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Geological Field-Trip Guide to the Emilia-Tuscany Northern Apennines and Alpi Apuane

13–14 June 2018

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Contents

Foreword

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 guide-book includes a short outline of the stratigraphic and tectonic evolution of units outcropping in the Northern Apennines and the description of itinerary and stops.

For people interesting in run the field trip by themselves the following guide-books could be also of interest:

- CARMIGNANI L., GATTIGLIO M., KÄLIN O. & MECCHERI M. (1987) - *Guida all'escursione sul Complesso Metamorfico delle Alpi Apuane. Escursione conclusiva della "Summer School" di Geologia e Petrologia dei Basamenti Cristallini", Settembre 1987*. CNR - Università di Siena, Tipografia Editrice Pisana, Pisa, 110 pp.
- BETTELLI G., BONAZZI U., FAZZINI P., GELMINI R. & PANINI F. (1987) - *La Geologia del Margine Padano dell'Appennino Settentrionale. Guida alla Escursione, Descrizione degli Stop*, pp. 95–155. Società Geologica Italiana - Università degli Studi di Modena, Istituto di Geologia, Modena, 25-28 Maggio 1987.
- ABBATE E. (1992) - *Guida alla Traversata dell'Appennino Settentrionale. Società Geologica Italiana - 76a Riunione Estiva - Firenze 16-20 Settembre 1992*. Società Geologica Italiana - Università di Firenze, Firenze, 262 pp.
- BORTOLOTTI V. (1992) - *Appennino Tosco-Emiliano*, Guide Geologiche Regionali, vol. 4. Società Geologica Italiana, BE-MA Editrice, Milano, 329 pp.
- BRUNI P., DE LIBERO C., PANDELI E. & PERILLI N. (1992) - *Escursione B3 - La Successione Torbiditica Oligo-Miocenica Macigno-Arenrie di M. cervarola*. In: *Società Geologica Italiana - 76a Riunione Estiva, Escursioni Post-Congresso - Firenze 24-25 Settembre 1992*, pp. 77–134. Società Geologica Italiana - Università di Firenze, Firenze.
- CARMIGNANI L., DISPERATI L., FANTOZZI P.L., GIGLIA G. & MECCHERI M. (1993) - *Tettonica Distensiva del Complesso Metamorfico delle Alpi Apuane - Guida all'Escursione*. Gruppo Informale di Geologia Strutturale, Siena.
- MOLLI G. (2002) - *Field Trip Eastern Liguria/Alpi Apuane. Gordon Research Conference on Rock Deformation*. Il Ciocco, Barga, Italy.
- CARMIGNANI L., CONTI P., MECCHERI M. & MOLLI G. (2004) - *Geology of the Alpi Apuane Metamorphic Complex (Alpi Apuane, Central Italy), Field Trip Guide Book - P38*. In: L. GUERRIERI, I. RISCHIA & L. SERVA (Eds.), *32° International Geological Congress, Florence 20-28 August 2004*, Memorie Descrittive della Carta Geologica d'Italia, vol. 63, pp. 1–40. Servizio Geologico d'Italia, Roma.
- MOLLI G. (2012) - *Deformation and fluid flow during underplating and exhumation of the Adria continental margin: A one-day field trip in the Alpi Apuane (northern Apennines, Italy)*. In: P. VANNUCCHI & D. FISHER (Eds.), *Deformation, Fluid Flow, and Mass Transfer in the Forearc of Convergent Margins: Field Guides to the Northern Apennines in Emilia and in the Apuan Alps (Italy)*, Geological Society of America Field Guide, vol. 28, pp. 35–48. The Geological Society of America.
- REMITTI F., BETTELLI G., PANINI F., CARLINI M. & VANNUCCHI P. (2012) - *Deformation, fluid flow, and mass transfer in the forearc of convergent margins: A twoday fi eld trip in an ancient and exhumed erosive convergent margin in the Northern Apennines*. In: P. VANNUCCHI & D. FISHER (Eds.), *Deformation, Fluid Flow, and Mass Transfer in the Forearc of Convergent Margins: Field Guides to the Northern Apennines in Emilia and in the Apuan Alps (Italy)*, Geological Society of America Field Guide, vol. 28, pp. 1–34. The Geological Society of America.

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, Modino unit and Cervarola unit;
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!

Paolo Conti
Gianluca Cornamusini
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San Giovanni Valdarno, 13 June 2018

Part I

Geological overview

1

The Emilia-Tuscany Northern Apennines

1.1 Geological setting

The Northern Apennines are a fold-thrust belt formed during the Cenozoic by the thrusting from west to east (in present day coordinates) of the Ligurian units onto the Tuscan-Umbria units (see Fig. 1 and Plates 1, 2 and 3).

