reconstruct the stratigraphic evolution and the deformation of this sector of the Northern Apennines. During the Oligocene-Miocene time-span, the system was diachronous with a progressive eastwards migration of the basin depocentres (linked with the eastwards migration of Apennine subduction) (Argnani and Ricci Lucchi, 2001). It is also clear that the foredeep basin system was complex and subdivided into some cohabiting and coeval basins that progressively underwent deactivation and cannibalization by the advancing orogenic wedge and by the contemporaneous development of new basins towards the foreland.

The Macigno turbidite system represents the first large foredeep system settled onto the Adria microplate during the late Oligocene-early Miocene, and its paleogeographic setting and stratigraphic-structural, as well as provenance relationships are well defined (Costa et al., 1992; Di Giulio, 1999; Cornamusini, 2004a, b). Differently, the Mt. Modino turbidite system still does not have a well constrained setting (see models in Chicchi and Plesi 1991 and Bettelli et al. 2002b).

In this regard, the following evidence can be summarized:

a) The Mt. Modino sandstone lies conformably on a marly-shaly succession (Marmoreto marl and Fiumalbo shale, respectively), which spans from the Lutetian to the late Chattian (Catanzariti and Perilli, 2009; Marchi et al., 2017), and has lithological and chronostratigraphical similarities with the marly-shaly succession lying below the Macigno, such as the Rovaggio Marl and the Scaglia Toscana.

b) The field relationships clearly show the tectonic superposition of the Mt. Modino sandstone (with Fiumalbo shale and Marmoreto marl at the base) onto the Macigno, as is well evident in the Mt. Modino - Mt. La Nuda - Fiumalbo - Mt. Cimone area, through the interposition of a chaotic complex containing Ligurian-derived blocks and slices coming from the accretionary wedge.

c) The chaotic complex at the base of the Mt. Modino succession is formed by slices and clasts derived from the Ligurian units (Bettelli et al., 1987; Abbate and Bruni, 1987; Chicchi and Plesi, 1991; Perilli, 1994; Puccinelli et al., 2009; Marchi et al., 2017), indicating the adjacency of a deformed Ligurian unit stack.

d) The age of the Mt. Modino sandstone, which is referable to the MNP25b-MNN1c-d interval (late Chattian to Aquitanian) (Plesi et al., 2000; Plesi, 2002; Botti et al., 2011; Catanzariti and Perilli, 2009), corresponds with that of the Macigno Fm.

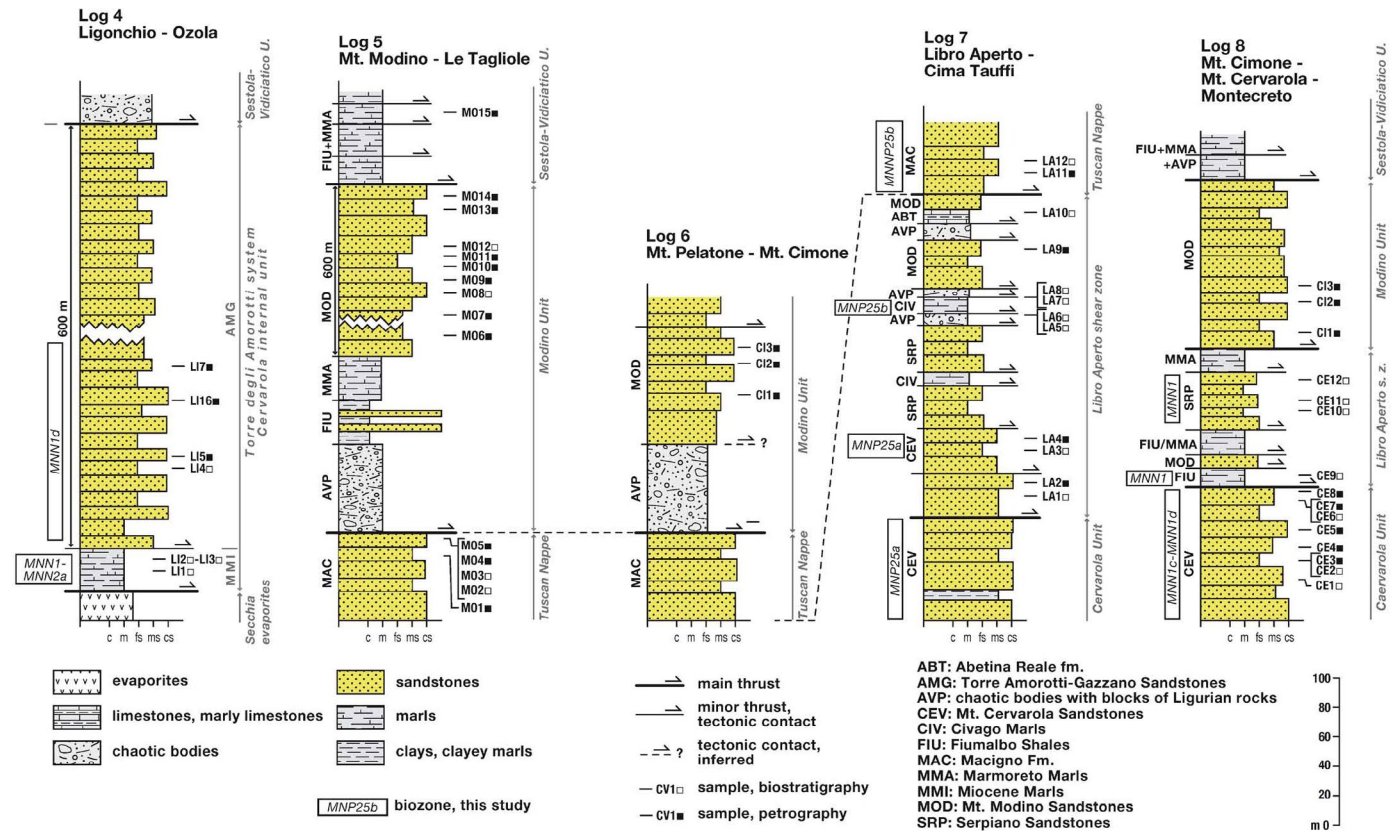


Fig. 6 - Stratigraphic logs in the Ligonchio, M. Modino and Abetone area (after Cornamusini et al., 2018).



- e) The petrographic features of the Modino sandstone show some differences with the sandstone of the Macigno Fm. and the Mt. Cervarola Sandstone type-area, as also emphasized in the literature data (Bruni et al., 1994a).

The Macigno and the Mt. Modino sandstone formations should therefore represent two different, but very similar, turbidite systems, as the lithological, sedimentological and architectural data seem to show (Abbate and Bruni, 1987; Bruni et al., 1994a). The petrographical data indicate a similar provenance, changing only in minor components such as carbonate grains, albeit in small quantities for the Mt. Modino sandstone (Bruni et al., 1994b; Valloni and Zuffa, 1984). As the two turbidite successions are almost coeval, with the only age discrepancy concerning an older base for the Macigno, the two turbidite systems had settled very close each other. This is also strengthened by the strong lithological affinities between the Paleogene marly-shaly successions lying below each of the two turbidite formations. Furthermore, the evidence suggests that the Cenozoic Mt. Modino succession lies on a chaotic Ligurian-derived complex, whereas the Macigno-Scaglia Toscana succession lies on a Triassic-Cretaceous series belonging to the Adria continental margin (see in Fazzuoli et al., 1985; Cornamusini et al., 2012; Ielpi and Cornamusini, 2013; Conti et al., 2019). This implies that the Mt. Modino succession, although deposited close to the Macigno, was settled in a more internal basin or portion of basin located on the advancing orogenic wedge.

During the sedimentation of the Mt. Modino sandstone and Macigno, more external minor sub-basins developed, with the sedimentation of the Torre degli Amorotti-Gazzano turbidite system, adjacent to the more external sub-basin of the Gova system.

The turbidite deposits of the Torre degli Amorotti - Gazzano system have few lithostratigraphic differences to the Mt. Modino system. The sedimentological and petrographical features are indeed very similar, which does not enable an easy distinction to be made between them in the field (Andreozzi, 1991; Mezzadri and Valloni, 1981; Andreozzi and Di Giulio, 1994). Differently, the Gova turbidite system shows more marked differences, both sedimentological and petrographical. In particular, the Gova succession with respect to the other more internal successions shows a lower sandstone/mudstone ratio, is richer in marlstone, and has thinner bedding and carbonate-rich sandstone; the beds are also more intensely bioturbated, with abundant horizontal and vertical trace fossils.

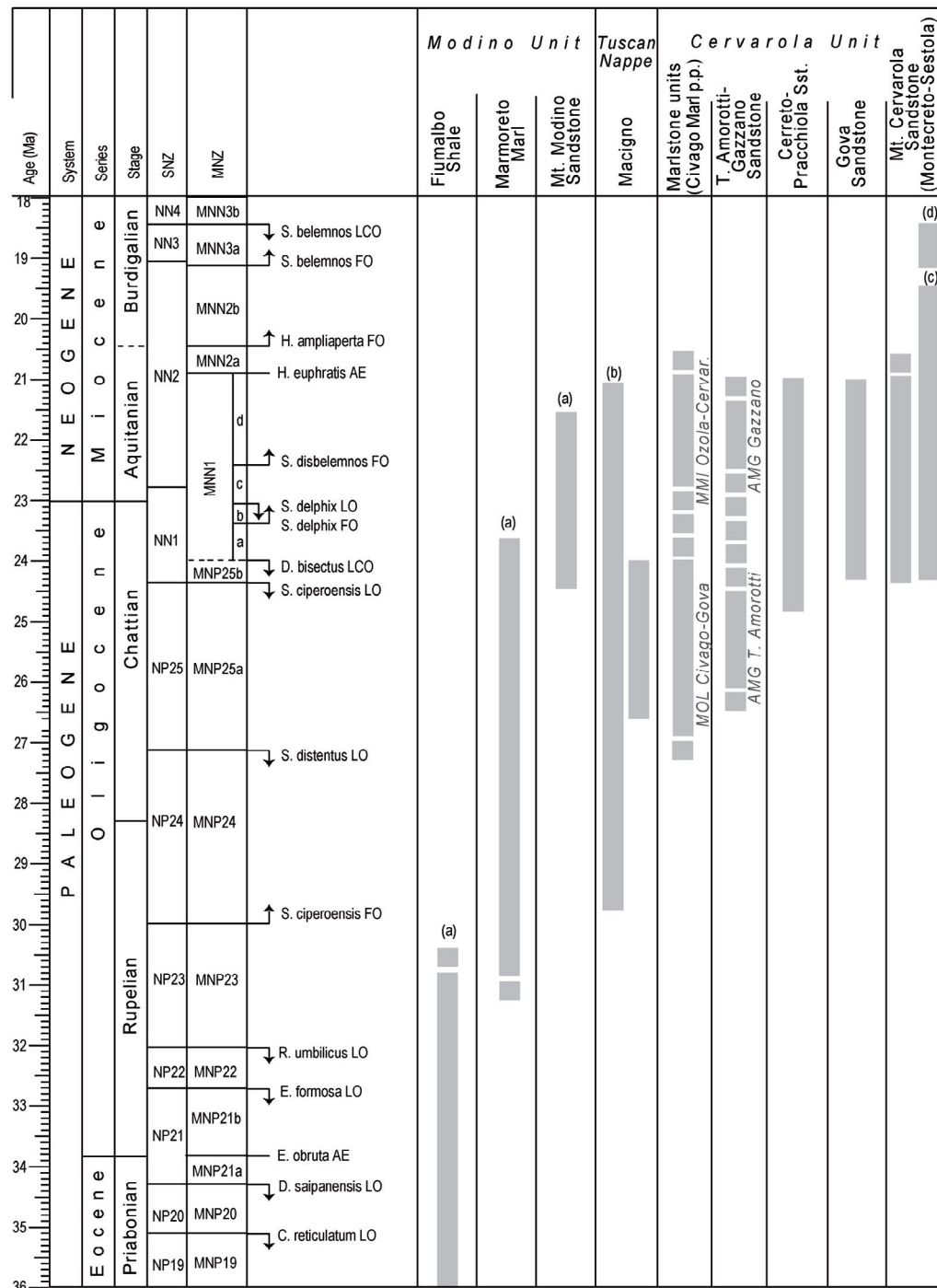
The more external turbidite system of the Mt. Cervarola area has been defined as the Fellicarolo-Dardagna turbidite system, belonging to the major and wider Cervarola turbidite complex (Günther and Reutter, 1985; Andreozzi, 1991; Andreozzi et al., 1995; Botti et al., 2002; Piazza, 2016; Tinterri and Piazza, 2019). The

sandstone has sedimentological and petrographical features that are similar to those of the Gova system and are rich in carbonate content and marly beds. It started its deposition during the latest Chattian- Aquitanian (Fig. 7), which is later than the other systems, meaning a later activation of a more external sub-basin. The Fellicarolo-Dardagna system fully developed during the late Aquitanian, contemporaneously with the closure of the innermost Mt. Modino system (Fig. 7), due to the advancing orogenic wedge. This development continued during the Burdigalian. At this time, due to the increase in the deformation and shortening rate, the inner sub-basins closed and the respective turbidite sedimentation deactivated, with external migration of the basin system and the development of other sub-basins belonging to the outer Mt. Cervarola complex (Fellicarolo-Dardagna, Castiglione dei Pepoli, Granaglione systems: Andreozzi, 1991; Andreozzi et al., 1995; Botti et al., 2002; Plesi, 2002; Valloni et al., 2002).

The basin model development presented here fits well in the migration basin concept of Ricci Lucchi (1986) and Argnani and Ricci Lucchi (2001), which provides the progressive migration in time and space of the foredeep depocentres toward the foreland. It also explains well the complex field relationships between the different turbidite successions and marly successions that represented: the hemipelagic sedimentation anticipating the turbidite systems; and the sedimentation in structural highs separating the sub-basins. The structuration of the foredeep of the Northern Apennines in migrating sub-basins could also explain some differences in composition and, consequently, in provenance, as testified by the different petrofacies and lithofacies.

The marlstones belong to two main lithostratigraphic units, as the Marmoreto marl of Oligocene age and the so-called Civago Marl of Early Miocene age. They revealed two main different geological settings, occurring both in the studied area: a) at the base of turbidite deposits, the Mt. Modino sandstone and the Mt. Cervarola Sandstone respectively; b) as tectonic slices both on top of the turbidite successions, and particularly within the Sestola-Vidiciatico unit, often highly deformed. In our opinion, these marlstones deposited either: before the turbidite sedimentation lying below the sandstone successions; and laterally of the respective turbidite systems, on structural/morphological highs separating the turbidite sub-basins. These two types of depositional setting well explain the positions of the marlstone successions, either stratigraphically below or tectonically on top of the sandstone units, or their occurrence in the form of tectonic slices within shear zones close to thrust fronts.

Specifically, the marlstone depositional unit of the Torre degli Amorotti-Civago log (MOL in Figs. 5, 7 and Fig. 8), which lies below the sandstone depositional units (AMS-AMG), is time-equivalent to the Marmoreto marl,



as well as the marlstones tectonically overlying the Gova Sandstone and the Pracchiola Sandstone in the Pracchiola window (Marra Marl of Zanzucchi, 1963). Differently, the younger marlstone units deposited in structural highs (MMI in Figs. 5, 7 and Fig. 8), and occurring in the Ligonchio area and tectonically on top of the Gazzano Sandstone, are time-equivalent with the Civago Marl of the literature. In the study area does not outcrop the stratigraphic base of the Cervarola Sandstones, due to tectonic elision. We agree with Bettelli et al. (2002a) and Benini et al. (2014) and consider the Marne di Villore, outcropping in eastern areas, the stratigraphic base of the Cervarola turbidites.

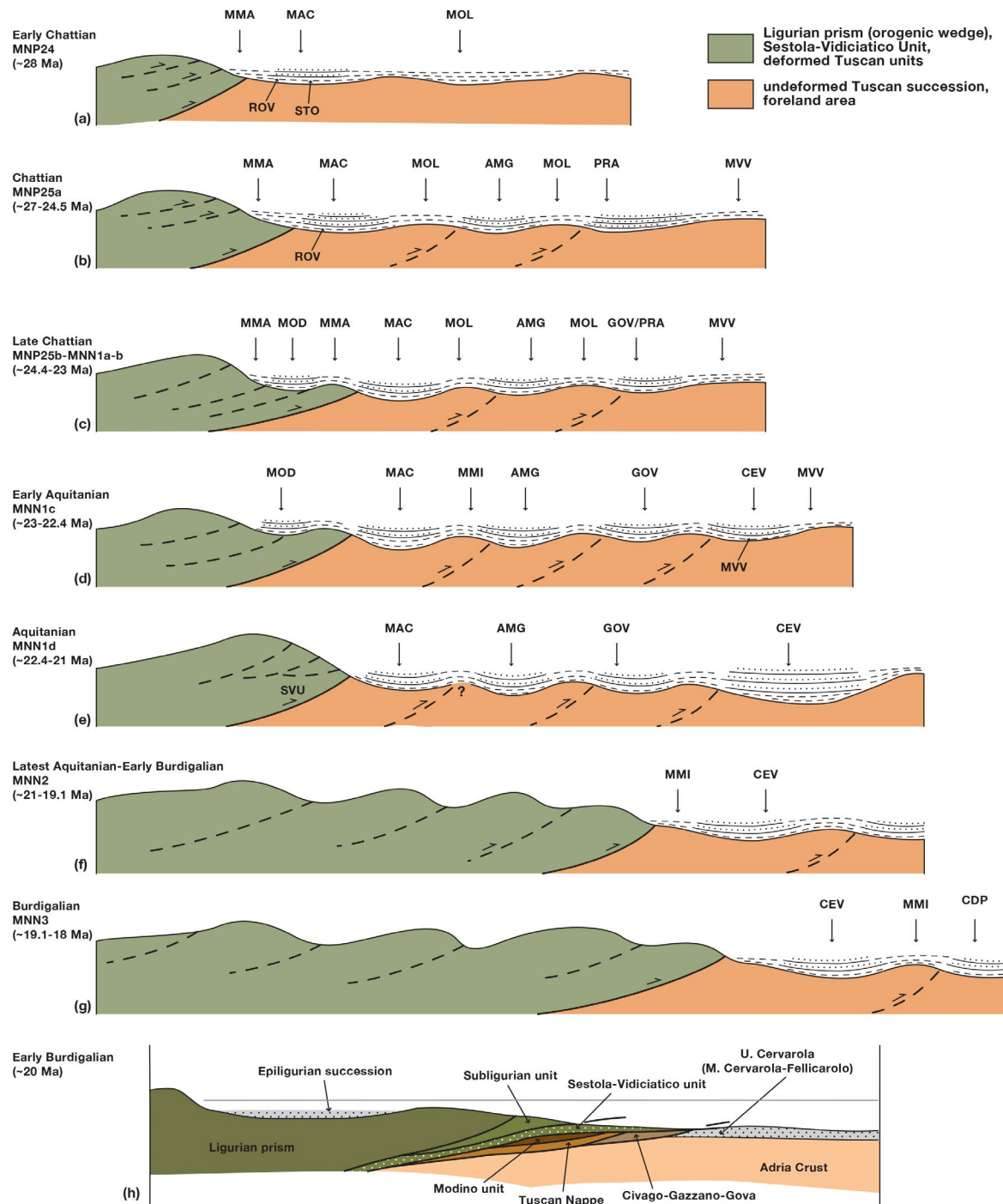
Time evolution of the basin system

The presented data allow us to draw the evolution of different stages of the Northern Apennines foredeep basin system during the Late Oligocene and Early Miocene.

Stage 1

Late Oligocene (early Chattian, MNP24 Zone, Fig. 8a): the Tuscan Domain foredeep was developing, with the deposition in the forming depocentre of: marly mudstone deposits such as the Rovaggio Marl; the

Fig. 7 - Bio-chronostratigraphic framework for the sandstone successions (after Cornamusini et al., 2018).



shales and marls of the Scaglia Toscana Fm.; the Marmoreto marl in an internal position close to the Ligurian and Subligurian tectonic wedge; and more external marls in the depocentre and on a growing structural high (MOL in Fig. 8).

Stage 2

Late Oligocene (Chattian, MNP25a subzone, Fig. 8b): the main depocentre continued to be filled by the Macigno turbidite system, whereas the marly sedimentation (Marmoreto marl) continued in the more internal part of the foredeep basin onto the front of the Ligurian orogenic wedge. Externally, two more minor depocentres developed, linked with active thrusts, that promoted the formation of basins

Fig. 8 – Evolution of the foredeep basin system in the Emilia-Tuscany Northern Apennines during Chattian-Burdigalian time span (a to g). (h) Tectonic setting (not to scale) at the Aquitanian-Burdigalian transition(modified from Cornamusini et al., 2018). AMG: Torre Amorotti-Gazzano Sandstones, CDP: Castiglion dePepoli Sandstones, CEV: Mt. Cervarola Sandstones: Fellicarolo-Dardagna System, GOV: Gova Sandstones, MAC: Macigno, MMA: Marmoreto marls, MMI: Miocene (Aquitanian) marls, MOD: Mt. Modino sandstones, MOL: Oligocene Marls, MVV: Villore Marls, PRA: Pracchiola Sandstones, ROV: Rovaggio Marls, STO: Scaglia Toscana Fm., SVU: Sestola-Vidiciatico unit.



and structural highs. The more internal basin was infilled by the Torre degli Amorotti - Gazzano turbidite system and the more external basin by the more carbonatic Pracchiola Sandstone, with the latter, as well as the foreland ramp, covered by marly deposits.

Stage 3

Latest Oligocene (late Chattian, MNP25b- MNN1a-b zone interval, Fig. 8c): a minor, most internal depocentre developed on the growing frontal thrusts of the Ligurian/Subligurian wedge, was filled by the Mt. Modino turbidite system that could also be partially heteropic with the similar and adjacent more external Macigno system. This latter fully developed, as the Torre degli Amorotti/Gazzano turbidite system and the more external and more carbonatic Gova turbidite system; this latter system could be correlated with the Pracchiola system. Marly deposition continued onto the structural highs separating the sub-basins and at the margins of the foredeep.

Stage 4

Earliest Miocene (early Aquitanian, MNN1c sub- zone, Fig. 8d): at this stage, we have the continuous infilling of the basins that developed in the previous stages, and the development of new and more external basins that received a siliciclastic-carbonate filling: the Fellicarolo- Dardagna turbidite system belonging to the more external Mt. Cervarola complex.

Stage 5

Early Miocene (Aquitanian, MNN1d subzone, Fig. 8e): the tectonic shortening phase that developed several sub-basins led to the closure of the Mt. Modino sub-basin that was incorporated in the accretionary thrust system. Within the other sub-basins, the hemipelagic sedimentation continued and led to the full development of the more external Fellicarolo- Dardagna turbidite system.

Stage 6

Early Miocene (latest Aquitanian-early Burdigalian, MNN2 Zone, Fig. 8f): at this time, ongoing tectonic activity (Tuscan phase or Burdigalian phase) led to further emplacement of the orogenic wedge, with the development of km-scale thrusting, closing the sedimentation in the internal sub-basins such as those of the Macigno, Torre degli Amorotti-Gazzano and Gova turbidite systems that were involved in the deformation. The more external sub-basin of the Fellicarolo-Dardagna turbidite system continued to develop (Fig. 8h).

Stage 7

Early Miocene (Burdigalian, MNN3 Zone, Fig. 8g): the shortening phase continued with the consequent migration of the basin depocentre and the development of the entire Mt. Cervarola succession, with sedimentation in the Fellicarolo- Dardagna sub-basin and the development of another more external sub-basin filled by the Castiglione dei Pepoli turbidite system, probably at least partially interfingered with the former. This evolution continued until the late Burdigalian, with the closing of the Mt. Cervarola system and the inception of a new, even more external, basin system: the Marnoso-arenacea Fm. See: Argnani and Ricci Lucchi (2001); Tinterri and Tagliaferri (2015); Cornamusini et al. (2017).

Kinematic evolution of tectonic units along a NE-SW transect

In Fig. 9a is illustrated a paleotectonic reconstruction for the Middle-Late Jurassic paleogeography of the Piedmont-Ligurian ocean and surrounding areas; in Fig. 9b is a section across the European margin, the Piedmont-Ligurian ocean and the Adriatic plate, following Stampfli et al. (1991).

The opening stages of the Piedmont-Ligurian ocean occurred during Jurassic -Late Cretaceous (Schmid et al. 2008, Handy et al 2010, Marroni et al., 2010, and references therein). During the Late Cretaceous – early Eocene E-dipping subduction of oceanic lithosphere below the European (Briançonnais, Sardinia-Corsica) led to formation of an accretionary wedge (Ligurian prism). At about 50 Ma flip of subduction polarity occurred (Molli, 2008; Molli and Malavieille, 2011; Malusà et al., 2015) and W-dipping subduction of the oceanic lithosphere occurred (Fig. 9c).

Relative movement of the European and Adriatic plate led to complete subduction of the oceanic crust and to continental collision. The younger Ligurian deposits deformed and incorporated in the accretion prism belong to the Tertiary Helminthoid flysch, middle Eocene (Lutetian) in age. Starting from the middle Eocene (Bartonian), the Epiligurian succession (Ori and Friend, 1984; Ricci Lucchi, 1986) unconformably deposited above the deformed Ligurian units. The Epiligurian succession is not affected by deformation recognizable in the underlying Ligurian rocks, the onset of sedimentation of the Epiligurian succession (about 40 Ma) marks therefore the end of Ligurian phases.

W-dipping subduction occurred at this time, with overall compression in the Ligurian prism. Late Rupelian W-dipping subduction with roll-back and retreat of the Adria plate occurred, as testified by the age of rifting and clastics deposition in the Liguro-Provençal basin (30 Ma: Gorini et al., 1993; Séranne, 1999).

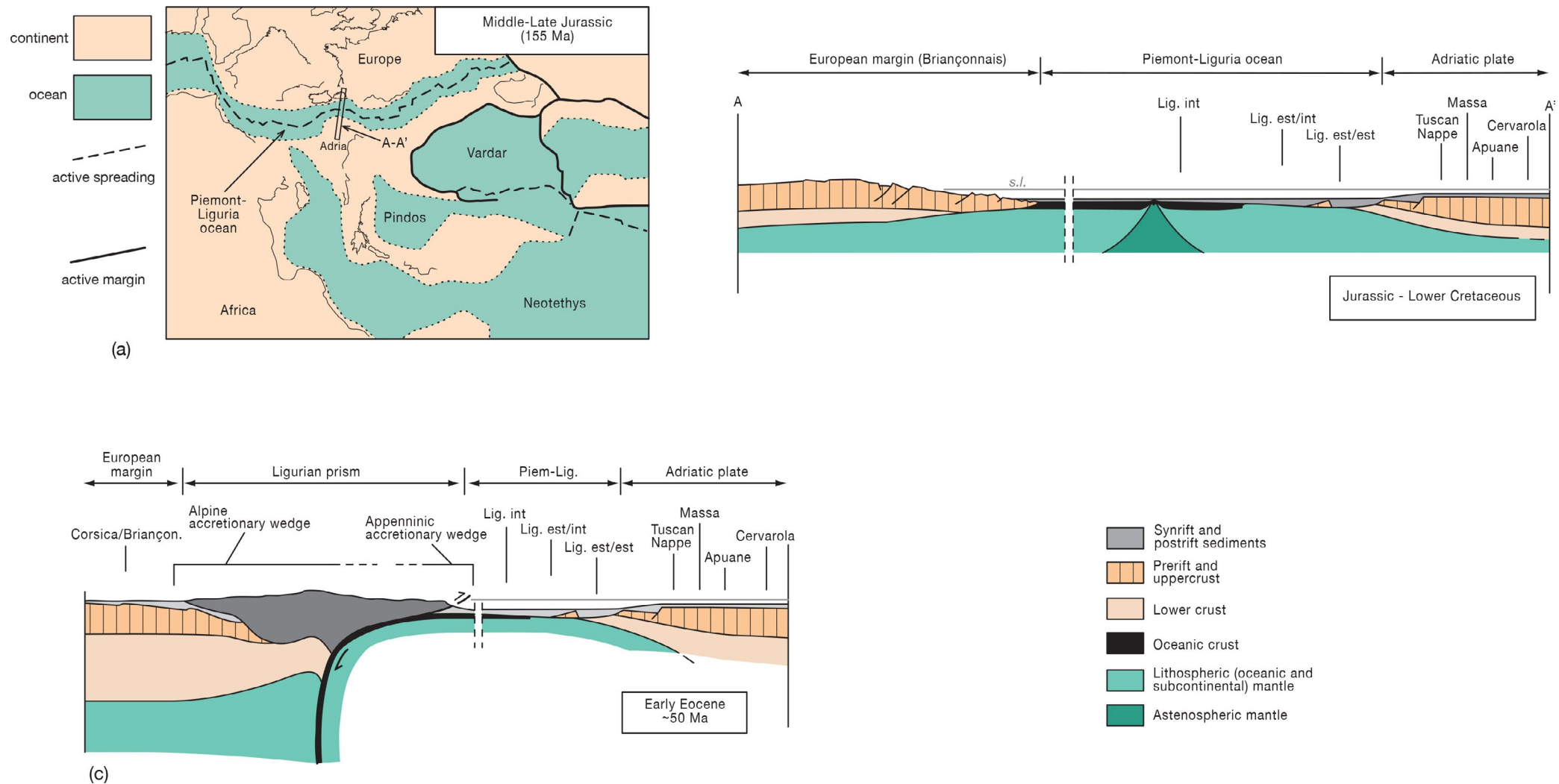


Fig. 9 – Evolution of tectonic units in the Emilia-Tuscany Northern Apennines, see text for discussion.

As a result of W-dipping subduction during late Eocene-early Miocene, the easternmost portion (in present day coordinates) of the Ligurian prism was thrust onto the Adriatic continental margin and developed an "Apenninic accretionary wedge". The rocks belonging to this part of the accretionary wedge are of Ligurian origin, strongly deformed, and with their stratigraphic primary relationships almost obliterated. During Oligocene - early Miocene (Aquitainian, Fig. 10a) Epiligurian deposition continued above the Ligurian prism. Deep water

Epiligurian sedimentation (Di Giulio et al., 2002) indicate that at this time the Ligurian prism was already collapsed and thinned.

On the Adriatic continental margin sedimentation is characterized by marl and marly limestone (Scaglia Fm.) deposition followed by turbiditic sandstones (flysch: Macigno Fm., Pseudomacigno, Mt. Cervarola Fm.). Sandstone deposition unconformably occurred also above deformed rocks of the Apenninic accretionary wedge emplaced above the Adriatic margin (Fig. 10a), this results in the sedimentation of the Petriagnacola/Aveto sandstones above the deformed Argille e Calcari fm. and in sedimentation of the Fiumalbo/Marmoreto/Modino sandstone fms. above the Modino basal complex.

Biostratigraphic data show that in the Aquitanian (Zone MNN1d) sedimentation stops in the Modino unit, Tuscan Nappe, in the Metamorphic units, and in the more internal part of the Cervarola unit paleogeographic domains (Fig. 7); sedimentation closed early (late Oligocene) for the Bratica sandstones. End of sedimentation is due to eastward migration of the orogenic wedge, and emplacement of Ligurian units above the Adria margin; all these tectonic events are collectively indicated here as "Tuscan phase" (Fig. 10).

In Fig. 10a are indicated the main thrust planes developing during this tectonic phase:

- a) a tectonic contact developed at the base of the Ligurian Units (thrust plane "a" in Fig. 10a). Along this plane the Ligurian Units are emplaced above all the more external units and above tectonic units derived from the Adria margin.
- b) the plane "b" thrusts rocks from the Ligurian prism (Argille and Calcari fm.) with their stratigraphic sandstone cover (Aveto and Petriagnacola formations) above more external units. The tectonic unit between the roof thrust "a" and the floor thrust "b" is the Subligurian unit.
- c) the plane "c" emplaces rocks from the Ligurian prism (Modino basal complex) with their stratigraphic cover (Mt. Modino sandstone) above more external units. The tectonic unit between the roof thrust "b" and the floor thrust "c" is the Modino unit.
- d) the thrust plane "d" thrusts a Triassic-Lower Miocene succession deposited on the Adria continental margin above more external units. The unit between the roof thrust "c" and the floor thrust "d" is the Tuscan Nappe tectonic unit.
- e) the thrust plane "f" thrusts a stratigraphic Paleozoic-lower Miocene succession above more external units. The unit between the roof thrust "e" and the floor thrust "f" will be subducted and experienced metamorphism. These rocks are the Tuscan Metamorphic units. In more detail we can distinguish a westernmost portion (Massa unit) and an easternmost portion ("Autochthon" unit) separated by the thrust plane "f".

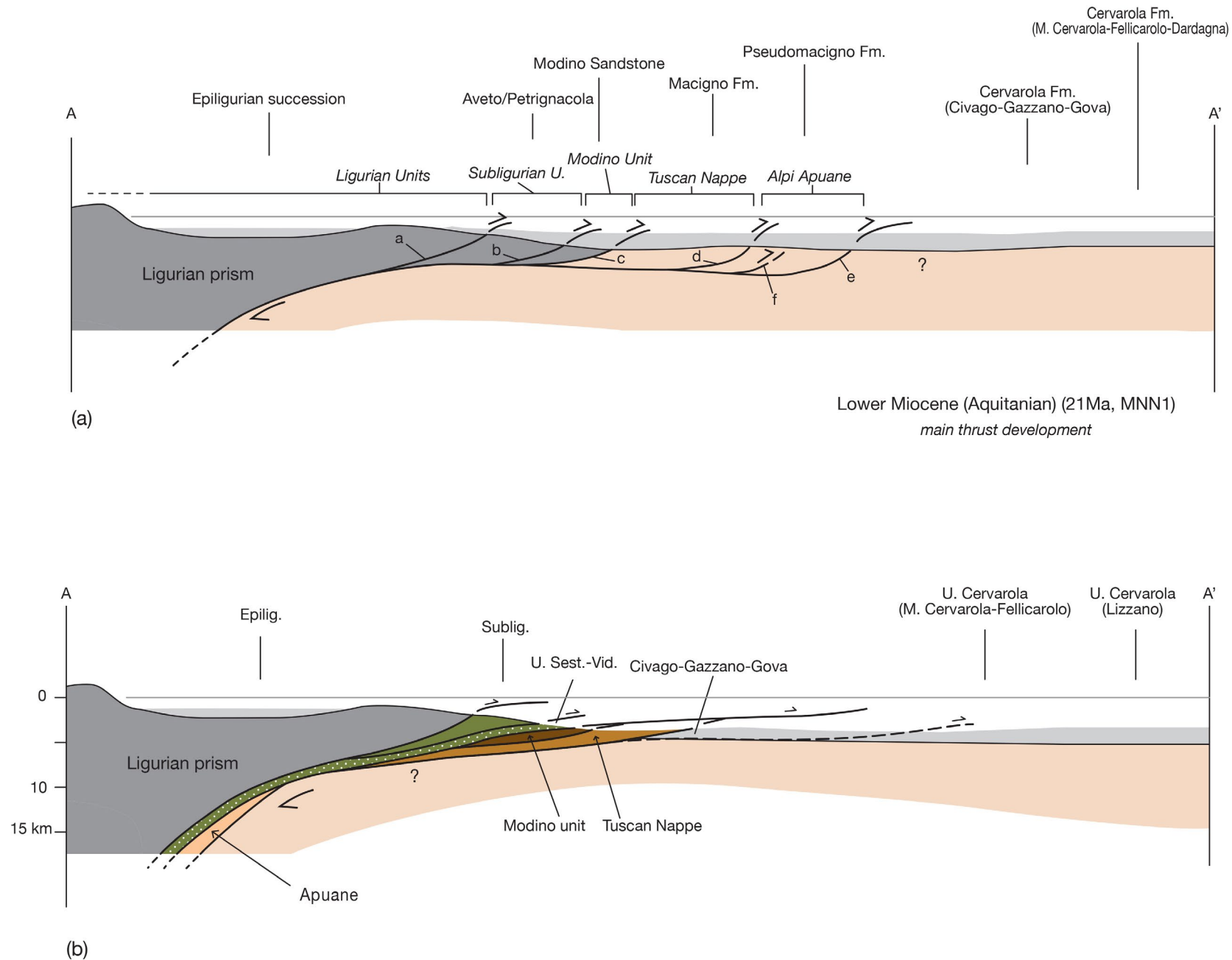


Fig. 10 – Evolution of tectonic units in the Emilia-Tuscany Northern Apennines, see text for discussion.



During the Tuscan phase main regional tectonic transport occurred along the thrust planes “b”, “d” and “e” of Fig. 10a. Along the thrust plane “b” a thick shear zone developed, the Sestola-Vidiciatico tectonic unit, considered the subduction channel between the prism and the subducting plate (Remitti et al., 2007; Vannucchi et al., 2008). Along the thrust plane “d” the Tuscan Nappe is emplaced above more external units and along the plane “e” the Alpi Apuane succession is subducted and reached the depth of about 20 km, where experienced greenschists facies metamorphism. Together with the Alpi Apuane it is also subducted a portion of Adria crust, now not exposed, that was paleogeographically located between the Alpi Apuane and the Cervarola unit (indicated by a question mark in Fig. 10). All these tectonic units are reported in Fig. 10b.

As middle Burdigalian is documented in the central Cervarola unit (M. Cervarola, Fellicarolo), emplacement of higher tectonic units (Tuscan Nappe, Modino unit, Ligurian units) above the central Cervarola unit occurred in post-middle Burdigalian time, i.e. at about 15-16 Ma (Fig. 10b). Emplacement of the Tuscan Nappe above the central Cervarola unit is well exposed along the ridge between Libro Aperto and Cima Tauffi, we refer therefore to this tectonic event as the “Libro Aperto” phase. During this phase developed the Libro Aperto shear zone (see Cornamusini et al., 2018), one of the main tectonic feature of the Emilia-Tuscany Northern Apennines.

Emplacement of the Tuscan Nappe above the Cervarola unit in this area was one of the earliest observations that led to recognize the nappe structure of the Northern Apennines (Baldacci et al., 1967). This thrusting is usually regarded as due to the main shortening phase in the Northern Apennines. In our interpretation this phase (the Libro Aperto phase) can be interpreted as a significant tectonic phase but subordinate to the Tuscan phase, when most of the shortening occur.

South of Serpiano, the Libro Aperto shear zone is cut by the Sestola-Vidiciatico tectonic unit, this confirms that underthrusting and deformation along plate boundary (i.e. deformation in the sestola-Vidiciatico tectonic unit) was still active during Burdigalian, as already inferred by Remitti et al. (2013), and that (at least final) deformations in the Sestola-Vidiciatico tectonic unit postdate activity along the Libro Aperto shear zone. In the Sestola area the later thrusting phase led to refolding of the Cervarola unit and its emplacement above the Sestola-Vidiciatico unit. As the Libro Aperto shear zone is cut by the basis of the Sestola-Vidiciatico unit, we infer a slightly older age for activity of the Libro Aperto shear zone respect to the later thrusting.

Later thrusting

In the Pracchia-Lizzano area (Fig. 4) some thrusts affect the external Cervarola unit and emplaced the Cervarola unit above the Sestola-Vidiciatico tectonic unit. The age of this thrusting event is poorly constrained, but it



likely postdates the turbiditic sandstone sedimentation in the external Cervarola unit (Castiglione dei Pepoli fm.: Langhian), i.e. Serravallian or younger in age, these thrust are here indicated as “Later thrusts”. Other later thrust planes affect the Tuscan units and emplace the Tuscan Nappe and the overlying Modino unit above the Sestola-Tectonic unit and the Subligurian units. These thrust are well exposed between M. Giovo and M. Cusna, south-west of Gazzano, and in the M. Orsaro area. These are thrusts in which the overlying strata are shortened by folding developing km-scale asymmetric inclined folds with overturned limb. This feature was early recognized by many authors and these folds are referred as “frontal ramp of Tuscan units” in the Italian geological literature of the area. More recent thrusting affected the more external Marnoso-Arenacea Formation and deformed Ligurian units along the Sillaro Line: these recent features are not discussed here.

Geological Setting of the Alpi Apuane

The Alpi Apuane is a mountain chain area in the Italian Northern Apennines, in Tuscany. It is bordered by the Ligurian sea to the SW, the Serchio river to the NE and SE and the Aulella river to the NW (Fig. 11). The maximum height is M. Pisanino, with 1947 m a.s.l.

The Alpi Apuane region is a tectonic window where different tectonic units derived from the Tuscan Domain are traditionally distinguished (Carmignani and Giglia, 1975; Carmignani and Kligfield, 1990):

- the Tuscan Nappe;
- the Massa unit;
- the “Autochthon” Auctt. unit (also “Alpi Apuane unit”).

The Tuscan Nappe

The Tuscan Nappe (Fig. 12) consists of a Mesozoic cover detached from its original basement along the decollement level of the Norian anhydrites and dolostones now totally transformed into cataclastic rocks called “Calcare Cavernoso” (Trevisan 1955).

The succession continues upward with Rhaetian to Hettangian shallow water limestones (*Rhaetavicula contorta*, Portoro and Calcare Massiccio fms.), lower Liassic to Cretaceous pelagic limestones, radiolarites and shales (Calcare selcifero, Marne a *Posidonomya*, Diaspri, Maiolica), grading to hemipelagic deposits of the Scaglia (Cretaceous-Oligocene) to end by siliciclastic foredeep turbidites of the Macigno (Fig. 12) (Late Oligocene- Early Miocene).

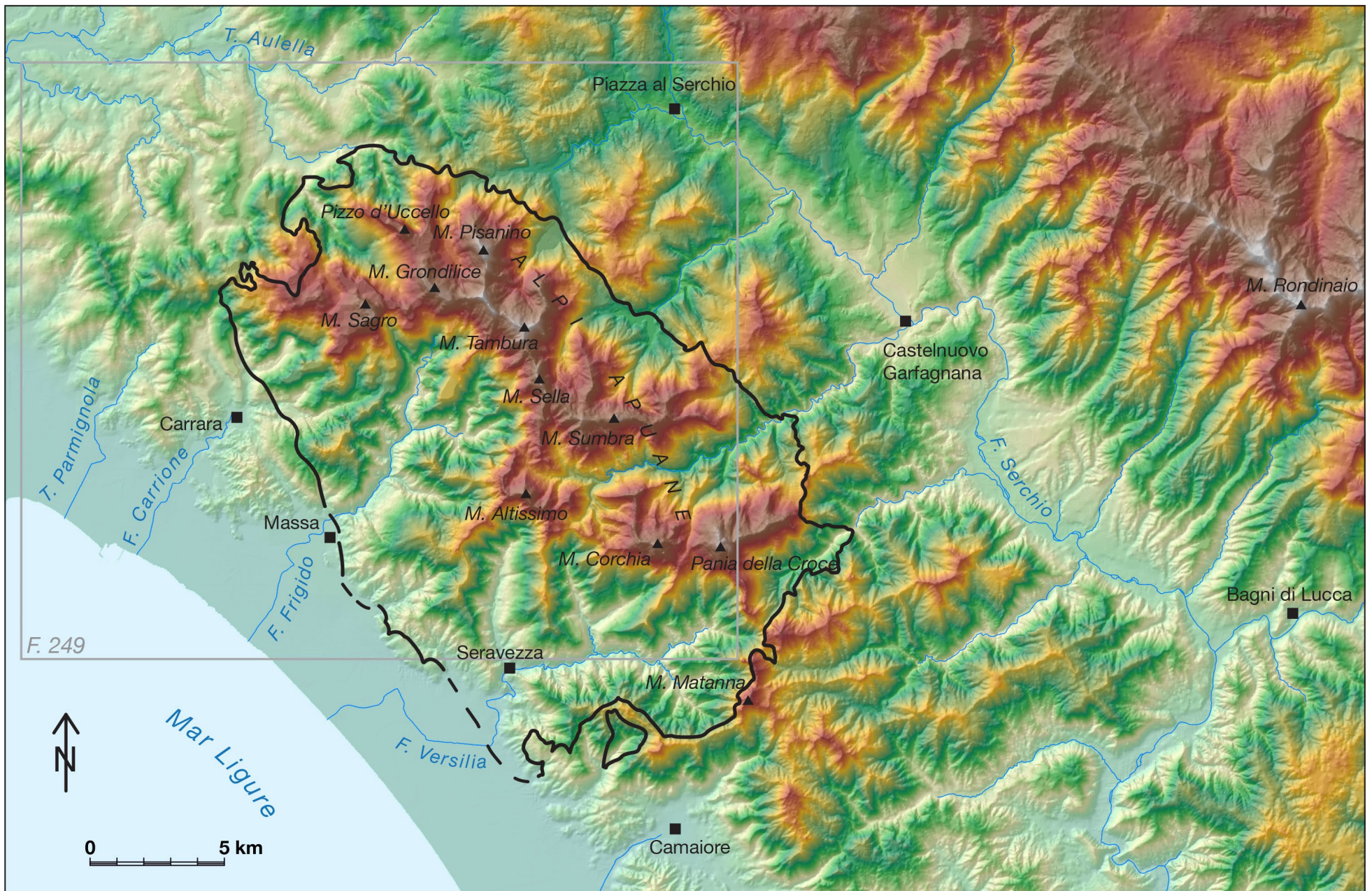


Fig. 11 - The Alpi Apuane region, Northern Apennines. The black line shows the border of the tectonic window of the Alpi Apuane Metamorphic Complex.