The Ligurian units represent remnants of the Ligurian-Piedmont Ocean (or Alpine Tethys), and also suffered deformation during the Cretaceous- Paleogene tectonic phases that are well documented in the Alps (TRÜMPY, 1975; FRISCH, 1979). The Tuscan-Umbria Domain represents the continental margin of the Adria (Apulia) plate and consists of a Hercynian basement and its Permian-Mesozoic to Cenozoic cover (CARMIGNANI *et alii*, 2004, and references therein). The eastwards motion of the European Plate with respect to Adria during the middle Eocene led to continental collision, with the closure of the Ligurian- Piedmont Ocean, the overthrusting of the Ligurian units above the Tuscan-Umbria units, and deformation in the Apulia margin (ELTER, 1973; VAI & MARTINI, 2001). Later, back-arc rifting led to the extension in the Tyrrhenian Sea and the Norther Apennines, with the eastwards migration of subduction, deformation and extensional tectonics (BOCCALETTI *et alii*, 1971; KLIGFIELD, 1979; PRINCIPI & TREVES, 1984; JOLIVET *et alii*, 1998; CARMIGNANI *et alii*, 2001, 2004; VAI & MARTINI, 2001; ARGNANI, 2002; MOLLI, 2008; MARRONI *et alii*, 2010; MOLLI & MALAVIEILLE, 2011; CORNAMUSINI & PASCUCCI, 2014, and references therein). The following main tectonic units are exposed (from top to bottom) in the study area:

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

The relative position of tectonic units is shown in Fig. 2

The Ligurian units are represented here by successions characterized by Helminthoid flysch deposits and sedimentary mélanges with blocks of ophiolite rocks (External Ligurian Domain: MARRONI *et alii*, 2001; ARGNANI *et alii*, 2006). These units are not investigated in this study.

The Sestola-Vidiciatico Unit (REMITTI *et alii*, 2007; VANNUCCHI *et alii*, 2008) is a thick (up to 500 m), strongly deformed tectonic unit, and represents a regional shear zone developed in the Miocene during a continental collision between the European and Adria plates. This unit is composed of juxtaposed tectonic slivers of different rock types that are detached from the overriding Ligurian units and underlying tectonic units and incorporated into the shear zones. Moving towards the northwestern areas, from Alpe di Cerreto to Pracchiola (3), the Sestola- Vidiciatico Unit is replaced by the Subligurian Unit (ELTER *et alii*, 2003; VANNUCCHI *et alii*, 2012). This latter unit is formed by stacked thrust sheets of Upper Cretaceous to Upper Oligocene shale, limestone and sandstone (PLESI *et alii*, 1998; CATANZARITI *et alii*, 2002)

The Modino Unit is represented by a succession that starts with a complex of Cretaceous Helminthoid Flysch (with Ligurian affinity) that is unconformably overlain by: Eocene-Oligocene shales, marls and marly limestones (Fiumalbo Shale and Marmoreto Marl); and in turn arenaceous turbidite deposits of Mt. Modino Sandstone. This unit is now overthrusted above the Tuscan Nappe tectonic unit.

The Tuscan Nappe Unit crops out extensively in the Northern Apennines and comprises a calcareous to shaly succession that is Triassic-Oligocene in age, with at the top the Macigno Fm., a thick arenaceous turbidite succession that is late Oligocene-early Miocene in age.

The Cervarola Unit covers wide areas in the Northern Apennines and is mainly formed by a thick arenaceous turbidite succession (Mt. Cervarola Sandstone). In the study area, the Civago Marl is considered to be the unit's stratigraphic base (GHELARDONI *et alii*, 1962); outside the study area, the Villore Shale Fm. (varicoloured shale) is regarded as the base of the Mt. Cervarola Sandstone.

1.2 Previous works and interpretations

A long-lasting debate is documented in the Italian geological literature about the geological setting of this sector of the Northern Apennines, particularly with respect to: the palinspastic position of the Modino and Tuscan Nappe- Cervarola units and their relative locations; and the nature of their boundaries (tectonic vs. stratigraphic). A comprehensive overview of the different interpretations was presented by CHICCHI & PLESI (1991).