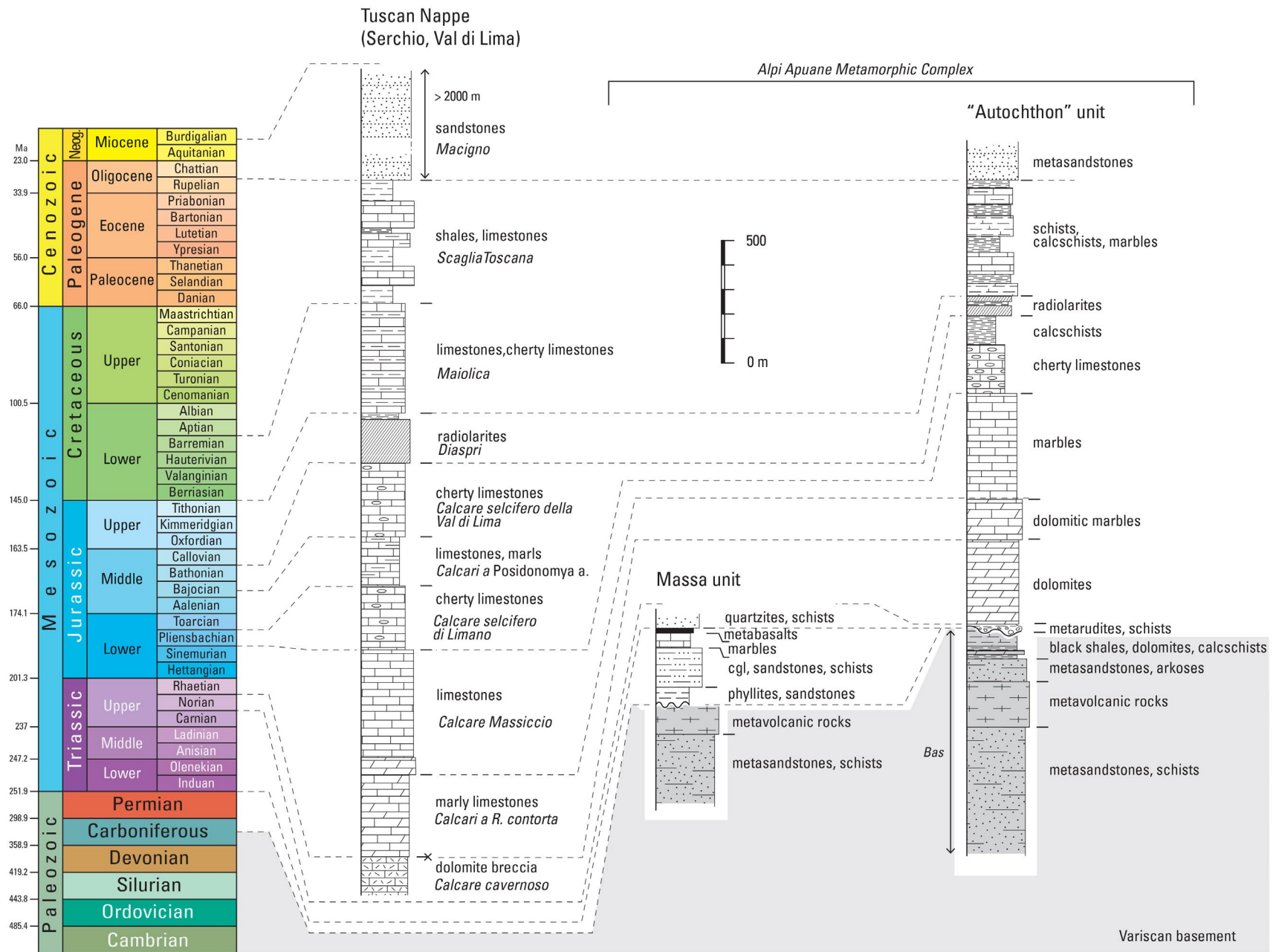


Fig. 12 - Stratigraphic sequence of the Tuscan units (Tuscan Nappe and metamorphic units) in the Alpi Apuane area (after Conti et al., 2019).



The entire sequence with a variable thickness between 2000- 5000 m shows in the Mesozoic carbonate part strong lateral and longitudinal variability related to irregular and locally rugged paleogeography heritage of block faulting and fragmentation of the passive margin during Liassic-Early Cretaceous rifting stage, but also to the weak Cretaceous-Eocene tectonic inversion produced by the northward movement of the Adriatic plate and the far field contractional tectonics related to the inception of the Piedmont-Ligurian ocean closure.

Peak metamorphic conditions does not exceed the anchizone/subgreenschist facies with estimated temperature around 250-280 °C on the basis of vitrinite reflectance, illite cristallinity, isotope studies and fluid inclusion analysis (Cerrina Feroni et al., 1983; Reutter et al., 1983; Carter and Dworkin, 1990; Montomoli et al., 2001).

The Massa unit

The Massa unit, exposed in the south-west part of the Alpi Apuane, is characterized by a pre-Mesozoic basement and a Middle to Upper Triassic cover (Fig. 12). The pre-Mesozoic basement is formed by ?upper Cambrian-?Lower Ordovician phyllites and quartzites, Middle Ordovician metavolcanics and metavolcanoclastic sediments now transformed in phyllites and schists with volcanic quartz and feldspar ("porphyroids and porphyric schists" *Auctt.*) associated to quartzitic metasandstones and phyllites and rare Silurian *Orthoceras*-bearing metadolostones and black phyllites.

The Mesozoic cover sequence consists of a metasedimentary Middle-Upper Triassic sequence (Verrucano) characterized by the presence of Middle Triassic metavolcanics.

The metasedimentary sequence is formed by quartzose clast-supported metaconglomerates associated with metasandstones, metasiltsstones and black phyllites that are overlain by marine deposits (Ladinian crynoidal marbles, carbonate metabreccias, calcschists and phyllites) intercalated with alkaline metabasalts (prasinities). Upwards the succession ends up with a transgressive continental cycle consisting of coarse-grained quartzitic metarudites, quartzites and muscovite phyllites.

The basement rocks in the Massa unit show evidence of a pre-Alpine greenschist-facies metamorphism which has been ascribed to the Variscan (Hercynian) orogeny. The Alpine metamorphism (as investigated in the Mesozoic cover rocks) is characterized by kyanite+chloritoid+ phengitic muscovite assemblages in metapelites. Peak conditions have been estimated in the range of 0,6-0,8 GPa and 420-500 °C (Franceschelli et al., 1986; Jolivet et al., 1998; Franceschelli and Memmi, 1999; Molli et al., 2000b).



The "Autochthon" Auctt. unit

The Autochthon Auctt. unit is made up by a Palaeozoic basement unconformably overlain by the Upper Triassic-Oligocene meta-sedimentary sequence (Fig. 12).

The Palaeozoic basement is formed by the same lithologies of the basement in the Massa unit, but here they are better exposed: ?upper Cambrian-?Lower Ordovician phyllites and quartzites, ?Middle Ordovician metavolcanics and metavolcanoclastics, ?Upper Ordovician quartz metasandstones and phyllites, Silurian black phyllites and *Orthoceras*-bearing metadolostones, ?Lower Devonian calcschists; moreover the ?upper Cambrian-?Lower Ordovician phyllites/quartzites and ?Middle Ordovician metavolcanics/metavolcanoclastics contain several thin lenses of alkaline to subalkaline metabasites corresponding to original dykes and/or mafic volcano-clastic deposits (Gattiglio and Meccheri, 1987; Conti et al., 1993).

Also basement rocks in the Autochthon Auctt. unit recorded a pre-Alpine deformation and greenschist facies metamorphism as the Massa unit (Conti et al., 1991), for which the most striking evidence is the regional angular unconformity at the base of the oldest Mesozoic formation (Triassic carbonates) stratigraphically lying on almost all the Palaeozoic formations. The Mesozoic cover (Fig. 12) includes thin Triassic continental to shallow water Verrucano-like deposits followed by Upper Triassic-Liassic carbonate platform metasediments consisting of dolostones ("Grezzoni"), dolomitic marbles and marbles (the "Carrara marbles"), which are followed by upper Liassic-Lower Cretaceous cherty metalimestones, cherts, calcschists. Lower Cretaceous to lower Oligocene sericitic phyllites and calcschists, with marble interlayers, are related to deep water sedimentation during downthrowing of the former carbonate platform. The Oligocene sedimentation of turbiditic metasandstones ("Pseudomacigno") closes the sedimentary history of the domain.

The Alpine metamorphism in the "Autoctono" unit is characterized by occurrence of pyrophyllite + chloritoid + chlorite + phengitic muscovite in metapelites. Peak-metamorphic conditions have been estimated by this assemblages in the range of 0,4-0,6 GPa and 350-450 °C (Franceschelli et al., 1986; Di Pisa et al., 1987; Jolivet et al., 1998; Molli et al., 2000b). Di Pisa et al. (1985) first recognized temperature variations from southwest (450 °C) to central and northeast part (380-350 °C), using the Ca/Do thermometer. Such data have been recently confirmed and used to interpret some of the microstructural variability in marbles.

Tectonics

The regional tectonic setting of the Alpi Apuane area is well known and generally accepted by researchers belonging to different geological schools (Fig. 13). On the contrary, different and often contrasting opinions do persist in interpreting the context of development of some deformation structures and the Cenozoic geological history responsible for such a setting; the most recent debate focus on the exhumation mechanisms and their geodynamic context (Carmignani and Giglia, 1977; Carmignani et al., 1978; Carmignani and Giglia, 1979; Carmignani and Kligfield, 1990; Storti, 1995; Cello and Mazzoli, 1996; Jolivet et al., 1998; Molli et al., 2000b).

In the Alpi Apuane metamorphic units, two main polyphasic tectono-metamorphic events are recognized: the D1 and D2 events (Carmignani and Kligfield, 1990), which are classically regarded as a progressive deformation of the internal Northern Apennines continental margin during collision (D1) and late to post-collisional processes (D2). During D1 nappe emplacement occurred with the development of kilometer scale NE-facing isoclinal folds, SW-NE oriented stretching lineations (L1) and a greenschist regional foliation (S1). In more detail, the D1 event can be subdivided into: (1) an early folding phase in which recumbent isoclinal folds and an associated flat-lying axial plane foliation are formed, and (2) a later antiformal stack phase which produces other isoclinal

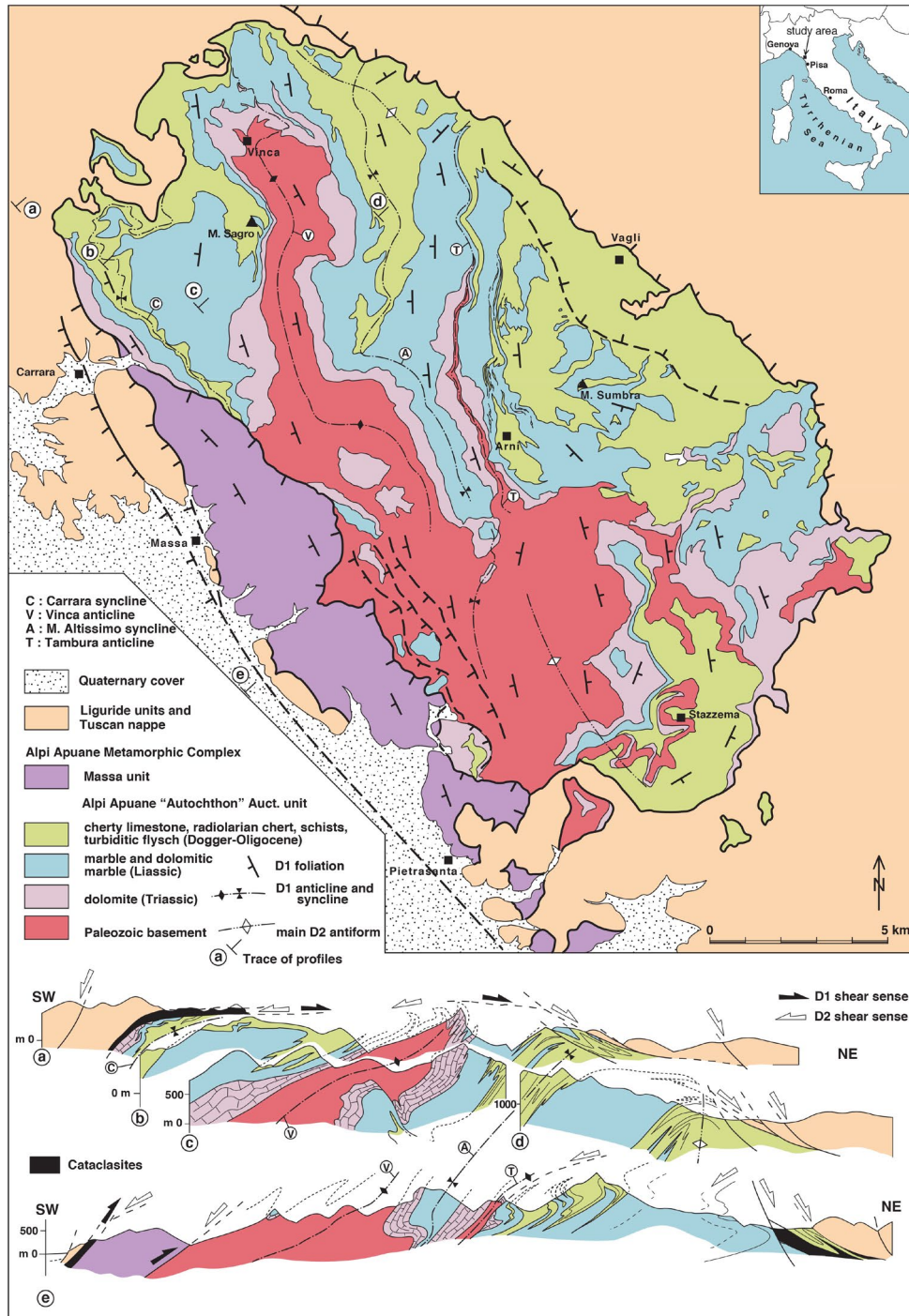


Fig. 13 – Geological sketch map of the Alpi Apuane area.



folds and localized metric to plurimetric scale shear zones with top-to-east/north east sense of movement.

During D2 the previously formed structures were reworked with development of different generations of folds and shear zones with top-NE and top-SW transport direction, leading to progressive unroofing and exhumation of the metamorphic units toward higher structural levels. Late stages of D2 are associated with brittle structures.

D1 structures

A main planar anisotropy (S1 foliation) of L-S type can be recognized in all the metamorphic units as the axial plane foliation of isoclinal decimetric to kilometric scale folds (Fig. 14).

Foliation bears a WSW-ENE trending mineral and stretching lineation (Fig. 15) which appears to be parallel to the long axes of the stretched pebble clasts in marble breccias and in quarzitic metaconglomerates. Finite strain data from deformed marble breccias, reduction spot and strain fringe indicate X/Z strain ratios of from 4:1 to 13:1 with an average of 7:1. The finite strain ellipsoid varies from the field of flattening to constriction with aspect ratios K between 0.14/0.64 in the west to 0.15/3.34 in the east (Kligfield et al., 1981; Schultz, 1996).

In the Autochthon Auctt. unit kilometric scale D1 isoclinal fold structures can be observed; from west to east are the Carrara syncline, the Vinca-Forno anticline, the Orto di Donna- M. Altissimo-M. Corchia syncline and the M.

Fig. 14 – D1 folds in marbles, Carrara, Alpi Apuane.



Tambura anticline. The two main antiform-anticline structures are cored by Palaeozoic basement rocks, whereas Mesozoic metasediments are present in the core of synclines (Fig. 13).

A nearly 90° change in orientation of D1 fold axes is described from the WSW to ENE across the Alpi Apuane (Carmignani and Giglia, 1977; Carmignani et al., 1978). D1 fold axes in the western area (Carrara) mainly trend NW-SE and are sub-horizontal with a D1 lineation plunging down-dip within the main foliation at 90° from fold axis. In the eastern region fold axes are parallel to sub-parallel to the down-dip stretching lineation and highly non-cylindric sheath folds appear (Carmignani and Giglia, 1984; Carmignani et al., 1993). This relationship has been proposed as an example of passive rotation of early formed folds into the extension direction during progressive simple shear (Carmignani et al., 1978).

The deformation geometries, strain patterns and kinematic data allowed to interpret the D1 history as the result of: (1) underthrusting and early nappe stacking within the Apenninic accretionary/collisional wedge (Fig. 16b); (2) "antiformal stack phase" in which further shortening and a crustal scale duplex are realized (Fig. 16b). The development of D1 structures is strongly controlled by the original paleogeography and lateral heterogeneities, as changes in limestone/dolomite facies and increasing thickness of shaly formations.

D2 structures

All the D1 structures and tectonic contacts are overprinted by generations of later structures referable to the post-nappe D2 deformation event.

The D2 structures are represented by syn-metamorphic, variously sized high strain zones and well developed recumbent folds mainly associated with a low dipping to sub-horizontal axial planar foliation (S2), of crenulation



Fig. 15 – Strongly boudinaged cherty limestone during D1 deformation, Capanne di Careggine, Alpi Apuane.

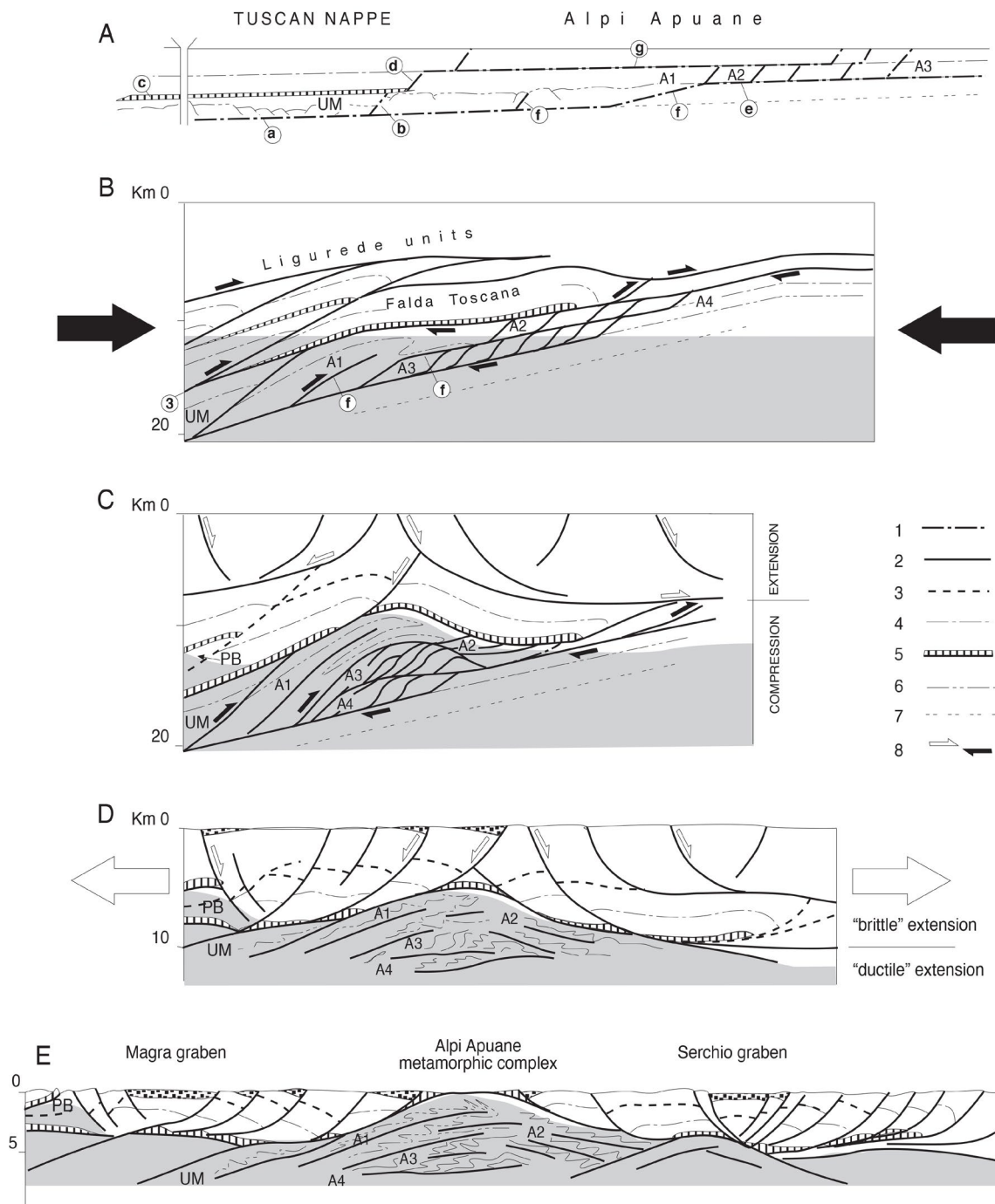


Fig. 16 – Tectonic evolution of the Alpi Apuane Metamorphic Complex and adjoining areas (after Carmignani and Kligfield, 1990, modified). (a) Pre-collisional geometry showing restored state traces of principal thrust faults and ramp-flat geometry. (b) Development of Alpi Apuane duplex structure. Metamorphic rocks showed in shaded pattern. (c) Development of antiformal stack geometry by rapid underplating and thickening of the accretionary wedge. Note simultaneous development of normal faults and compressional faults at upper and lower-crustal levels, respectively. Legend: 1: Thrust fault trace. 2: Active thrusts and normal faults. 3: Inactive thrusts. 4: Base of flysch. 5: Triassic evaporite. 6: Top of Palaeozoic phyllites. 7: Top of crystalline basement. M: Massa unit. A1 and A2: SW and NE portions of metamorphic complex, respectively. All diagrams at same scale with no vertical exaggeration. (d) Initiation of tectonic extension results in simultaneous ductile extension at mid-crustal levels (Alpi Apuane metamorphic sequences, shown in shaded pattern) and brittle extension at upper-crustal levels (Tuscan Nappe and Liguride units). Metamorphic features associated with tectonic extension at mid-crustal conditions require that significant crustal thinning occurred prior to uplift. Differentiation of the core complex into upper-late nonmetamorphic rocks and lowerplate metamorphic rocks is aided by the adoption as a detachment horizon of the evaporite-bearing overthrust faults of the earlier compressional phases. (e) Further crustal thinning, now accompanied by denudation and uplift, results in exposure of Alpi Apuane metamorphic core complex. High-angle brittle normal faults of the surrounding Magra and Serchio graben systems are interpreted to root downward against earlier low-angle normal faults.