Extensive investigations in the Emilia-Tuscany Northern Apennines, which produced a modern geological model follow-

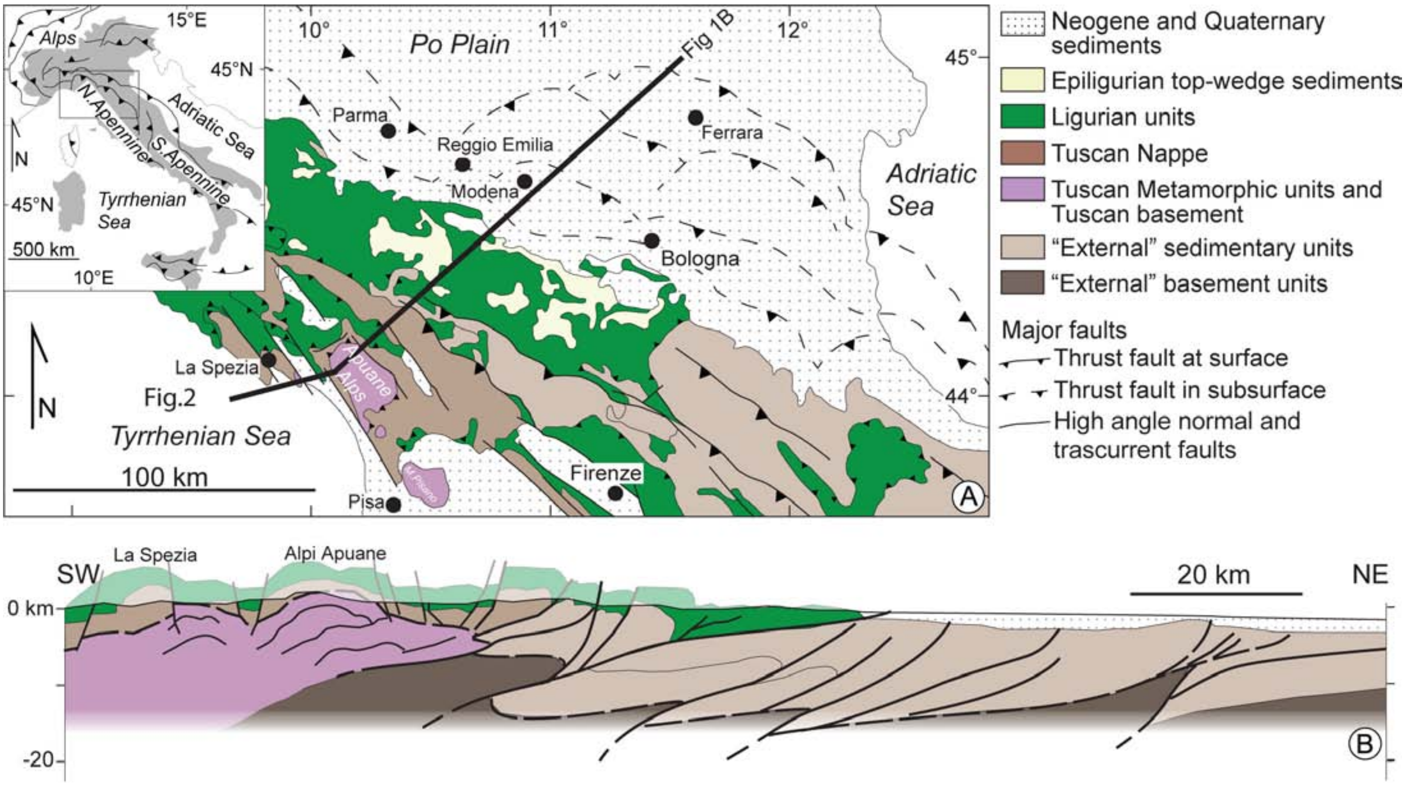
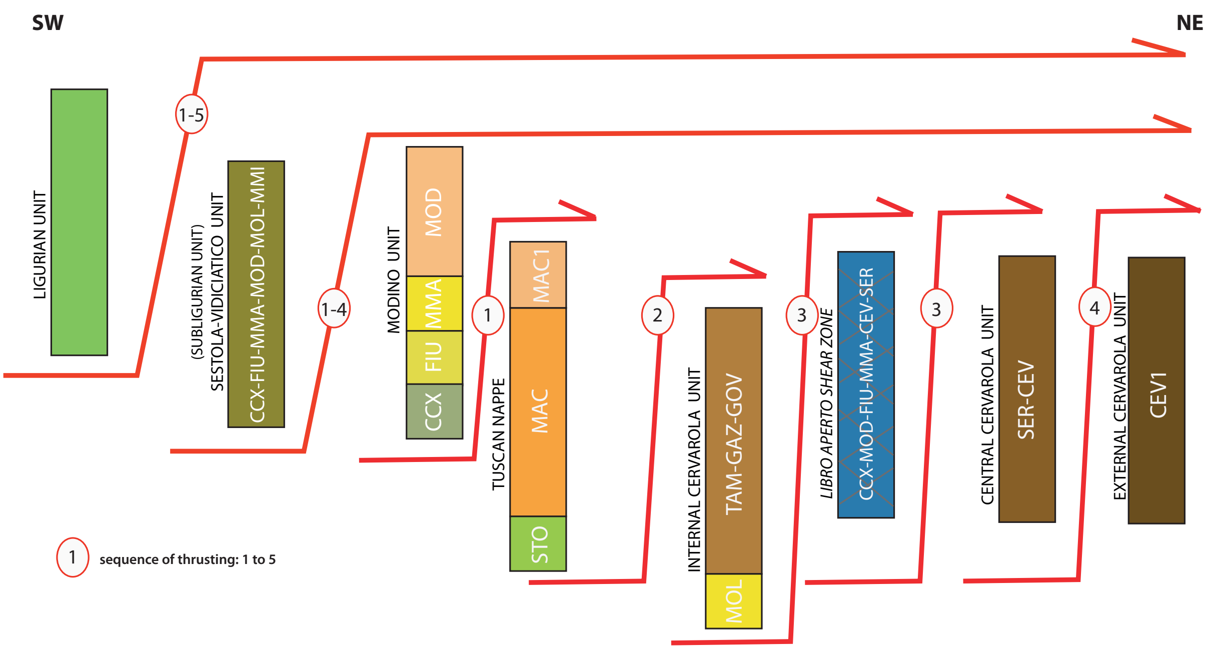