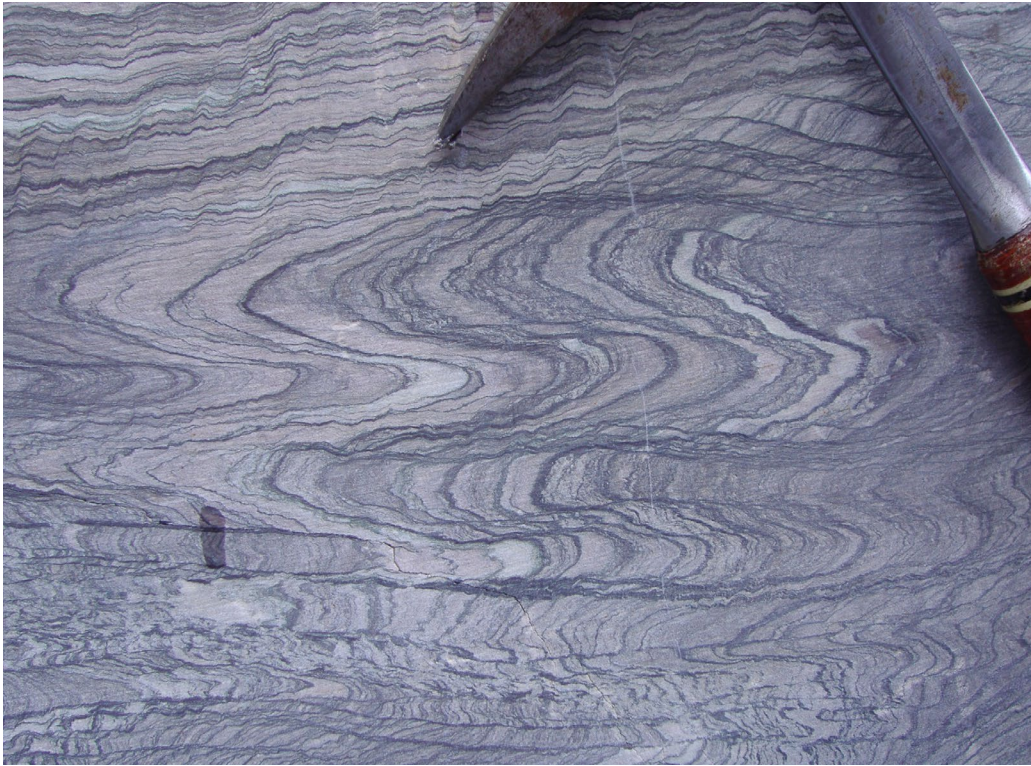


Fig. 17 – D2 folds in Cretaceous calcschists, Valle Turrice, Alpi Apuane.

type (Fig. 17). Late D2 structures are mainly represented by upright kinks and different generations of brittle faults, that accommodate the most recent tectonic history.

According to classical interpretations (Carmignani et al., 1978; Carmignani and Giglia, 1979; Carmignani and Kligfield, 1990) a complex mega-antiform with Apenninic trending axis (nearly N 130°-170°), and corresponding to the entire width of the Alpi Apuane window, was realized as result of the D2 history. A second order asymmetric parasitic folds facing away from the dome crests occur and, at scale of the whole Alpi Apuane, having "S" and "Z" sense of asymmetries can be observed on the southwestern and northeastern flanks, respectively. These minor structures form series of folds at different scale (from centimeters to kilometers) with variable morphologies related to rock competence.

The tectonic meaning of D2 structures has been object of different interpretations during the years:

- they formed during a post-nappe refolding related to a continuous contractional history. This deformation is framed in a context of: a) hangingwall collapse during overthrusting on a deeper ramp (Carmignani et al., 1978); b) interference patterns between two folding phases at high angle (Carmignani and Giglia, 1977) or two high angle synchronous folding produced through one directional contraction in a multilayer with different mechanical properties (Carmignani and Giglia, 1977); c) domino-like rigid blocks rotations with antithetic shear during progressive eastward thrusting (Jolivet et al., 1998);
- they produced as reverse drag folds overprinting complex highly non-cylindric D1 sheath folds during late rebound by vertical isostatic re-equilibration of former thickened crust (Carmignani and Giglia, 1979);
- they developed as passive folds related to distributed shear within kilometric scale shear zones accommodating crustal extension (Carmignani and Kligfield, 1990; Carmignani et al., 1994).

Deformation - metamorphism relationships

The presence of some minerals (chloritoid and kyanite) in suitable rock-types (metagreywackes) allowed the study of relative time relationships of mineral growth and deformation structures.

In the Massa unit the chloritoid grew since the early stage of the D1 foliation development; post-tectonic growth of chloritoid on D2 crenulation cleavage was never observed, only some samples could suggest its syn-kinematic growth during the early stage of development of the D2 crenulation. Kyanite has been observed in the D1 foliation and is also included in chloritoid crystals, therefore a syn-kinematic growth during the early stage of the D1 foliation development can be inferred. In the Autochthon Auct. unit chloritoid in association with pyrophyllite (Franceschelli et al., 1997) can be observed in syn- to post tectonic relationships with the D1 foliation. The chloritoid mainly predates the D2 crenulation in the uppermost geometrical levels of the unit, e.g. W of Mt. Sagro (Fig. 13). On the contrary, at deeper structural levels (Forno valley, inland of Massa) chloritoid can be observed in clear syn- to post-tectonic relationships with the sub-horizontal D2 crenulation cleavage testifying a different thermo-mechanical history in different geometrical positions within the same unit.

Age of deformation

In the metamorphic units of the Alpi Apuane the youngest sediment involved in the syn-metamorphic deformation is the Pseudomacigno containing microfossils of Oligocene age (Dallan Nardi, 1976). Moreover available K-Ar and Ar-Ar dates (Kligfield et al., 1986) suggest that greenschist facies metamorphism and ductile deformation within the region began about 27 Ma (late Oligocene) and were over by 10-8 Ma (late Miocene). The dating at 27 Ma of metamorphism in the Alpi Apuane by Kligfield et al. (1986) is a matter of debate (Patacca et al. 2013 and references therein) and it is in contrast with evidence of ongoing sedimentation in the Macigno during early Aquitanian and Pseudomacigno during Oligocene. A metamorphism not older than 20 Ma seems to be more representative for metamorphic units in the Alpi Apuane area, but new radiometric measurements are needed. The younger history can be constrained using apatite fission tracks suggesting that between 5 and 2 Ma (Abbate et al., 1994; Fellin et al., 2007) the metamorphic units passed through 120 °C, approximately at a depth of 4-5 km depending on the coeval thermal gradient (Carmignani and Kligfield, 1990). This uplift stages can be further constrained by sedimentary record, since north and north-east of the Alpi Apuane region the basin fill of the Lunigiana and Garfagnana tectonic depressions contains upper Pliocene-lower Pleistocene conglomerates with metamorphic clasts derived from the Alpi Apuane metamorphic units (Bartolini and Bortolotti, 1971; Federici and Rau, 1980; Bernini and Papani, 2002; Argnani et al., 2003; Balestrieri et al., 2003).



The Alpi Apuane marbles

In the Alpi Apuane region marbles derive from stratigraphically different levels, the Liassic marbles however are the thickest succession and represent the world-wide known white variety called Carrara marble.

The Carrara marble is extensively used both as building stones and statuaries (this use dates as far back as the Roman age) as well as in rock-deformation experiments (Rutter, 1995; Casey et al., 1978; Spiers, 1979; Schmid et al., 1980, 1987; Wenk et al., 1987; Fredrich et al., 1989; De Bresser, 1991; Rutter, 1995; Covey-Crump, 1997; Pieri et alii, 2001; De Bresser et al., 2005; Bruijn et al., 2011) where is widely used because:

- a) it is an almost pure calcite marble;
- b) it shows a nearly homogenous fabric, with no or weak grain-shape or crystallographic preferred orientation;
- c) it usually develops large grain-size microstructure.

All the above features can be found in large volumes of marbles cropping out in the Carrara area, i.e. in the northwestern part of the Alpi Apuane region, however at the scale of the Alpi Apuane region a variability of microstructure has been described.

In the local usage the term "Alpi Apuane marbles" indicates all the marble formations cropping out in the whole Alpi Apuane area, while "Carrara marble" stands for Liassic marbles mainly located in the northwestern Alpi Apuane area in the surroundings of the town of Carrara (Fig. 18). Carrara marbles are the most intensely quarried marble variety within the entire Alpi Apuane. Due to their economic and cultural importance, Carrara marbles have been the object of geological investigation for a century (Zaccagna, 1932; Bonatti, 1938), with modern studies about their structure since the sixties (D'Albissin, 1963; Di Sabatino et al., 1977; Di Pisa et al., 1985; Coli, 1989).

Marble types and their microstructures

In the Alpi Apuane three main groups of marbles can be distinguished according to their mesoscopic features (Fig. 19 and Fig. 20):

the white-light gray, more or less massive marbles (with or without light grey to dark "veins", lenses or spots) mainly indicated with commercial names such as Ordinario, Venato, Bianco Carrara, Bianco P., Statuario; the metabreccias (monogenic or polygenic, more or less in *situ*, clast- or matrix-supported) with the main commercial varieties Arabescato and Fantastico, and grey marbles named Nuvolato and Bardiglio. These three main groups encompass more than fifty different commercial varieties quarried in the Alpi Apuane region (Meccheri et al., 2007b; Blasi and Ragone, 2010).

These distinctions represent the end-member of a wide range of transitional types which in some cases can be observed superimposing each other (see detailed description in Molli and Heilbronner Panozzo, 1999 and Molli et al., 2000a).

This type of microfabric is characterized by equant polygonal grains (granoblastic or “foam” microstructure, Fig. 22a), with straight to slightly curved grain boundaries that meet in triple points at angles of nearly 120°. C-axis orientations show a random distribution or a weak crystallographic preferred orientation. These microfabrics are observable in marble layers belonging to km-scale D1 isoclinal folds, where also minor parasitic folds developed. The presence of such microstructures within D1 folds indicates that the grain growth which

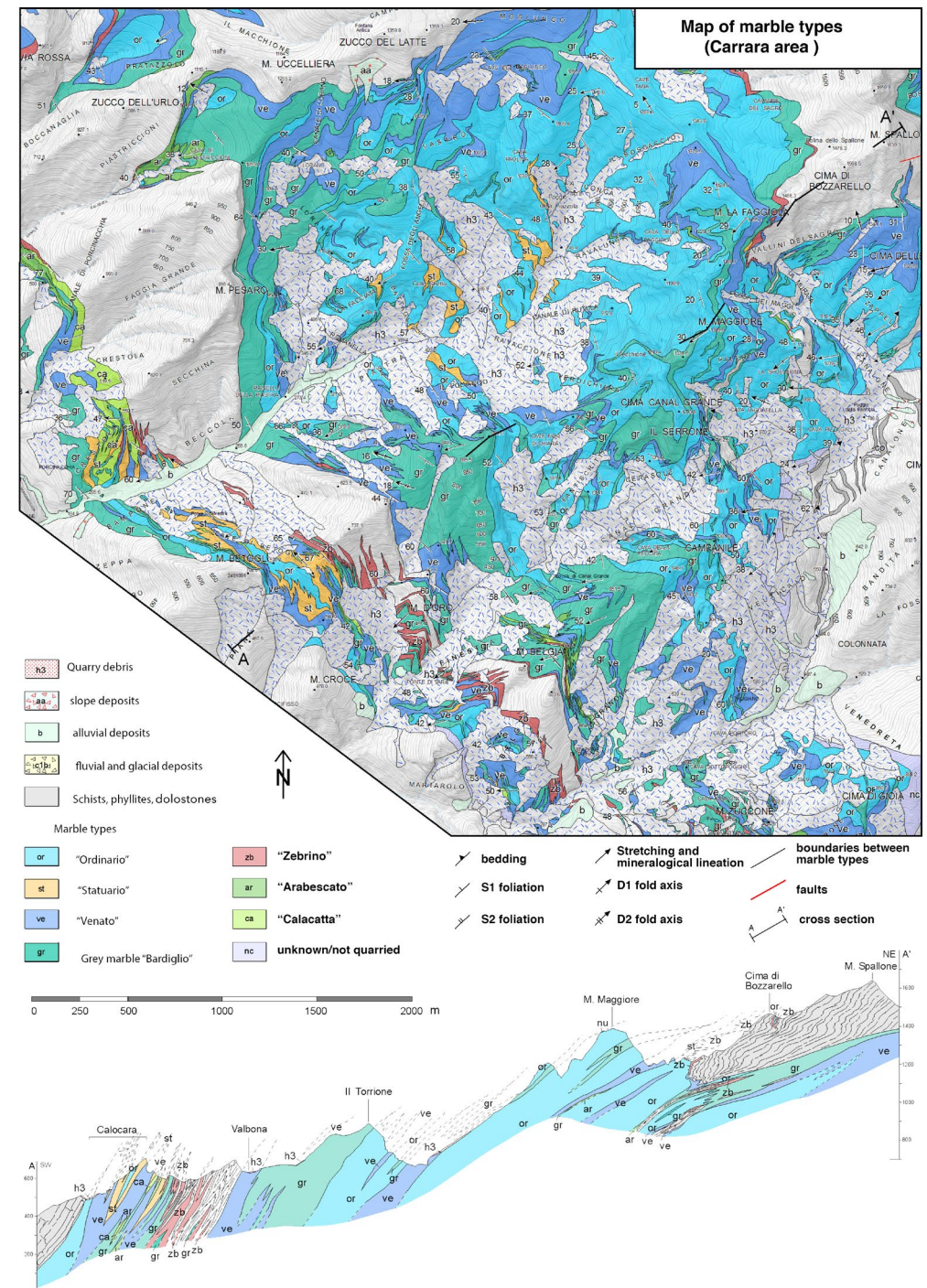


Fig. 18 – Map of marble types in the area north of Carrara.



produced type A microfabric occurred after the main D1 folding phase, and obliterated all earlier syntectonic microstructures associated with folding. However, the presence of a texture in some samples has been related to the pre-annealing deformation history (Leiss and Molli, 2003).

Marbles with this type of microstructure can be observed in the western, central and eastern parts of the Alpi Apuane, with a medium grain size decreasing from west to east (300-150 μm to 100-80 μm) and from geometrically deeper to higher structural levels.

Dynamically recrystallized microfabrics (type-B microfabrics)

Within type-B microfabrics two end-members of microstructures can be recognized:

- a) microstructures exhibiting strong shape preferred orientation, coarse grains and lobate grain boundaries (type B1);
- b) microstructures with shape preferred orientation, smaller grain size and predominantly straight grain boundaries (type B2).

Fig. 21 shows representative examples of the two types of microfabrics. These two types of microstructures are both interpreted as related to high strain and high

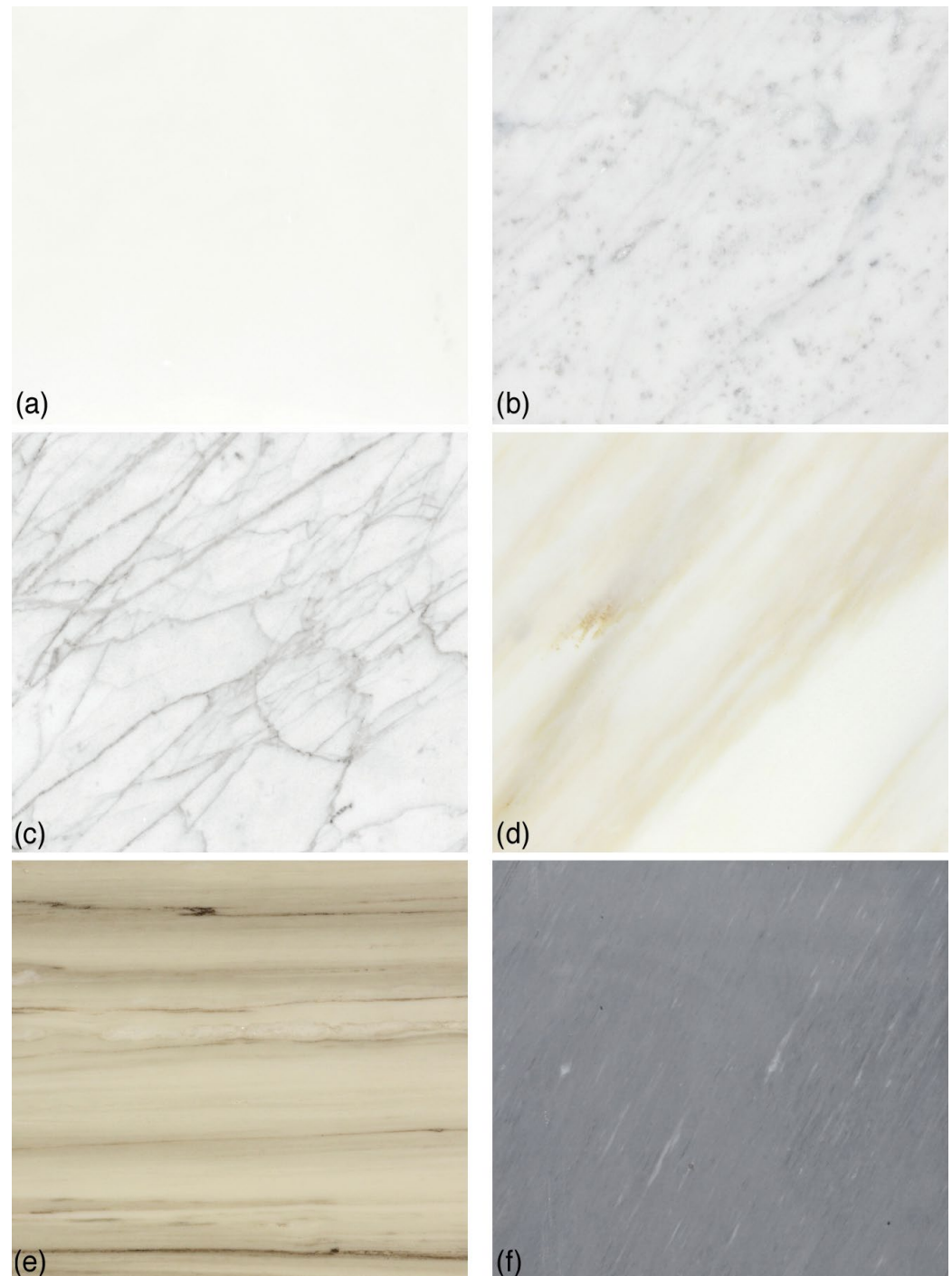


Fig. 19 – Some marble types from the Alpi Apuane: (a) "Statuario". (b) "Bianco". (c) "Venato". (d) "Calacatta". (e) "Zebrino". (f) "Bardiglio". Photo width: 50 cm.



temperature (350- 400 °C) crystal plastic deformation mechanisms (dislocation creep). Whereas grain boundary migration recrystallization can be considered as predominant in type B1 microfabric, an important contribution of both rotation recrystallization and grain boundary migration can be inferred to prevail in type B2 microfabric.

Twinned microfabric (type-C microfabric)

The third type of microfabric is related to low-strain and low-temperature crystal plastic deformation mechanisms. Characterized by thin straight e-twins, it occurs in all the marble outcrops of the Alpi Apuane region, overprinting both type A and type B microfabrics. It is mostly developed in coarse grained marble.

Microfabric evolution and tectonic history

The variability of statically and dynamically recrystallized microfabrics in the Liassic Alpi Apuane marbles has been inserted in the following evolutionary tectonic model.