Fig. 1 – Tectonic map of the Northern Apennines, with cross section. After MOLLI (2008).



CCX-Chaotic Complex (*Cretaceous*); FIU-Fiumalbo Shale (*Bartonian-Rupelian*); MMA-Marmoreto Marl (*Rupelian-Chattian*); MOD-Modino Sandstone (*Chattian-Aquitanian*);
MOL-Oligocene marlstones (*Rupelian-Chattian*); MMI-Lower Miocene marlstones - Civago Marl (*Aquitanian*); STO-Scaglia Toscana (*Paleocene-Oligocene*);
MAC-Macigno sandstone Fm. (*Rupelian-Aquitanian*); MAC1-Macigno Fm. thin-bedded-sandstones (*Chattian-Aquitanian*);
TAM-Torre Amorotti Sandstone-GAZ-Gazzano Sandstone-GOV-Gova Sandstone (*Chattian-Aquitanian*);
SER-Serpiano Sandstone (*Aquitanian*); CEV-Mt. Cervarola Sandstone (*Chattian-Burdigalian*); CEV1-Mt. Cervarola Sandstone - Granaglione-Castiglion dei Pepoli system (*Burdigalian-Langhian*)

Fig. 2 – Tectonic units in Emilia-Tuscany Northern Apennines and their relative relationships.

ing the fundamental paper by MERLA (1951), were first carried out by NARDI (1965) and BALDACCI *et alii* (1967), and then by geologists from Berlin University (GÜNTHER & RENTZ, 1968; REUTTER, 1969; GÜNTHER & REUTTER, 1985), who envisaged a single (albeit complicated) stratigraphic succession for the Modino-Cervarola succession.

The stratigraphic and structural position of the Modino Unit has led to a debate that is still ongoing, but different interpretations can be brought back to two end-members:

a) the Mt. Modino Sandstone that is in a stratigraphic succession above the Macigno Fm. of the Tuscan Nappe, with the interposition of a thick gravitational chaotic complex called "Monte Modino Olistostrome" (ABBATE & BORTOLOTTI, 1961; NARDI, 1965; BALDACCI *et alii*, 1967; MARTINI & SAGRI, 1977; BOCCALETTI *et alii*, 1980; ABBATE & BRUNI, 1987; LUCENTE & PINI, 2008);
b) the Mt. Modino Sandstone that is in a tectonic relationship with the underlying Macigno Fm., through the interposition of a tectonic basal complex (REUTTER, 1969; PLESI, 1975; MARTINI & PLESI, 1988; BETTELLI *et alii*, 1987; CHICCHI & PLESI, 1991; CERRINA FERONI *et alii*, 2002; PLESI, 2002).

Recent investigations in the Emilia-Tuscany Northern Apennines (CORNAMUSINI *et alii*, 2018) reveal a complex unit stack setting, where the arenaceous-marly successions are part of different tectonic units. In particular, whereas the Macigno Fm. 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. 3).

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 evolution of the sedimentation 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). 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 relationships are well defined. Differently, the Mt. Modino turbidite system still does not have a well constrained setting (see models in CHICCHI & PLESI 1991 and BETTELLI *et alii* 2002).