During the early D1 stage (main regional deformation phase, Fig. 23a), nappe emplacement, km-scale NE-facing isoclinal folds, stretching lineations and main

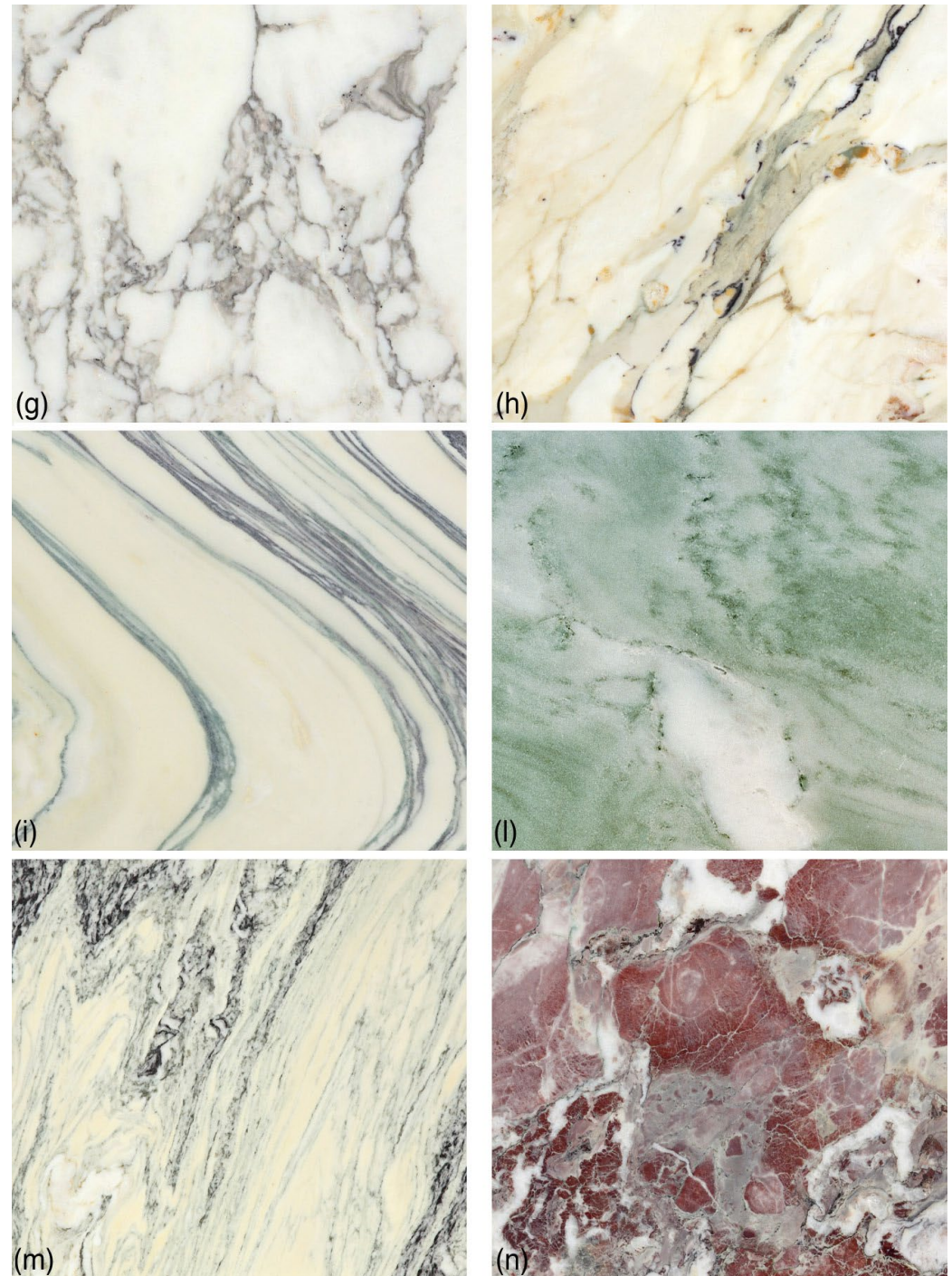


Fig. 20 – Some marble types from the Alpi Apuane: (g) "Arabescato". (h) "Breccia Capraia". (i) "Fantastico". (l) "Cipollino". (m) "Crema". (n) "Fior di Pesco". Photo width: 50 cm.

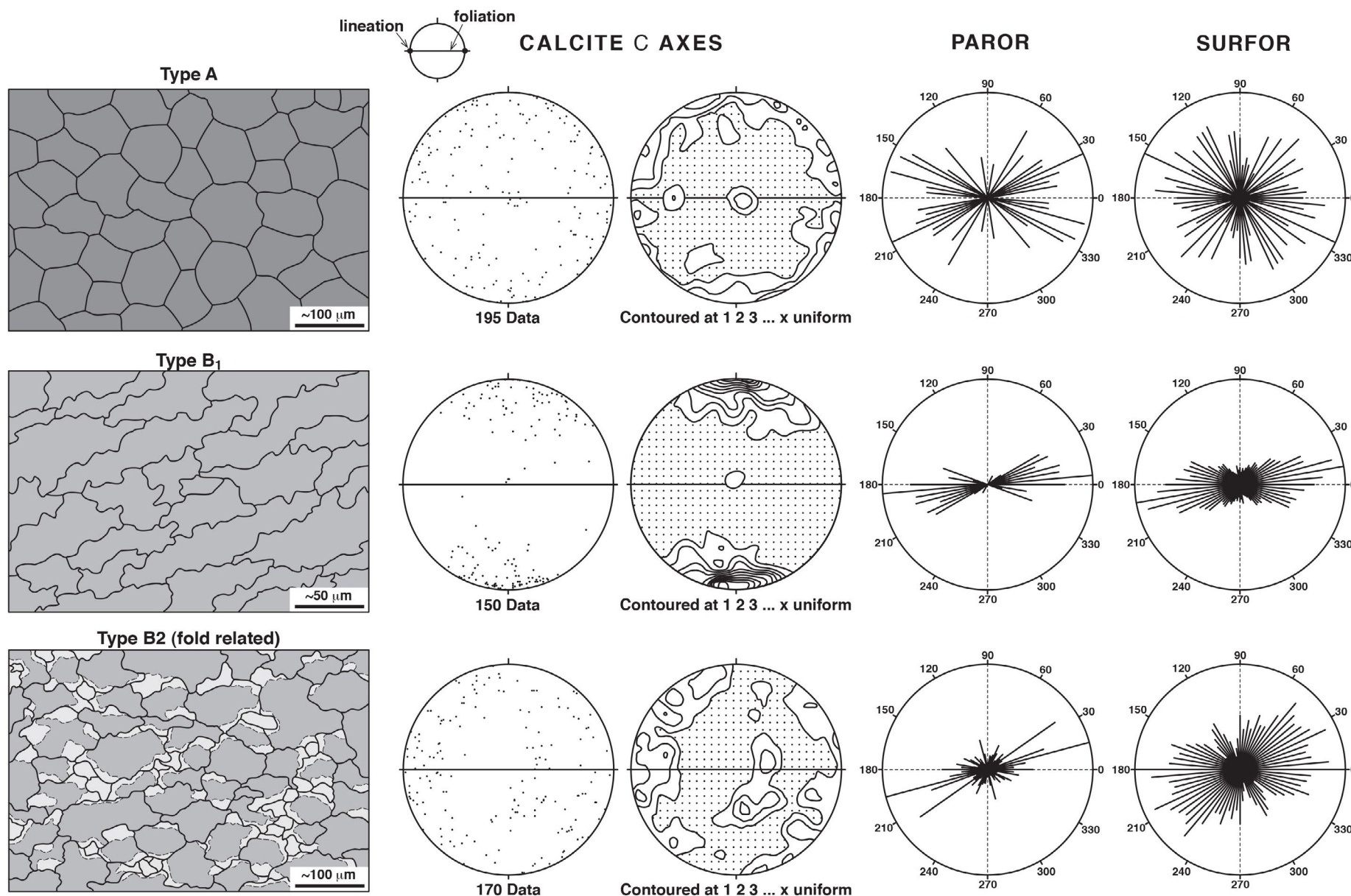


Fig. 21 – Line drawing of microstructures, c-axis orientation (from universal stage measurements) and results of PAROR and SURFOR analysis for calcite microfabric of type-A and type-B. Number of grains analysed with PAROR and SURFOR routines is more than 200 (from Molli et al., 2000a).

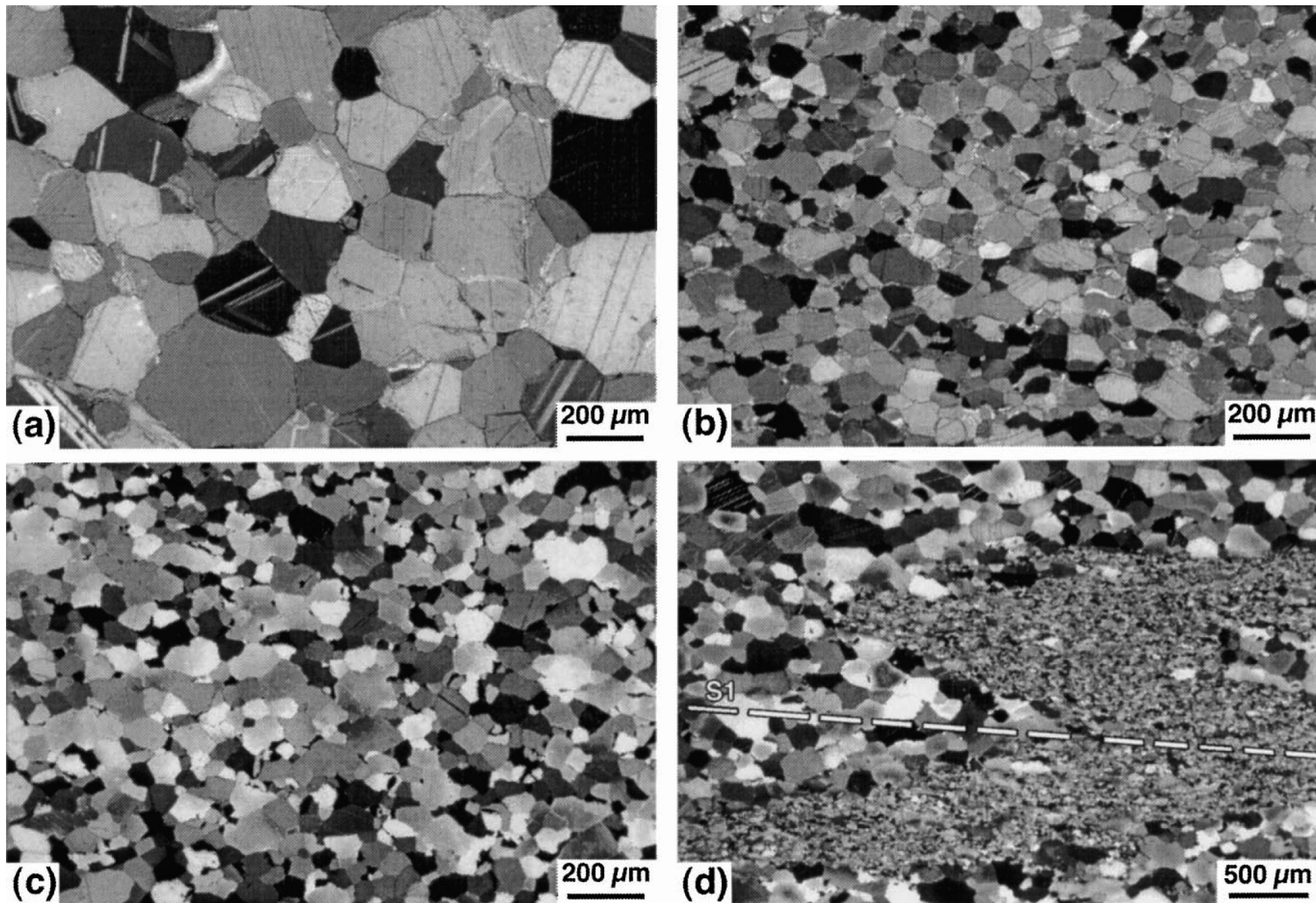
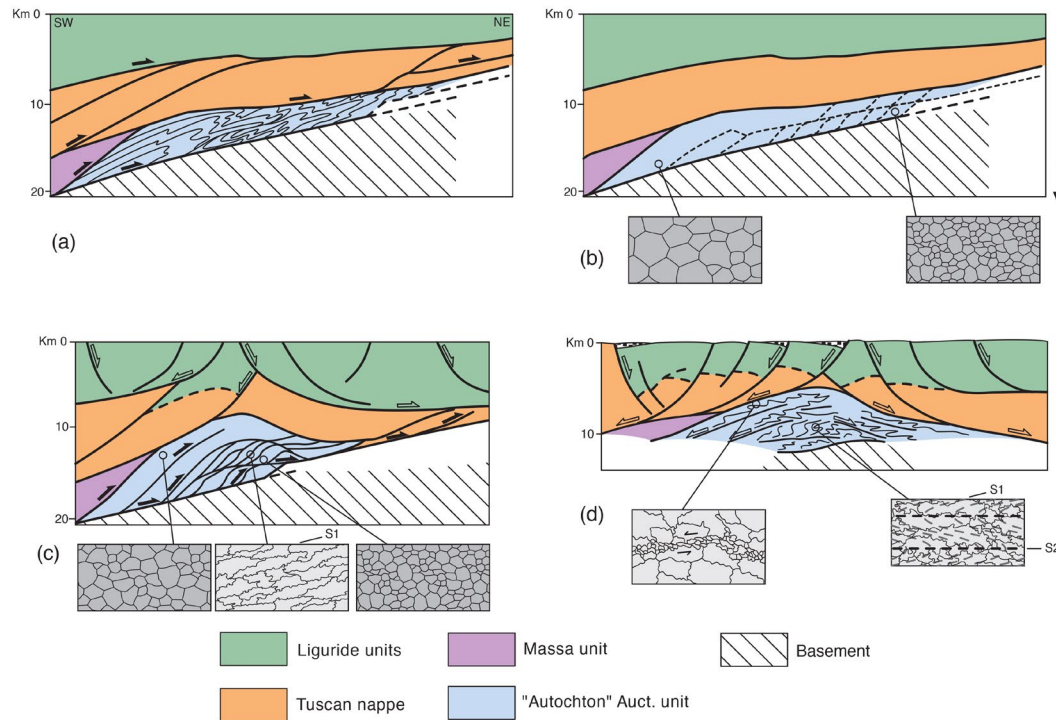
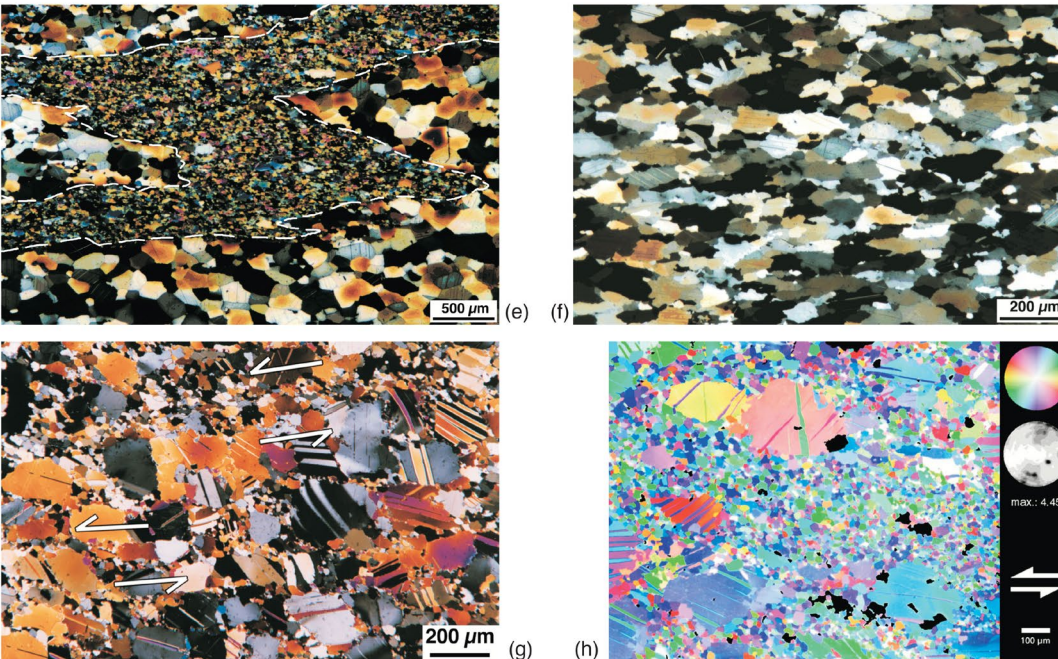


Fig. 22 – Annealed microstructures in Alpi Apuane marbles: (a) Sample 34 (western Alpi Apuane). (b) Sample 39. (c) Sample 180 (eastern Alpi Apuane). (d) D1 fold overgrown by granoblastic microstructure (locality Belgia, western Alpi Apuane). The folded layer, made up of fine-grained, calcite dolomite and phyllosilicates, represents a former stratigraphic layer. From Molli et al. (2000a).



foliation developed in the Apuane unit. After early D1 deformation, thermal relaxation and heating (and/or only a decreasing strain rate) produced statically recrystallized fabrics (type A microfabrics, Fig. 23b). The westernmost rocks were located in the deepest positions, and marbles developed the largest grain sizes and higher calcite/dolomite equilibrium temperature; easternmost marbles were in a higher position, and developed smaller grain sizes at lower temperature. During the late stage of

Fig. 23 – Microfabrics in Alpi Apuane marbles (after Molli et al., 2000a). (a) D1 phase, with main foliation and km-scale isoclinal folds developed. (b) After D1 main folding phase annealing occurred, with static recrystallization and complete obliteration of earlier microfabrics. (c) During final D1 NE transport along thrusts annealed microstructures are passively transported toward NE or reworked in shear zones along thrusts. (d) D2 deformation led to fold and shear zones development along low angle normal faults. Earlier microstructures are reworked in D2 shear zones or along D2 fold axial planes. (e) Typical D1 folds, overprinted by annealed microstructure. (f) Shape preferred orientation of calcite grains parallel to axial plane foliation of D2 fold. (g) Dynamically recrystallized microstructures along D2 shear zone. Strain is associated with core-mantle structure, grain size reduction and rotation recrystallization. (h) C-axes orientations image revealed by computer-aided microscopy (Heilbronner Panozzo and Pauli, 1993). The thin section image is colour coded according to its c-axis orientation and a stereographic Colour Look-up Table. The thin section shows a strong crystallographic preferred orientation oriented normal to the shear zone boundary.





the D1 event (antiformal stack phase, Fig. 23c), further shortening was accomplished. In this phase, dynamically recrystallized microstructures (type B1 microfabrics) were produced in localized, meter to decameter-thick shear zones, where earlier type A annealed fabrics were reworked. These shear zones accommodate the transport of the originally deeper westernmost tectonic levels toward NE in higher positions within the nappe stack.

The D2 history was associated with further exhumation in retrograde metamorphic conditions (Fig. 23d). During this event, narrow millimeter- to decimeter-thick shear zones developed in the higher levels of the Alpi Apuane metamorphic complex (Carrara area), whereas folding occurred at lower levels (Arni area). The temperature was lower during D2 deformation than during D1, but high enough to produce syntectonic recrystallization (type B2 microfabric). This is testified by fine-grained calcite in D2 shear zones, and recrystallized calcite grains elongated parallel to the axial surface of D2 folds. The difference in the temperature during the D2 event (380 °C in the east, 340 °C in the west) can be related to the deeper position of rocks from the eastern area relative to rocks from the western area at the beginning of D2 deformation (Fig. 23d). This frame fits well with the different styles of D2 marble deformation, with predominant structures represented by large scale folding in the east as opposed to localized shear zones in the west (Di Pisa, 1985; Molli et al., 2002).

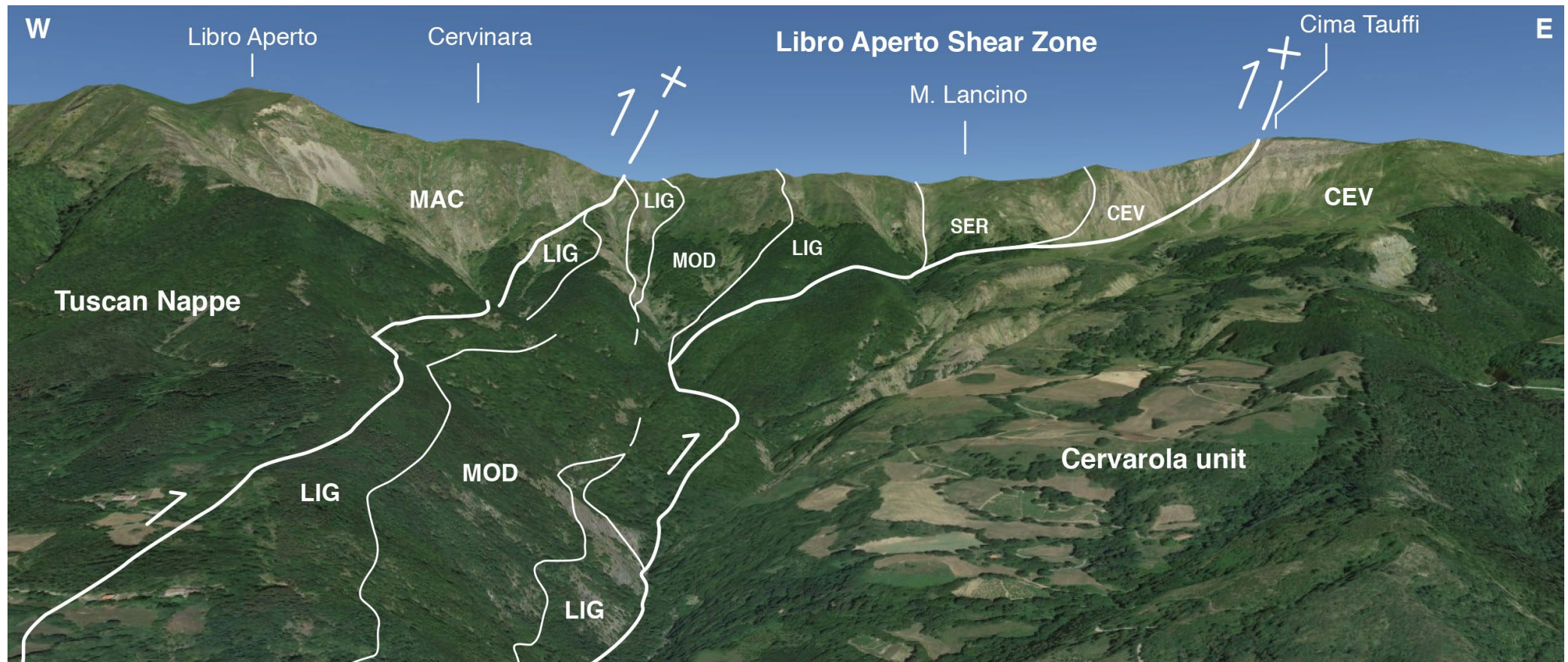


Fig. 25 – Panoramic view from Pianosinatico with geology, Stop 1.1. MAC: Macigno; LIG: Ligurian slice complex; MOD: Mt. Modino sandstones; SER: Serpiano sandstones; CEV: Mt. Cervarola Sandstones.

the thrust onto the Mt. Cervarola Sandstone of Cima Tauffi. The marly-shaly terms of the slices internal to the shear zone, show a marked tectonization, whereas the sandstone terms keep a significant stratigraphic order, with mainly overturned bed attitude.

We continue along the road SS 66 passing the Abetone Pass, from which we can look northwards at the southern slope of the Mt. Cimone and the Libro Aperto; then at the Dogana turn left to Rotari-Lago Santo along the narrow provincial road.



Stop 1.2: Mt. Modino

Coordinates: 44° 9'49.45"N – 10°37'24.49"E

Topics: The M. Modino succession, relationships between the M. Modino sandstone and the M. Modino "basal complex"; Tuscan Nappe and M. Modino tectonics.

We leave the car close to a small chapel, then we take the path to Mt. Modino, 10 minutes walk. Along the southern side of Mt. Modino the whole succession of the Modino unit can be observed (Fig. 27).

From bottom upwards, first outcrop disrupted limestone blocks within chaoticized grey shale belonging to the Ligurian Rotari flysch (Fig. 28a) Cretaceous in age, part of the Chaotic Complex lying at the base of the Modino unit succession.

Through an angular unconformity it is overlain by the Fiumalbo shale, represented by red to dark grey shales with interlayered occasional thin siltstone and fine sandstone beds, middle Eocene to early Oligocene in age. The Fiumalbo shale shows fold structures in the upper part close to the contact with the above Marmoreto marl (Fig. 28b).

The Marmoreto marl lies above the Fiumalbo shale through a minor angular unconformity. It consists from bottom upwards of: a) a pebbly mudstone bed 80 cm thick, showing dispersed rounded to subangular pebble to cobble of Ligurian/Subligurian limestone englobed in a marly matrix lacking of any sedimentary structure; b) a fine to medium sandstone bed 70 cm thick showing marked lenticularity with thinning to right and thickening to left. In detail, on the left side is observable the below pebbly mudstone bed interlayered within sandstone beds forming a lenticular stacked bed horizon 3 m thick with marlstones at the base and closing laterally onto the deformed shales of the Fiumalbo shale fm. It could represent a channel-filling body onlapping onto the Fiumalbo shale. Above, another pebbly mudstone horizon few meters

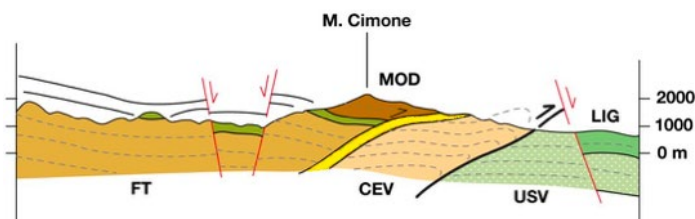
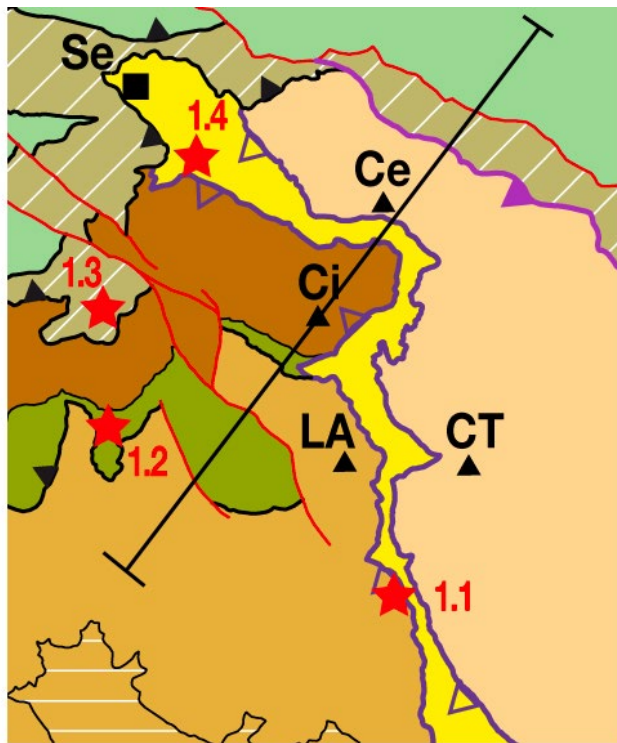


Fig. 26 – Relationships among the Modino unit, Tuscan Nappe, and Cervarola unit in the Cimone-Cervarola area with stops from 1.1 to 1.4. Se - Serpiano village; Ce - Mt. Cervarola; Ci - Mt. Cimone; LA - Mt. Libro Aperto; CT - Mt. Cima Tauffi; FT - Tuscan Nappe; MOD - Modino unit; CEV - Cervarola unit; USV - Sestola-Vidiciatico unit; LIG - Ligurian unit.

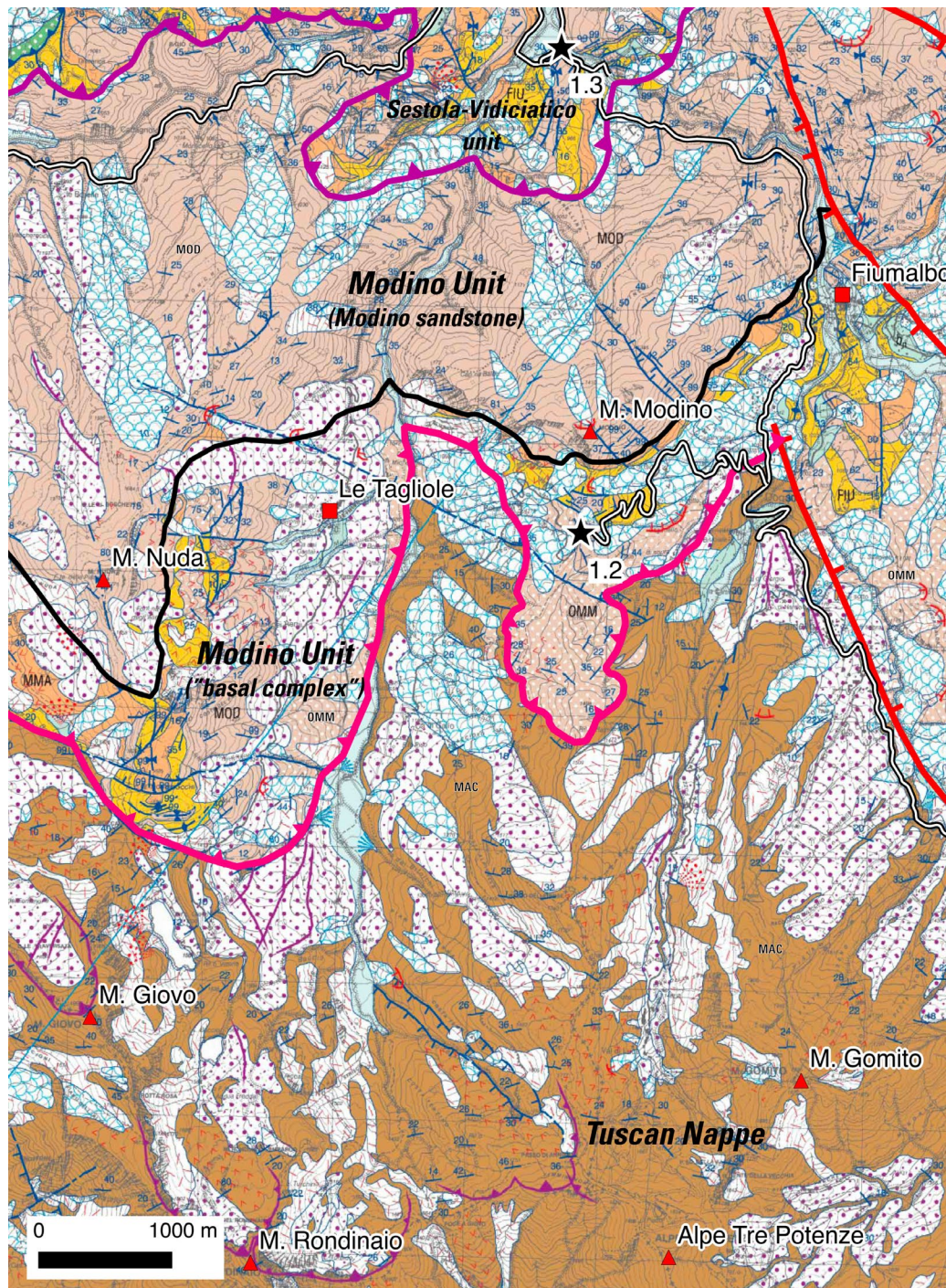


Fig. 27 – Sketch map of the area of Stops 1.2 and 1.3, modified from Puccinelli et al. (2010) and Botti et al. (2011). The thick purple line is the tectonic base of the Sestola-Vidiciatico unit, the thick pink line is the tectonic base of the Modino unit, the black line is the stratigraphic boundary between the Mt. Modino sandstones and their basal complex, the red lines are normal faults.

thick occurs. It has similar features of the below bed, but this shows a transition to cleaner marly mudstone lacking or with minor detritus within. The marlstones show some thin sandstone beds interlayered.

The Marmoreto marl passes through a sharp but parallel boundary to thin bedded sandstones, the base of the Mt. Modino sandstone. This horizon, 10 meters thick, is built of thin-bedded turbidite sandstones (*sensu* Mutti, 1977), showing typical sedimentary structures (i.e. partial Bouma sequence, flute and groove marks, fluid escapes). Above, up to the top of the cliff, thicker turbidite sandstone beds of the Mt. Modino sandstone occur. A moderately 10° dipping angular unconformity is present within the middle- upper part of the formation, as observable looking from east.

A complete panoramic view is observable from Mt. Modino (Fig. 29). Looking around we'll see the Mt. Cimone characterized by the Modino unit and particularly by an overturned slice forming its top, the Abetone Pass and the Libro Aperto behind, the Mt. Gomito, the Alpe Tre Potenze, the Mt. Rondinaio and the Mt. Giovo, where the wide monocline with the Macigno sandstone succession dipping to northeast, shows an



Fig. 28 – Stop 1.2, Mt. Modino. (a) Outcrop of deformed beds of the Rotari flysch, part of the Monte Modino basal Complex. (b) Outcrop of the upper part of the Modino unit, with in evidence the sedimentary bodies (white lines) and the unconformity dashed red line.



upwards sharp reduction in bed thickness, that Bruni et al. (1994b, and references therein) interpreted as the stratigraphic boundary between the Macigno and the Mt. Modino sandstone, lacking of the chaotic unit in between. Looking to WSW we'll see the Mt. Nuda showing the prolongation of the Mt. Modino settings. In the Northern Apennines geological framework, the Monte Modino succession has been interpreted in two different ways. The Florence school and others (Bruni et al., 1994b, and references therein) consider it as the product of a large submarine slide within the Tuscan turbidite sandstone basin during the Late Oligocene and called it as "Mt. Modino Olistostrome" (see also Lucente et al., 2006). Following this interpretation the submarine slide should be placed conformably at the top of the Macigno or in the lower part of the Mt. Modino sandstone representing the upper continuation of the turbiditic sedimentation. At the opposite a tectonic interpretation (Plesi et al., 2000, with references therein) consider the Ligurian rocks as a basal tectonic complex linked with the orogenic wedge development, with sedimentation on top (Fiumalbo shale to Mt. Modino sandstones) and only later then thrust onto the Macigno. We'll discuss this topic in terms of structural framework, relationships

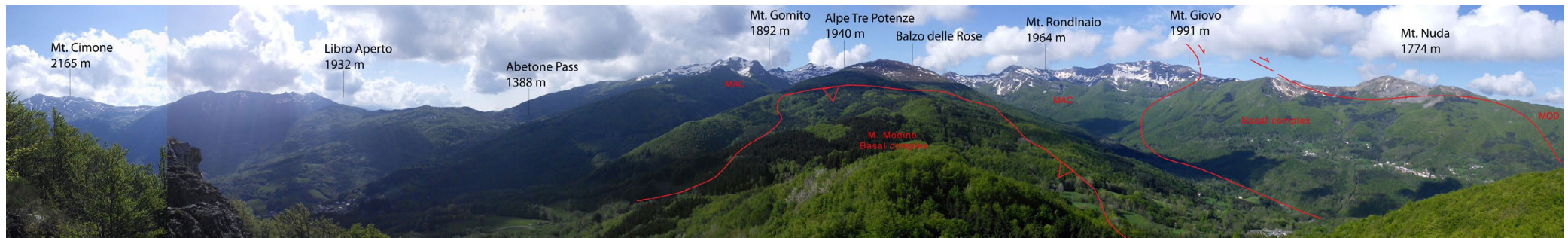


Fig. 29 – Panoramic view from Mt. Modino (Stop 1.2).

between tectonics and sedimentation (tectonic complexes vs submarine mass wasting and debris flow), age and stratigraphic constraints, palaeogeographic inferences.

We'll go back to Dogana and follow the SS 66 up to Ponte Modino, then turn right along the road to Riolutato and then turn right again along a small road parallel to the Scoltenna Creek, leading to the San Michele ENEL power station.

Stop 1.3 Ponte Modino (2 km before Pievepelago)

Coordinates: 44°11'45.30"N – 10°37'17.98"E

Topics: Deformation of tectonic units overlying the Modino and Cervarola units: the Sestola-Vidiciatico unit.

A short walk along the road in the Ponte Modino locality along the Scoltenna river allows to have a well representative overview of the deformation style in the Sestola-Vidiciatico unit, close to the tectonic contact with the underlying Modino unit (Fig. 30).

Along the road beautifully exposed sandstones crop out, with beds dipping 60° toward NE. The sandstones show alternation of thin to thick beds with typical turbidite structures and a slump horizon about 1 m thick. The sandstones pass downwards to strongly deformed and foliated marlstones, referable to the Marmoreto marl. The internal structure and deformation style of Marmoreto marl are well exposed along the cliff above the San Michele ENEL Power station (Fig. 31a). A steep cliff along the Scoltenna valley (Fig. 31b, c) shows the typical setting of the Sestola-Vidiciatico unit, where tectonic contacts between sandstones and shales slivers are very well developed. The red shales (Fiumalbo shale) show a chaotic setting with disharmonic folds at all scales and

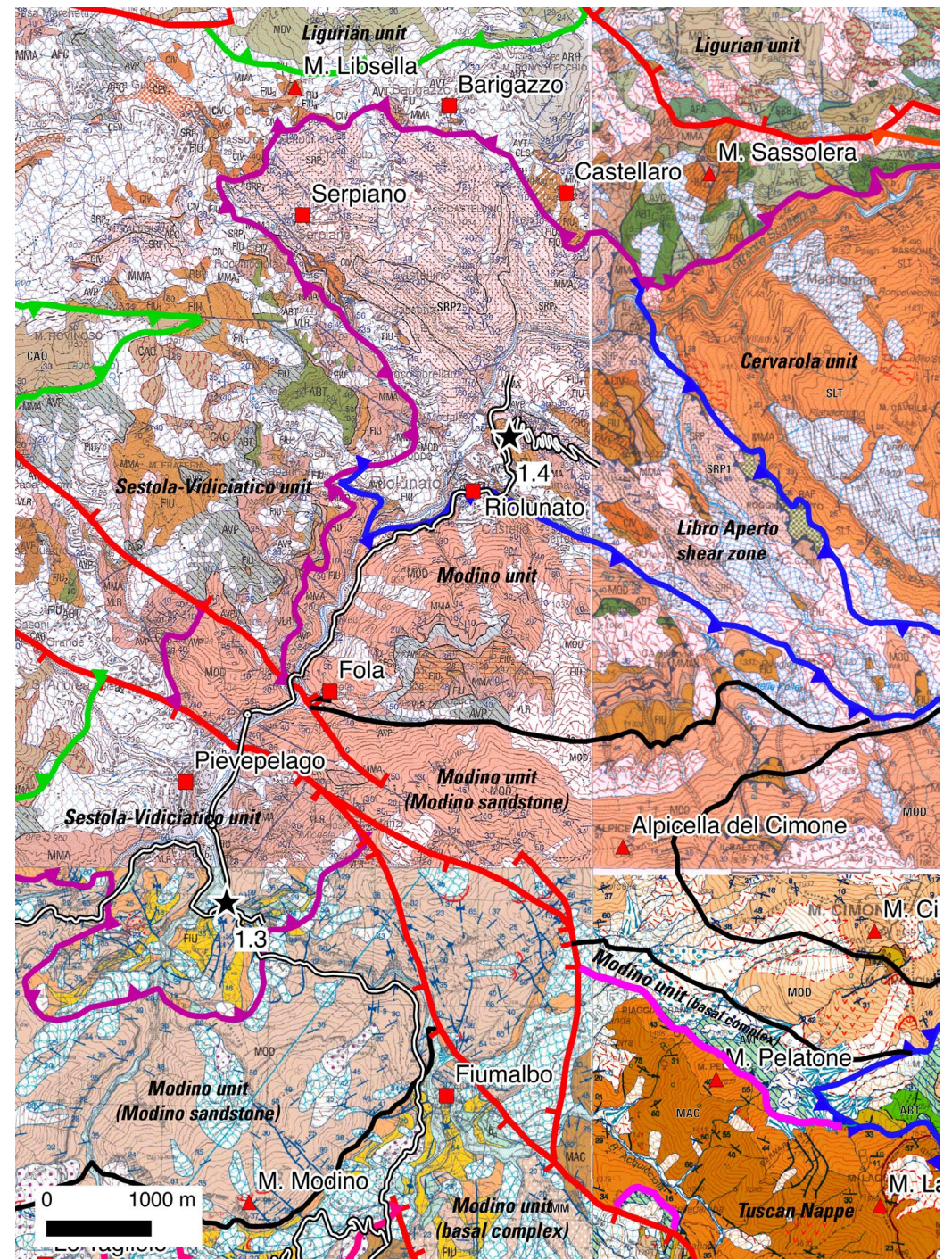


disrupted remnants of sandstone beds. The outcrop also allows to have a close look to the network of tectonic surfaces.

In the whole outcrop here we can appreciate the internal structure of the Sestola-Vidiciatico unit, formed by imbricated tectonic slivers characterized by strongly deformed portions of Mt. Modino sandstone, Marmoreto marl and Fiumalbo shale. The Sestola-Vidiciatico unit is emplaced above the Modino unit during subduction-related shortening; this interpretation is shared with the more comprehensive studies on the Sestola-Vidiciatico unit carried out in recent years by geologists of Florence, Modena and Reggio Emilia universities (Remitti et al., 2004, 2007, 2011, 2013; Vannucchi et al., 2008, 2009, 2010, 2012, and references therein).

All the rocks and tectonic features we observed in this Stop were alternatively interpreted in the past as belonging to the Pievepelago unit or Pievepelago fm. (Nardi, 1965; Plesi et al., 2002, among the others),

Fig. 30 – Sketch map of the area of Stops 1.3 and 1.4, modified from Bettelli et al. (2002); Plesi (2002); Puccinelli et al. (2010); Botti et al. (2011). The green line is the tectonic base of the Ligurian unit, the purple line is the tectonic base of the Sestola-Vidiciatico unit, the pink line is the tectonic base of the Modino unit, the blue lines are the main tectonic thrusts confining the Libro Aperto shear zone, the black line is the stratigraphic boundary between the Mt. Modino sandstones and their basal complex, the red lines are normal faults.





(a)



(b)



(c)

tectonically of stratigraphically located above the Mt. Modino sandstone.

We take again the road to Riolutato, and after the village we'll turn right toward the ski station of Le Polle.

Stop 1.4: Riolutato – Le Polle

Coordinates: 44°14'7.65"N – 10°39'20.57"E

Topics: Deformation in the Libro Aperto Shear zone, relationships between the Modino unit/Cervarola unit/Sestola-Vidiciatico unit.

Riolutato: park in front of the cemetery.

Here we'll have a look at the internal structure of the Libro Aperto Shear Zone (Figs. 30, 32), close to its southern border with the overlying Mt. Modino sandstone of the Modino unit, whereas the tectonic contact with the underlying Mt. Cervarola Sandstone of the Cervarola unit outcrops northward, along the Scoltenna River. Here rocks in the Libro Aperto Shear Zone are represented by strongly deformed marlstones (Marmoreto marl), associated with grey to red shales (Fiumalbo shale).

A walk along the road will allow us to observe thin-bedded turbidite sandstones lying tectonically below the marlstones, called Serpiano sandstone correlated

Fig. 31 – The Sestola-Vidiciatico unit at Ponte Modino, Scoltenna Valley (Stop 1.3). (a) San Michele ENEL Power Station: tectonic contact between sandstones and marlstones. (b) Outcrop of sandstones and marlstones slivers, strongly deformed. (c) Detail of (b), red box.



with the lower and/or thinner portion of the Mt. Cervarola turbidite system, showing overturned or vertical attitude of beds. At the road bend (helicopter landing area) crops out again the above marlstones. This outcrop allows to look the deformational structures (foliation, S-C fabric) affecting the marlstones in the Libro Aperto Shear Zone.