In this regard, the following evidences 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 & PERILLI, 2009; MARCHI *et alii*, 2017), and has lithological and chronostratigraphical similarities with the marly-shaly succession lying below the Macigno Fm., such as the Rovaggio Marl and the Scaglia Toscana Fm.
b) The field relationships clearly show the tectonic superposition of the Mt. Modino Sandstone (with Fiumalbo Shale and Marmoreto Marl fms at the base) onto the Macigno Fm., 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 Ligurian-derived slices and clasts (BETTELLI *et alii*, 1987; ABBATE & BRUNI, 1987; CHICCHI & PLESI, 1991; PERILLI, 1994; PUCCINELLI *et alii*, 2009; MARCHI *et alii*, 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 alii*, 2000; PLESI, 2002; BOTTI *et alii*, 2011; CATANZARITI & PERILLI, 2009), corresponds with that of the Macigno Fm.
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 alii*, 1994a).

The Macigno and the Mt. Modino Sandstone fms should therefore represent two different, but very similar, turbidite systems, as the lithological, sedimentological and architectural data seem to show (ABBATE & BRUNI, 1987; BRUNI *et alii*, 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 alii*, 1994b; VALLONI & ZUFFA, 1984). As the two turbidite successions are almost coeval, with the only age discrepancy concerning an older base for the Macigno Fm., the two turbidite systems should settle adjacently. 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. This implies that the Mt. Modino succession, although deposited close to the Macigno Fm., 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 Fm. 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 petrographi-

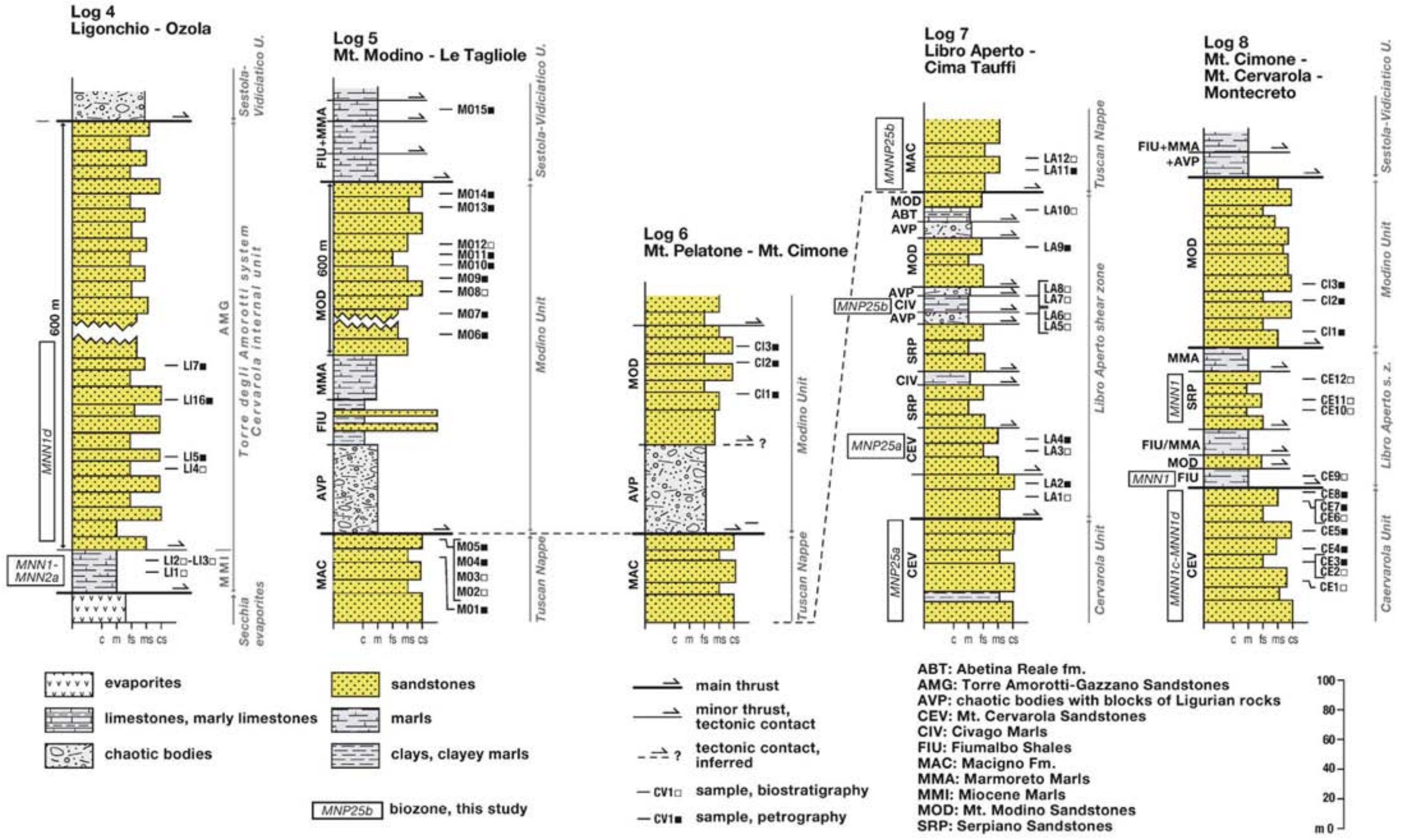


Fig. 3 – Stratigraphic logs in the Ligonchio, M. Modino and Abetone area. From Cornamusini *et alii* (2018).