From this point we have a panoramic view on the Scoltenna Valley, showing the units bordering the Libro Aperto Shear Zone (Fig. 32a). More in detail (Fig. 30), the shear zone is delimited southward by the Modino unit of Mt. Cimone structured in tectonic slices involving Mt. Modino sandstone and its basal complex, whereas northwest of Riolunato and Serpiano, the tectonic contact with the above-lying Sestola-Vidiciatico unit, here represented by deformed rocks of the Modino unit and Ligurian basal complex terms, crops out. Northward we recognize the high-angle overturned dipping beds of the Serpiano sandstone, part of the Libro Aperto Shear Zone, delimited at the top by the approximately horizontal tectonic boundary with the Sestola-Vidiciatico unit, that seals also the tectonic upper and lower boundaries of the shear zone. On top of the slope of Mt. Cantiere, the tectonic boundary with the above Ligurian unit is recognizable.



(a)



(b)



(c)

Fig. 32 – Stop 1.4. (a) Relationships between the Libro Aperto Shear Zone and the Sestola-Vidiciatico unit. (b) Deformed Marmoreto marls in the Libro Aperto Shear Zone. (c) Overturned Serpiano sandstones in the Libro Aperto Shear Zone.



The meaning and structure of the Libro Aperto Shear Zone will be discussed, particularly its tectonic timing and relationships within the geological framework of the Northern Apennines. Important will be also to discuss the features, mechanisms and timing of emplacement of the Sestola-Vidiciatico unit, that records important and progressive tectonic events.

Take the road back to Ponte Modino, then turn left to Sant'Anna in Pelago-Passo delle Radici.

Stop 1.5: San Pellegrino in Alpe

Coordinates: 44°11'27.73"N - 10°29'59.73"E

Topics: Deformation in the frontal part of the Tuscan Nappe, later thrusting of tectonics units, relationships with Modino unit and Sestola-Vidiciatico unit, panoramic view of the Garfagnana graben and Alpi Apuane Metamorphic complex.

We'll arrive at Radici Pass and turn left to S. Pellegrino in Alpe. Before the village we'll take a road on the left to Mt. Spicchio. In proximity of Mt. Spicchio, we'll leave the car and we'll walk to La Cimetta (Fig. 33).

Along the slope to La Cimetta overturned steep inclined

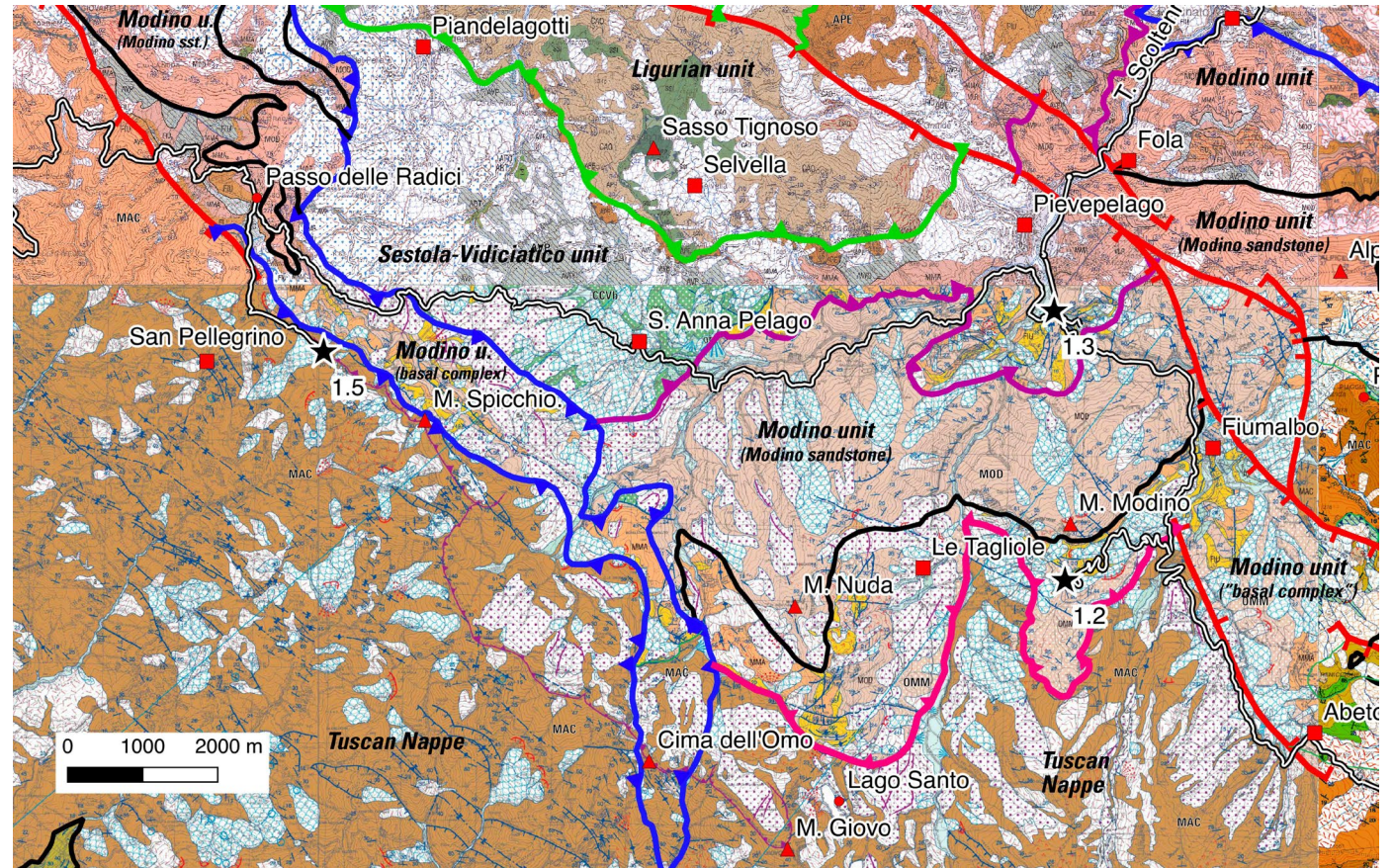


Fig. 33 – Sketch map of the area of Stop 1.5, modified from Plesi (2002) and Puccinelli et al. (2010). The green line is the tectonic base of the Ligurian unit, the purple line is the tectonic base of the Sestola-Vidiciatico unit, the pink line is the tectonic bottom of the Modino unit, the blue lines are out-of-sequence thrusts, the black lines are stratigraphic boundaries between the Mt. Modino sandstones and their basal complex, the red lines are normal faults.



sandstone beds of the Macigno are observable. Turbidite structures and tool marks and trace fossils occur at the base of the beds. On the top of the La Cimetta and along the ridge, crop out sandstone overturned beds of the Macigno representing the narrow overturned limb of a frontal anticline (S. Pellegrino in Alpe Anticline) of the Tuscan Nappe.

Below the ridge, a thrust emplaces the Tuscan Nappe above the Modino unit (Mt. Spicchio thrust). This thrust, NNW-SSE oriented and with top-NE transport direction, crops out near the Radici Pass, whereas its northwards prolongation is cut by a NNW-SSE normal fault SW-dipping.

From the La Cimetta northwards outcrops of marlstones and shales belong to the Modino unit are observable, whereas the panoramic view towards east allows to appreciate the extension of the Sestola-Vidiciatico unit and of the above Ligurian unit. The view towards west allows to recognize the Macigno of the Tuscan Nappe and to have a look to the Apuan Alps behind. The meaning of the late thrust of the Modino unit onto the Sestola-Vidiciatico unit and the frontal thrust of the Tuscan Nappe will be the object of the discussion in the field. The all around panoramic view will be the occasion to discuss the whole framework of this part of the Northern Apennines and the relationships with the Alpi Apuane Metamorphic Complex.

2nd day - Alpi Apuane

Field Trip Route

Corfino – Castelnuovo Garfagnana – Arni – Seravezza – Massa.

Topics

Tectonics of the Alpi Apuane Metamorphic Complex, exhumation and uplift of metamorphic units, relationships with overlying units, microfabric development in marbles.

Stop 2.1: Turrite Secca

Coordinates: 44° 4'52.15"N – 10°21'32.53"E

Topics: Cataclastic rocks of the Calcare Cavernoso at the top of the metamorphic units.

From Castelnuovo Garfagnana we take the SP 13 and after about 7 km we park on the left side of the road, along the Turrite Cava River (Fig. 34).



Fig. 34 – Sketch map of the area of Stops 2.1, 2.2, 2.3 and 2.4, modified from Puccinelli et al. (2010) and Conti et al. (2018). The thick red lines are low-angle normal faults, orange lines with barbs show the tectonic base of the Calcare Cavernoso.

In this small outcrop we can observe, although not very well exposed, the Calcare Cavernoso. This formation, considered in the local literature the stratigraphic base of the Tuscan Nappe, is a thick (> 200 m) cataclasite developed first during nappe emplacement and later during low-angle normal faulting contemporaneous with exhumation and uplift.

In these rocks the typical vacuolar structure can be observed (cornieules, rauhewacke), with dolomite/calcite clasts and an overall brecciated structure (Fig. 35). Clasts derive mainly from Tuscan Nappe formations, but clasts of metamorphic rocks are also present.

We infer that most of cataclastic flow in rocks occurred during low-angle normal faulting (exhumation and uplift) and not during activities of faults now bordering the Alpi Apuane Metamorphic Complex.

Stop 2.2: Vianova

Coordinates: 44° 5'44.29"N – 10°19'25.92"E

Topics: Tectonic contact between the Tuscan Nappe and the "Autoctono" unit in the Eastern Alpi Apuane.

At this stop, along the road from Capanne di Careggine to Vianova, we can observe the contact between the Apuane metamorphic core and the unmetamorphosed Tuscan Nappe (Fig. 36). The Calcare Cavernoso (carbonate-cataclasite base of Tuscan Nappe) is not observed here, and the contact is between Liassic carbonates ("Calcari ad Angulati") and the Oligocene metasandstones and slates (Pseudomacigno).

The contact is characterized by a fault zone 10s of meters thick in which it is possible to distinguish different domains.



In the footwall rocks formed by metasediments of the Pseudomacigno, D2 folds with wavelengths of decimeters to half of meters are associated with a sub-horizontal axial planar foliation. The metasediments are affected by well developed veins. The dominant vein system, whose geometry indicates a syn- to late development with respect to folding, shows an en echelon arrangement that suggests a top-to-the east kinematics. At the top of folded domain, a meter-thick layer of cohesive, fragmented metasediments of the Pseudomacigno can be recognized. This cataclastic domain is in contact with a meters-thick fault gouge, with evidence for confined fluid infiltration indicated by the red, violet, and yellowish color of the matrix. The matrix contains variable size clasts of footwall and hangingwall rocks and some folds with decimeter wavelength may be recognized. Although evidence of non- cylindrical folds can be observed, the vergence of most of these folds is consistent with top-to-the-east kinematics. The fault gouge is overlain by the cataclastic Liassic-type carbonates of Tuscan Nappe. Well-developed P-foliations and a variety of Riedel-type fractures can be observed, still coherent with the general top-to-the-east kinematics.

The fault zone is interpreted as part of a low-angle normal fault system related to footwall exhumation of the metamorphic units based on the geometric relationships between: (1) original bedding S_0 , R-R/ fractures and P-foliation in hangingwall carbonates; (2) sub-horizontal D2 foliation within footwall units and the fault zone; and (3) the absence of the Calcare Cavernoso indicating a cut-down section in the hangingwall stratigraphy. Thermochronological analyses (zircon and apatite fission tracks and HeAp and HeZr) performed as part of the RETREAT project (M. Brandon, 2002, written commun.) on the metasediments of Pseudomacigno in the footwall and Macigno in the hangingwall of the fault may be found in Fellin et al. (2007). The Pseudomacigno sample from the metamorphic core in the footwall of this structure yielded a ZHe age of 3.6 ± 0.3 Ma, whereas the Macigno in the hangingwall yielded a ZHe age of 12.5 ± 1 Ma, which may be only a partially reset age.



Fig. 35 – Cataclasite (Calcare Cavernoso), Stop 2.1, Turrite Cava.

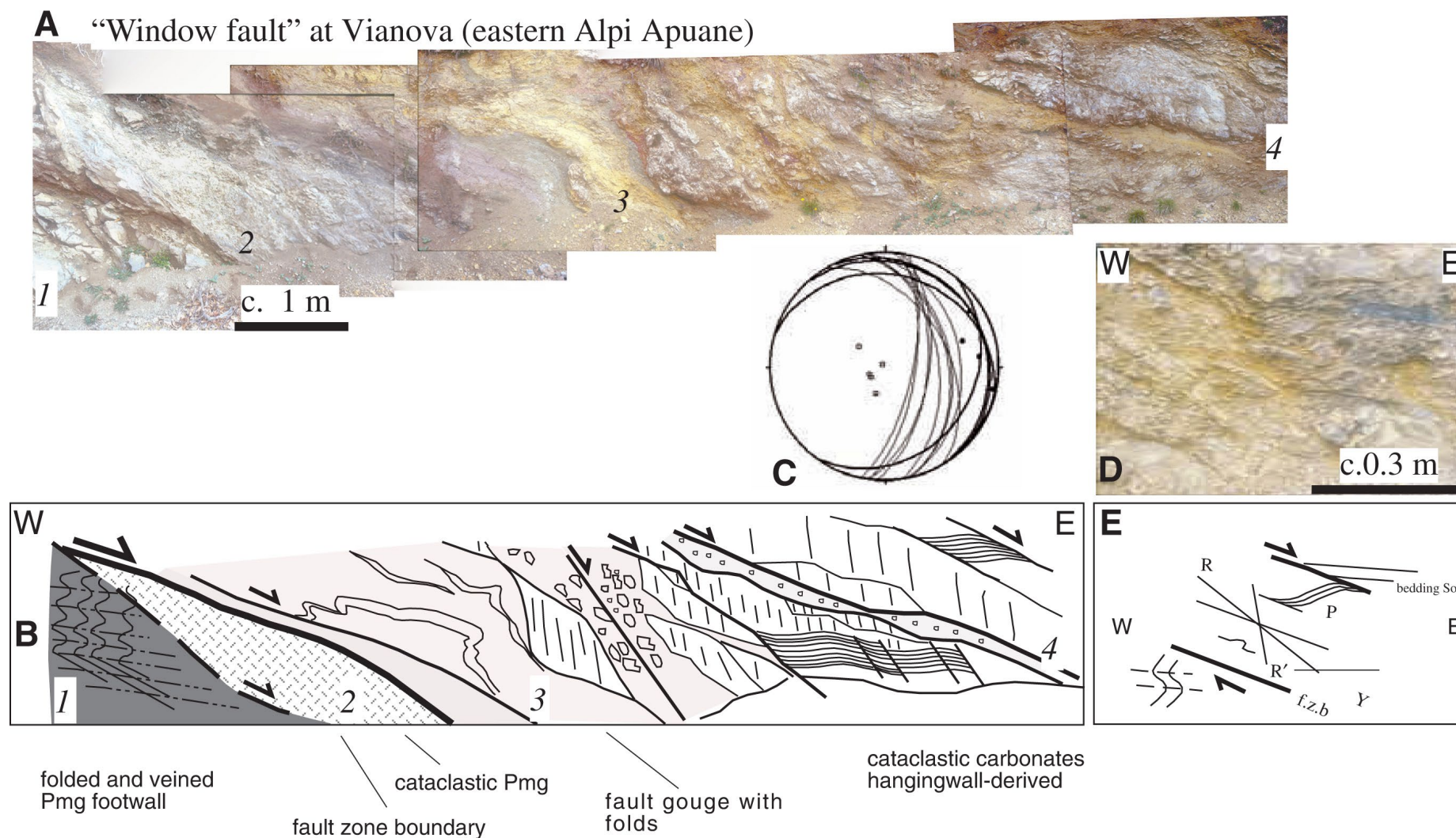


Fig. 36 – Stop 2.2. (A) General view (scale bar 1 m) and schematic representation (B) of the structural elements of the tectonic “window fault” between the unmetamorphic Tuscan Nappe and metamorphic Apuane Core Complex, a fault that is observable at Vianova (road toward Capanne di Careggine) eastern Apuane. (C) Equal area lower hemisphere stereograms of structural data showing the poles (open dots) of the main slip surfaces (bold great circles), slicklines (full dots), R0 fractures and veins in footwall domain (light great circles). (D) Detailed view of foliated cataclasite derived from impure Jurassic limestone of the Tuscan Nappe. Scale bar 0.3 m. (E) Main fault-related structural elements observable; f.z.b.—fault zone boundary; R, R’—Riedel fractures; Y—slip surfaces; P—foliation. After Molli (2002).



The contrasting exhumation paths of the Alpi Apuane core and its cover suggest that the removal of a crustal thickness of the order of 3.6 ± 0.5 km must have occurred along the eastern Apuane window fault under brittle conditions (at temperatures lower than 200 °C) between 6 and 4 Ma. Since 4 Ma, the metamorphic core and the overlying unmetamorphic units, already resting at very shallow levels, reached the surface, probably via erosion, as a single coherent body (Fellin et al., 2007).

Stop 2.3: East of Capanne di Careggine

Coordinates: 44° 4'19.85"N – 10°19'33.42"E

Topics: Mylonitic cherty limestones.

About 1 km E of the Capanne di Careggine Village along the road metamorphic cherty limestones ("Calcari selciferi" fm.) crop out (Fig. 34). In this area severe shear deformation affect Upper Jurassic - Early Miocene rocks. Cherty limestones, calcschists (metamorphic "Scaglia Toscana") and phyllites and metasandstones (Pseudomacigno) are here strongly foliated and bedding is completely transposed along S1 foliation. S1 foliation bears a L1 stretching lineation NE-SW oriented.

We stop where the "Calcari selciferi" fm. crops out (Fig. 37). The main foliation recognizable at outcrop scale (S1) is the axial plane foliation of some isoclinal folds showing NE-facing. Some of these folds refolds an earlier foliation, we interpret this features as related to progressive deformation during D1 deformation (subduction-

related), but some shearing and deformation during exhumation processes cannot be ruled out.

The intense shearing and strain the rocks suffered is testified by strong boudinaged of cherty lenses, now completely transposed along S1. Most of dynamic recrystallization occurred in carbonate-rich layer, now marbles. Deformation therefore occurred in a temperature interval above inception of dislocation creep



Fig. 37 – Mylonitic cherty limestones at Stop 2.3.



in calcite and below plasticity in quartz. Some of cherty clasts derived by boudinaged cherty lenses, but some clasts derived from deformed veins.

Shear sense indicators are present but somehow ambiguous (both top-NE and top-SW present), this could indicate a strong flattening component during shearing.

We walk westward and we reach metaradiolarites ("Diaspri") and calcschists of the metamorphic "Scaglia Toscana".

Stop 2.4: Capanne di Careggine

Coordinates: 44° 4'8.69"N – 10°18'50.83"E

Topics: Deformation in the Pseudomacigno. In this outcrop, just W of the Capanne di Careggine village, the Pseudomacigno Fm. is strongly deformed and folded. The Pseudomacigno can be correlated with the Macigno of the Tuscan Nappe (Chattian-Early Aquitanian), after deformation and greenschists facies metamorphism. In less deformed parts of the Pseudomacigno graded bedding and some primary features can still be observed.

In this outcrop the Pseudomacigno is represented by metasandstones and phyllites strongly foliated (Fig. 38). The main foliation at outcrop scale is the S1 foliation, throughout refolded by D2 NE-facing folds. Axial plane foliation of D2 folds is usually represented by a crenulation cleavage spaced in more quartz-rich levels and more penetrative in fine grained or phyllitic levels.



Fig. 38 – D2 folds in the Pseudomacigno, Stop 2.4.



Stop 2.5: Passo del Vestito

Coordinates: 44° 3'51.85"N – 10°13'24.02"E

Topics: Panoramic view toward the northern Alpi Apuane.

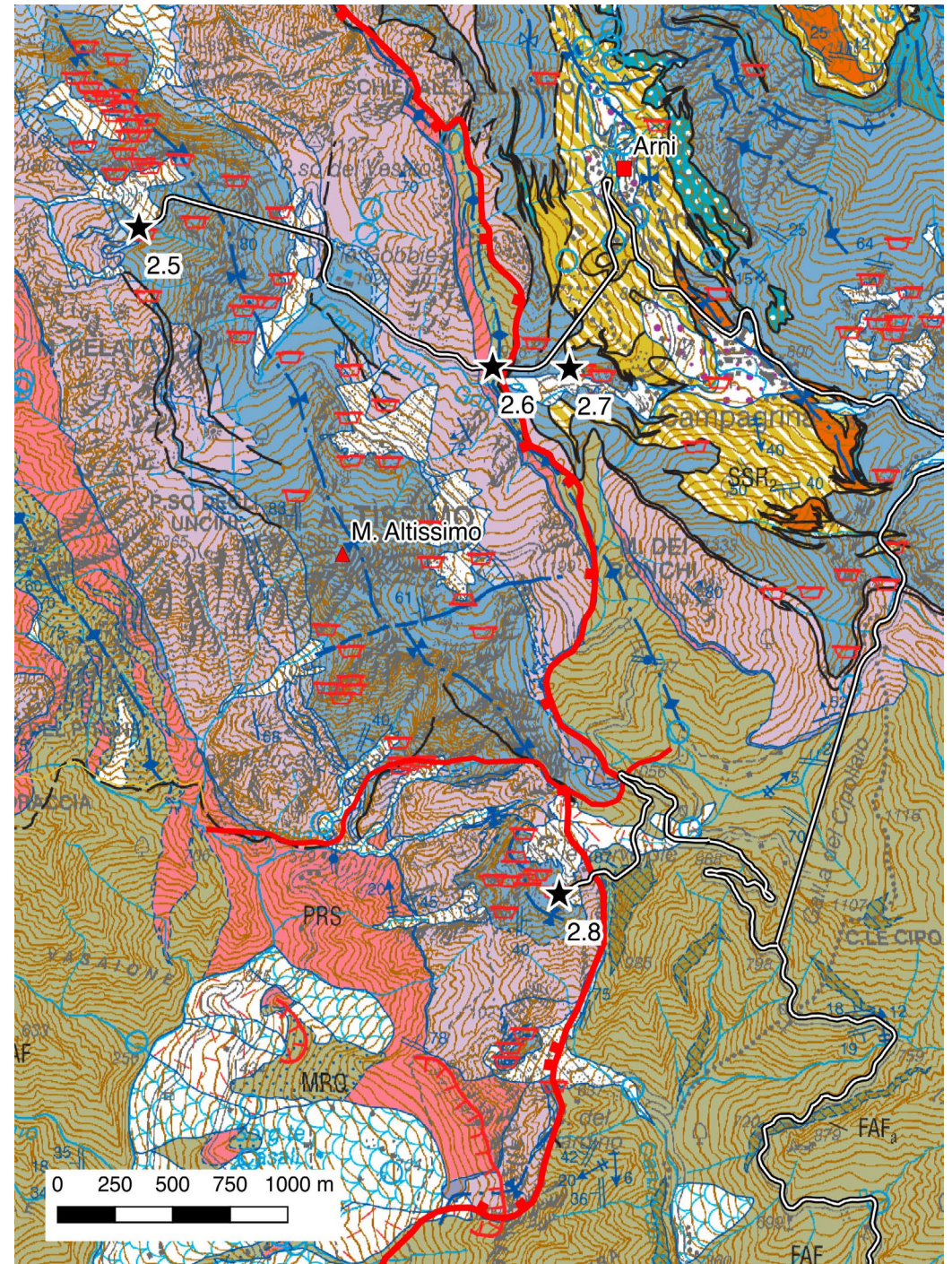
At this stop (Fig. 39), a panoramic view of the western side of the Alpi Apuane region can be observed from the Tyrrhenian Sea to the eastern Alpi Apuane (Figs. 40, 41).