cal features are indeed very similar, which does not enable an easy distinction to be made between them in the field (Andreozzi, 1991; Mezzadri & Valloni, 1981; Andreozzi & 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 & Reutter, 1985; Andreozzi, 1991; Andreozzi *et alii*, 1995; Botti *et alii*, 2002; Piazza, 2016). 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. 4), 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. 4), 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 subbasins 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 alii*, 1995; Botti *et alii*, 2002; Plesi, 2002; Valloni *et alii*, 2002).

The basin model development presented here fits well in the migration basin concept of Ricci Lucchi (1986) and Argnani & Ricci Lucchi (2001). 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.

The marlstones belongs to two main lithostratigraphic units, as the Marlstone Marl those of Oligocene age and the so-called Civago Marl those of Early Miocene age. They revealed two main different geological settings for both: 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 englobed 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 po-

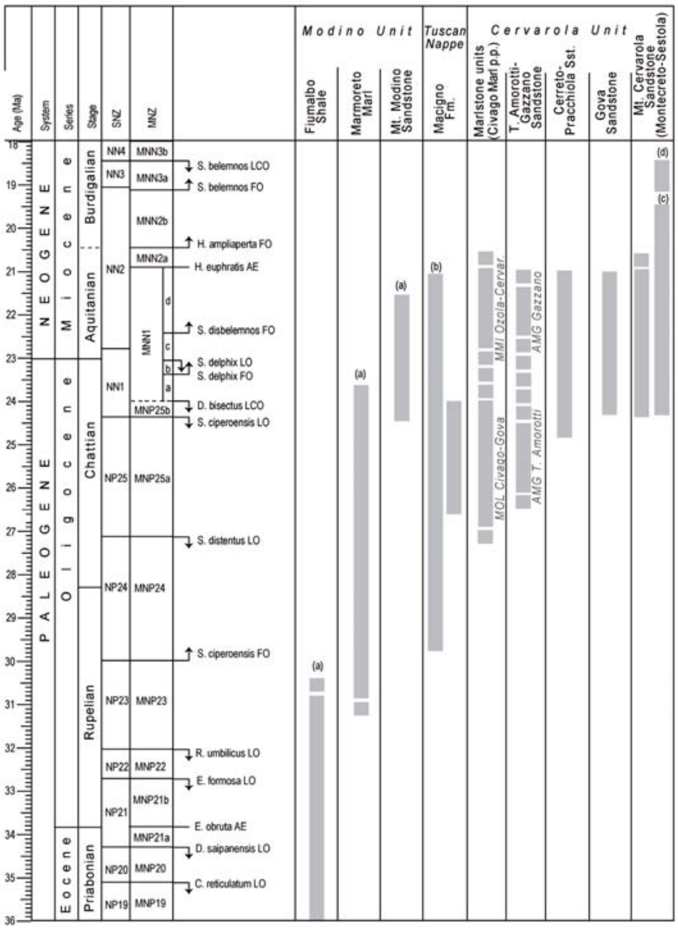


Fig. 4 – Bio-chronostratigraphic framework for the sandstone successions (after CORNAMUSINI *et alii*, 2018).

sitions 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 Fig. 2 and Fig. 5), 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 Fig. 2 and Fig. 5), and occurring in the Ligonchio area and tectonically on top of the Gazzano Sandstone, are time-equivalent with the Civago Marl of the literature.

1.3 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. 5): the Tuscan Domain foredeep was developing, with the deposition in the forming depocentre of: marlymudstone deposits such as the Rovaggio Marl; the 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. 5).