The panorama is characterized by two main ridges. First the Mandriola crest (above the village of Resceto), toward the NE it joins at M. Cavallo; in the distance the ridge includes from east to west the peaks of the mountains: Tambura, Cavallo, Contrario, Grondilice, Rasori, Sagro, Spallone.

The westernmost structure is the overthrust of the Massa unit (higher grade metamorphism 450–500 °C; 0,6–0,8 GPa) at the top of the lower grade "Autoctono" unit (350–400 °C; 0,4–0,6 GPa). The fold axes of the structures dip shallowly (10°–20°) toward the north and therefore from north toward the south deeper parts of the structure crops out.

The normal limb of the D1 Vinca anticline crops out in the relief of M. Spallone-Sagro, and is moderately dipping towards the west and, from the east toward the west includes Grezzoni, dolomitic marbles,

Fig. 39 – Sketch map of the Stops 2.5, 2.6, 2.7 and 2.8, modified from Conti et al. (2018). The thick red lines are normal faults.



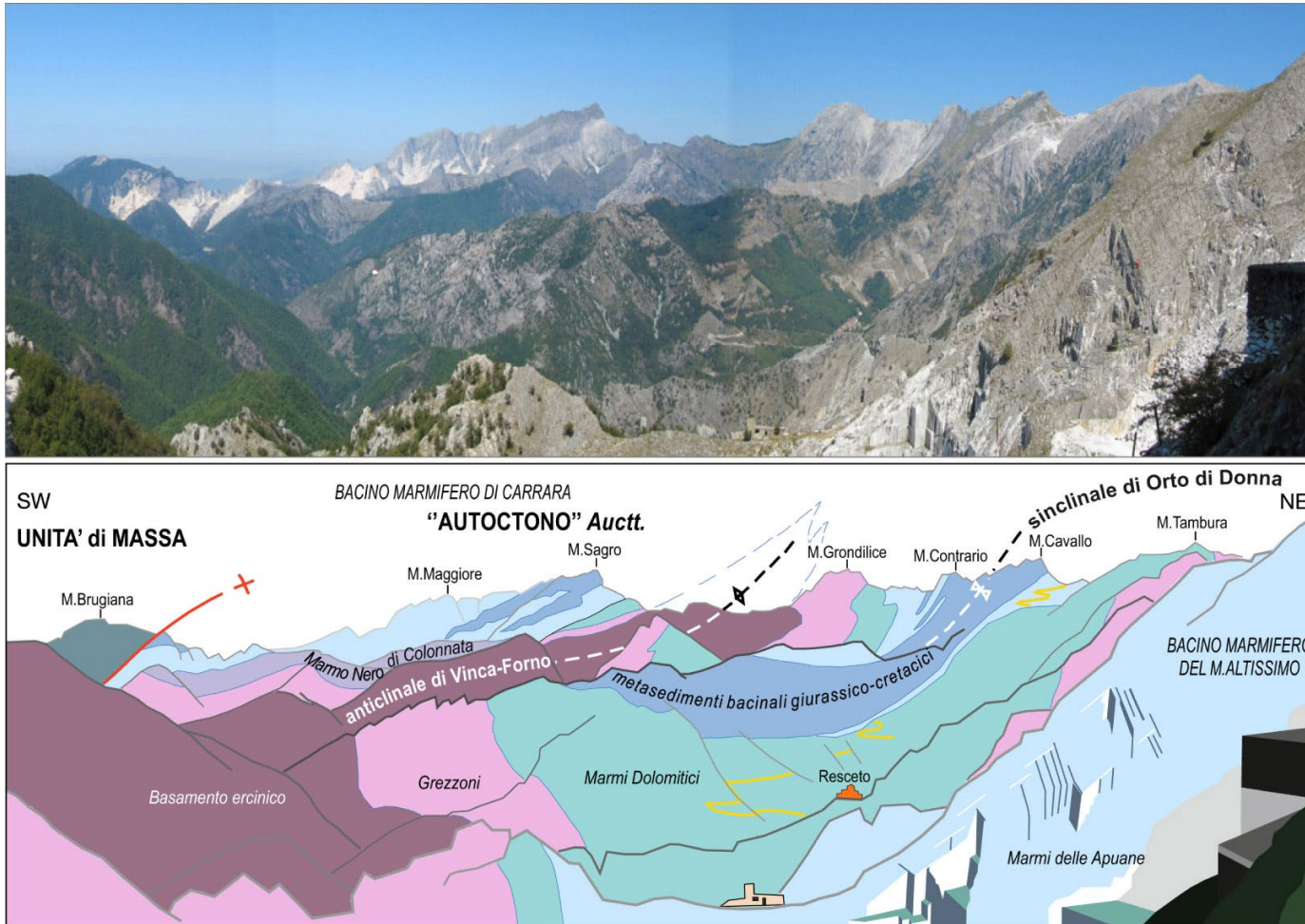


Fig. 40 – Panoramic view of the northern Alpi Apuane, from Stop 2.5, Antona-Arni road, W of the Passo del Vestito tunnel. Line Drawing by E. Patacca and P. Scandone, in Conti et al. (2018).

Marbles (east edge of Sagro and M. Spallone) and Cherty limestones (peak of M. Sagro and M. Spallone). The core of the Vinca anticline is made of phyllite and volcanic rocks of the Palaeozoic basement and crops out at the crest of M. Rasori between M. Sagro and M. Grondilice and further south toward the Forno valley from our point of observation. The overturned limb of the Vinca anticline crops out between M. Grondilice and M. Cavallo, and from west to east, includes Grezzoni (M. Grondilice), dolomitic marble and marble (Passo delle Pecore), cherty limestone.

The core of the D1 Orto di Donna syncline consists of Chert, Entrochi cherty limestone, and it is developed for several km between M. Cavallo and the Mandriola.

Toward the east of M. Cavallo to M. Tambura the normal limb of the Orto di Donna syncline crops out. The thin Paleozoic core of the next

anticline (M. Tambura Anticline) comes in to the eastern side of the panorama at Campaniletti. The effects of the post-collisional tectonics are quite evident at a large scale on the southern side of M. Grondilice: the overturned limb of the Vinca Anticline is folded by a synform with a core of basement phyllite and by an antiformal with a core of Liassic marbles (M. Rasori synform and antiformal). The complex structure in

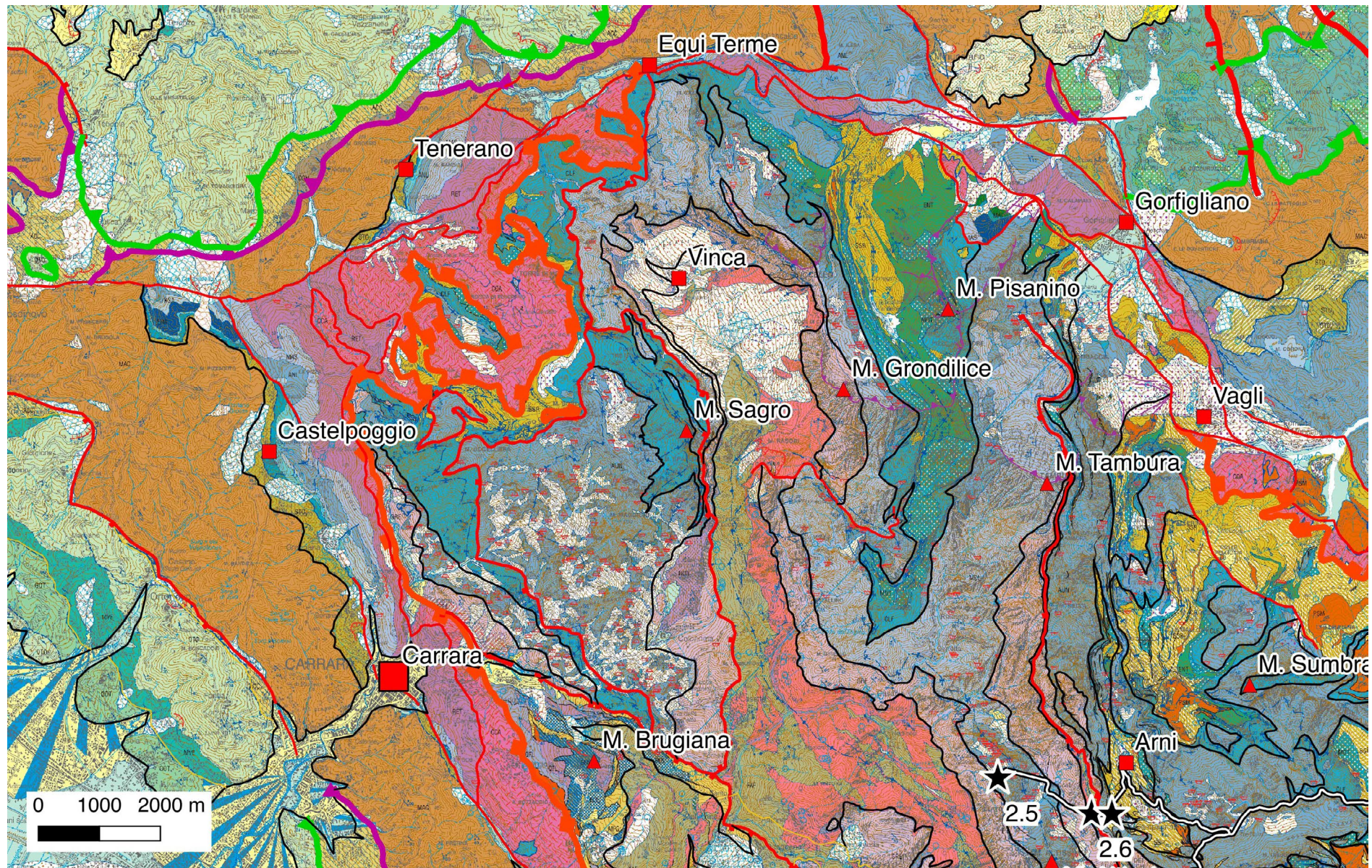
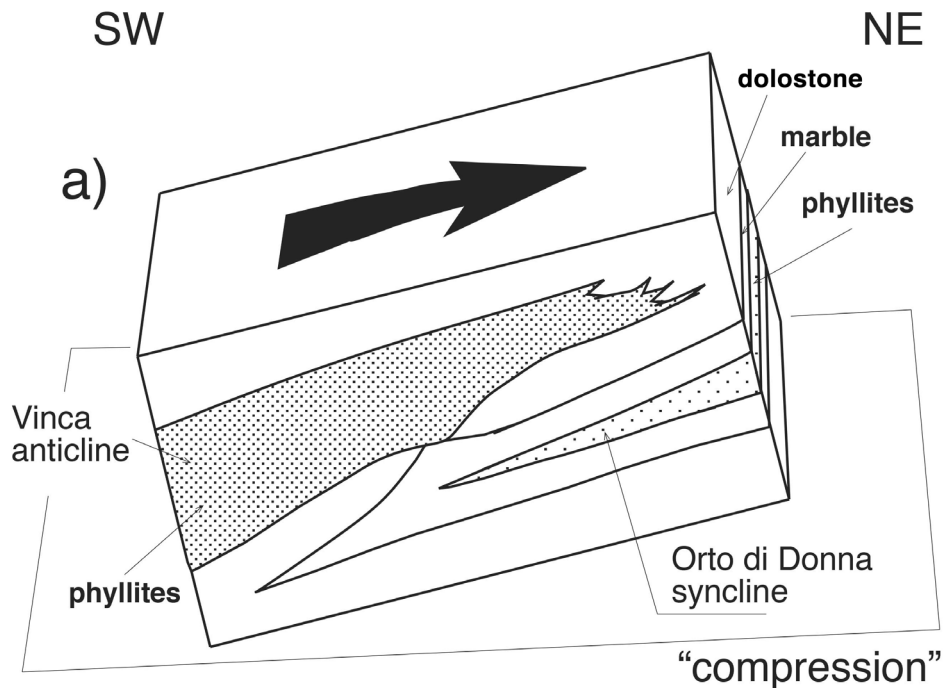


Fig. 41 – Sketch map of the northern Alpi Apuane, modified from Conti et al. (2018). The thick green lines are the tectonic base of the Ligurian unit, the thick purple lines are the tectonic base of the Subligurian Unit, the thick red lines are the tectonic base of the Calcare Cavernoso, the red lines are normal faults, the black lines are stratigraphic boundaries.



the overturned limb of the Vinca Anticline is produced by activity of D2 extensional shear zones in the less competent formations of the Orto di Donna syncline (Cretaceous-Eocene Phyllite and calcschist) and the Vinca anticline (Palaeozoic phyllites) that superpose and interfere with the earlier (D1) structures. A large-scale this is a type-3 interference pattern that can be observed in the central part of the view, outlined by Triassic dolostone in the inverted limb of the Vinca-Forno anticline refolded in normal position by a D2 kilometer-scale structure.

A kinematic sketch of the evolution of this area during D1 and D2 deformation is reported in Fig. 42.

Stop 2.6: Castellaccio

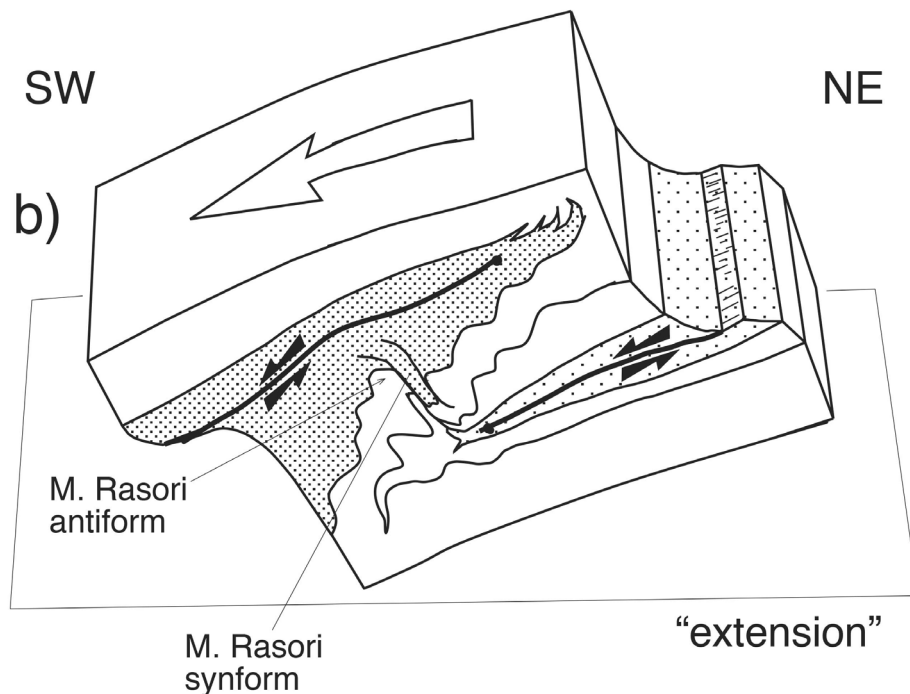
Coordinates: 44° 3'33.11"N – 10°14'32.93"E

Topics: Core of the Tambura anticline.

In this stop it is possible to walk across a major Alpi Apuane structure, the Tambura anticline (Fig. 39 and Fig. 41).

Along the road the core of the D1 isoclinal M. Tambura anticline crops out and the "Filladi inferiori" fm. (phyllites) are here exposed. This antiform have an extension of about 10 km in map view. The Grezzoni formation

Fig. 42 – D1 and D2 deformation superposition in the Frigido valley (Stop 2.5). Late structures in the inverted limb of the D1 Vinca anticline are interpreted as "transfer folds" between two ductile shear zones.





(dolostones) of the overturned limb is reduced to a few metres of cataclastic dolomite, often budinaged, and usually in the area the Palaeozoic basement rocks are tectonically in contact with the Marble formation. The Tambura antiform is related to the D1 tectonic deformation. Visible in the phyllites are minor D2 phase folds that are overturned to the west and indicate that the phyllitic core of the anticline acted as a ductile extensional shear zone during D2. Also the contact between the Grezzoni formation and the Marble in this area is a D2 normal fault marked by non- metamorphic cataclasites.

Stop 2.7: Landi quarries

Coordinates: 44° 3'32.92"N – 10°14'47.92"E

Topics: Deformed marble breccias; D1 structures and relationships with early D2 deformation; non-cylindric folds; marble meso- and microstructures, flanking-folds.

With a short walk we enter in an abandoned quarry ("Cave Landi") below the main road where we can observe the typical marble variety "Arabescato" with late D1 folds. exposed in variably oriented vertical and horizontal cuts.

As a whole, the quarry is located in the hinge zone of a large-scale late D1 antiform only weakly affected by west-dipping D2 foliation, which is well expressed in Cretaceous calcschists and impure marbles.

Distributed and localized strain features (folds and shear zones) occurred at different stages of the tectonic evolution and may be recognized on the basis of crosscutting relationships and calcite microstructures. Late phase flanking folds (Passchier, 2001) can also be observed in this quarry.

Stop 2.8: Cervaiole

Coordinates: 44° 2'21.67"N – 10°14'45.91"E

Topics: Deformed marble breccia; origin of brecciation and structures of the area; Palaeozoic basement rock types; quarrying technology.

Just after the Cipollaio tunnel we take the road to the Cervaiole quarry.

Figure 39 illustrates the geology of Cave Cervaiole–M. Altissimo and the surrounding area. If the weather conditions permit, we will have a magnificent panoramic view of the coastal plain and southeasternmost Apuane where the geology of Mount Corchia is in clear view.



The marble exploitation in the Cervairole quarry dates back to 1700 when Napoleon's General Henraux started the activity, which continues still today as it provides a very appreciated metabreccia variety named "arabescato Cervairole," and minor amounts of "ordinario" and "statuario" marble types (see Meccheri et al., 2007a for a comprehensive overview of the M. Altissimo marble basin). The "ordinario" type in this area looks like a regularly stratified marble with thicker (up to 3–4 m), whitish beds that are more persistent than the minor gray interlayers of "nuvolato" type. The "Arabescato" marbles are whitish, clast-supported metabreccias with marble clasts ranging in size from centimetersized pebbles to boulders several meters across, in a minor gray to greenish gray calcitic matrix with variable amounts of phyllosilicates (muscovite and chlorite), dolomite, quartz and pyrite Fe-oxides. In many cases, the quarry faces intersect the contacts between the ordinary marble and the Arabescato, showing that the latter is mainly derived from the original brecciation of the ordinary marble along pre-metamorphic sets of fractures and/or faults that dissected the lower Liassic carbonate sediments.

The overall stratigraphic character of the M. Altissimo area and the abundance of breccias provide evidence for a paleotectonic setting of proximal to or part of a structural high (Molli et al., 2002). The structural setting of the M. Altissimo and M. Corchia areas appear to be closely related to the mechanical stratigraphy of units involved in the deformation, in particular the Palaeozoic phyllites, dolomites and marbles. Dolomite-phyllite and dolomite-marble show evidence for a contrast in competence during deformation that results in a modified cartographic-scale dome and basin interference pattern, with cusate and lobate fold geometries which may be observed on the map and in cross sections. Throughout the area, vertical cross sections show coaxial refolding and type-3 interference patterns between close to isoclinal folds (D1) with wavelengths of 100s of meters with associated steeply dipping axial plane foliation and open to tight D2 folds associated with sub-horizontal axial plane crenulation (D2).

The overall structure of the M. Altissimo–M. Corchia region may be interpreted as the result of dome-shaped refolding (antiformal stack-related) of a kilometer-scale hinge zone culmination related to a recumbent sheath-shaped D1 megasyncline. The D1 fold-axes are parallel to the trend (60° N) of the regional extension lineation (L1), with D1 constrictional type finite strain (X/Z ratios up to 8:1 and K value higher than 3) in the "rotated" culmination, whereas it is oblate- to near plane-type far from this structural domain. The pre-existing deformation features (i.e., the refolded and steeply dipping, D1 culmination of sheath-like megasyncline) have controlled the geometries of D2 folding and the variability of the D2 patterns of strain and fold interference (Carmignani and Giglia, 1983; Molli and Vaselli, 2006; Meccheri et al., 2007a).



The deformation character of D1 regional folds appears to be in turn, strongly controlled by the original paleotectonic framework, calling for a general fold-inheritance model (Molli and Meccheri, 2012).

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