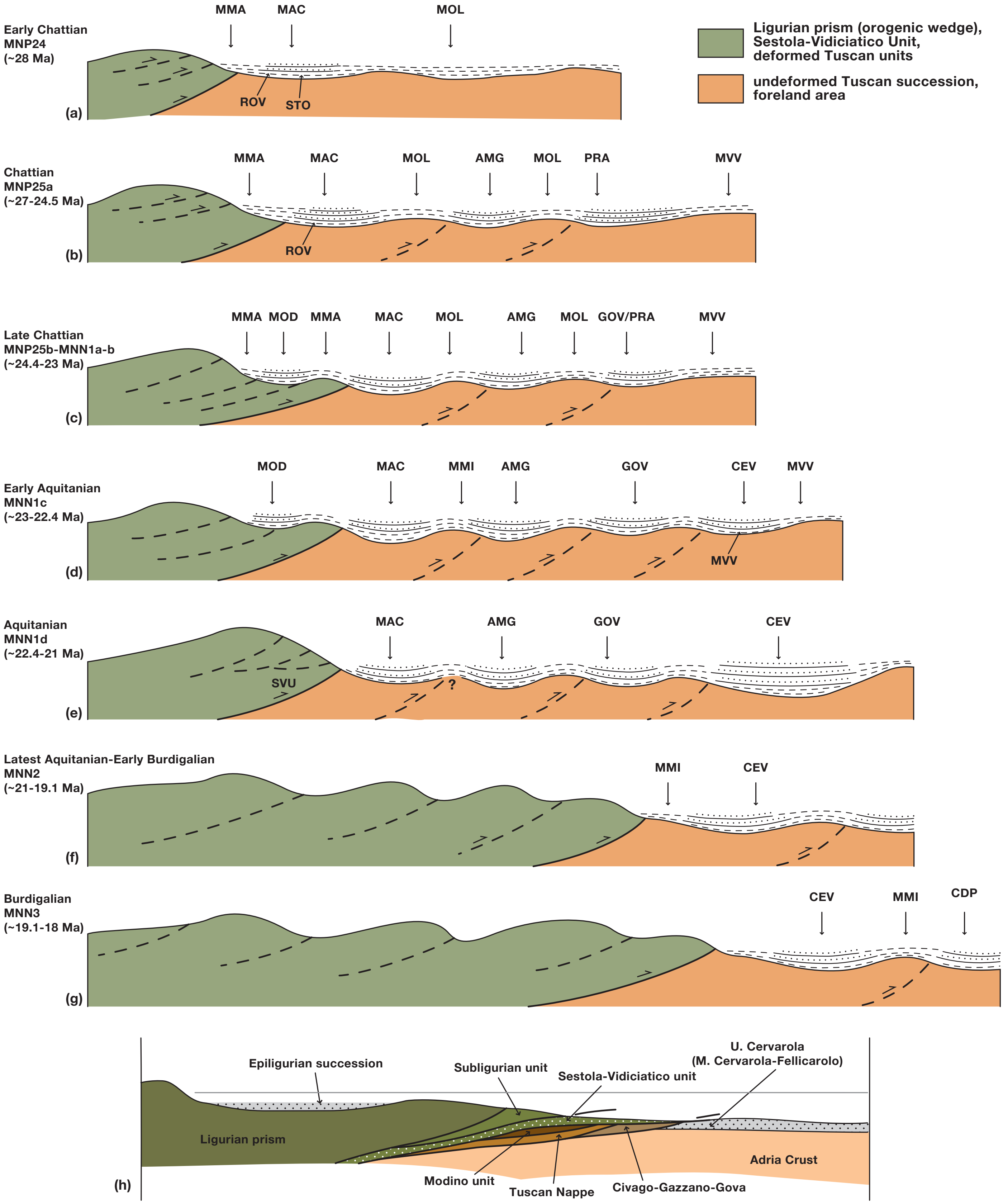
Stage 2 Late Oligocene (Chattian, MNP25a subzone, Fig. 5b): the main depocentre continued to be filled by the Macigno turbidite system, whereas the marly sedimentation (Marmoreto Marl) continued in the more internal part of the foredeep basin onto the front of the Ligurian orogenic wedge. Externally, two more minor depocentres developed, linked with active thrusts, forming basins 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. 5c): 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 subbasins and at the margins of the foredeep.

Stage 4 Earliest Miocene (early Aquitanian, MNN1c subzone, Fig. 5d): 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. 5e): 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. 5f): 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. 5h).



AMG: TorreAmorotti-Gazzano Sandstones, CDP: Castiglion de Pepoli Sandstones, CEV: Mt. Cervarola Sandstones: Fellicarolo-Dardagna System, GOV: Gova Sandstones, MAC: Macigno Fm., 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

Fig. 5 – 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. From CORNAMUSINI *et alii* (2018).

Stage 7 Early Miocene (Burdigalian, MNN3 Zone, Fig. 5g): 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 Castiglion 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. ARGNANI & RICCI LUCCHI (2001); TINTERRI & TAGLIAFERRI (2015); CORNAMUSINI *et alii* (2017)

1.4 Kinematic evolution of tectonic units along a NE-SW transect

The evolution is presented in different stages of deformation along a cross section with SW-NE orientation, in present day coordinates, and illustrated in Fig. 6, Fig. 7 and Fig. 8.

Accretion and subduction of the Piemont-Ligurian Ocean: Ligurian phases (80–40 Ma)

In Fig. 6a is illustrated a paleotectonic reconstruction for the Middle-Late Jurassic paleogeography of the Piemont-Liguria ocean and surrounding areas; in Fig. 6b is a section across the European margin, the Piemont-Liguria ocean and the Adriatic plate, following STAMPFLI *et alii* (1991).

The opening stages of the Piemont-Liguria ocean occurred during Jurassic -Upper Cretaceous (MARRONI *et alii*, 2010, and references therein). In the Upper Cretaceous - Lower Eocene time span E-dipping subduction of oceanic lithosphere below the European (Brianconnais, Sardinia-Corsica) led to formation of an accretionary wedge (Ligurian prism) incorporating sedimentary successions deposited above oceanic crust, and continental fragments. Starting at about 50 Ma flip of subduction polarity occurred (MOLLI, 2008; MOLLI & MALAVIEILLE, 2011; MALUSÀ *et alii*, 2015) and W-dipping subduction of the oceanic lithosphere occurred (Fig. 6c). In the geological literature of the Northern Apennines all tectonics phases affecting the orogenic wedge during Upper Cretaceous-Lower Eocene are collectively indicated as "Ligurian phases". Deformation events linked with E-dipping subduction are usually indicated as "Alpine" tectonic phases, while deformation events linked with W-directed subduction, producing N-E facing folds and thrusts, are indicated as "Apenninic" tectonic phases.

Closure of the Piemont-Liguria ocean, continental collision and subduction (40–21 Ma)

Ongoing relative movement of the European and Adriatic plate led to complete subduction of the oceanic crust and to continental collision (Fig. 6d). Age of younger deposits deformed and incorporated in the Ligurian prism is Middle Eocene (Lutetian), for the Tertiary Helmintoid flysch. Starting Middle Eocene (Bartonian) a sedimentary succession unconformably deposited above the deformed Ligurian units, the Epiligurian succession (ORI & FRIEND, 1984). The Epiligurian succession is not affected by deformation recognizable in the underlying Ligurian rocks, the onset of sedimentation of the Epiligurian succession mark therefore the end of Ligurian phases and therefore a Lutetian/Bartonian age (about 40 Ma) can be considered the age for continental collision and closure of the Piemont-liguria ocean in this part of the Apennine orogen.

W-dipping subduction occurred at this time, with overall compression in the Ligurian prism. Starting late Rupelian W-dipping subduction with roll-back and retreat of the Adria plate occur, as constrained by age of rifting and clastics deposition in the Liguro-Provencal basin (30 Ma: GORINI *et alii*, 1993; SÉRANNE, 1999).

As result of W-dipping subduction during Late Eocene-early Miocene, the easternmost portion (in present day coordinates) of the Ligurian prism is thrusted onto the Adriatic continental margin and developed an "Apenninic accretionary wedge" (Fig. 6d). The rocks belonging to this part of the accretionary wedge are of Ligurian origin, strongly deformed, and with their stratigraphic primary relationships almost obliterated. This rocks are now exposed as the basal succession of the Subligurian Unit (Argille e Calcari di Canetolo Fm. and Groppo del Vescovo Fm.) and the basal succession of the Modino unit (Modino basal complex: shales, limestones, Abetina Reale Fm.).

During Oligocene - Lower Miocene (Aquitanian) time span Epiligurian deposition continued above the Ligurian prism. Deep water Epiligurian sedimentation (DI GIULIO *et alii*, 2002) indicate that at this time the Ligurian prism was already collapsed and thinned.

On the Adriatic continental margin sedimentation in this time interval is characterized by marls and marly limestones (Scaglia Fm.) followed by turbiditic sandstones (flysch: Macigno fm., Pseudomacigno fm., Mt. Cervarola Fm.). Sandstone deposition unconformably occurred also above deformed rocks of the Apenninic accretionary wedge emplaced above the Adriatic margin (Fig. 7a), this results in the sedimentation of the Petrignacola/Aveto sandstones above the deformed Argille e Calcari fm. and in sedimentation of the Fiumalbo/Marmoreto/Modino Sandstone fms. above the Modino basal complex.

During this time span subduction still goes on, deformation is now accommodated by shortening in the Ligurian prism and in the adjacent Adria margin, as testified by olistostrome emplacement and syn-depositional deformation features in the Macigno, Pseudomacigno and in the Mt. Cervarola Sandstone fms.

Main emplacement onto Adriatic margin: the Tuscan phase (20 Ma)

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 parte of the Cervarola unit paleogeographic domains (Fig. 4); sedimentation closed early (Late Oligocene) for the Bratica Sandstones. End of sedimentation is due to eastward migration of the orogenic wedge, emplacement of Ligurian units above

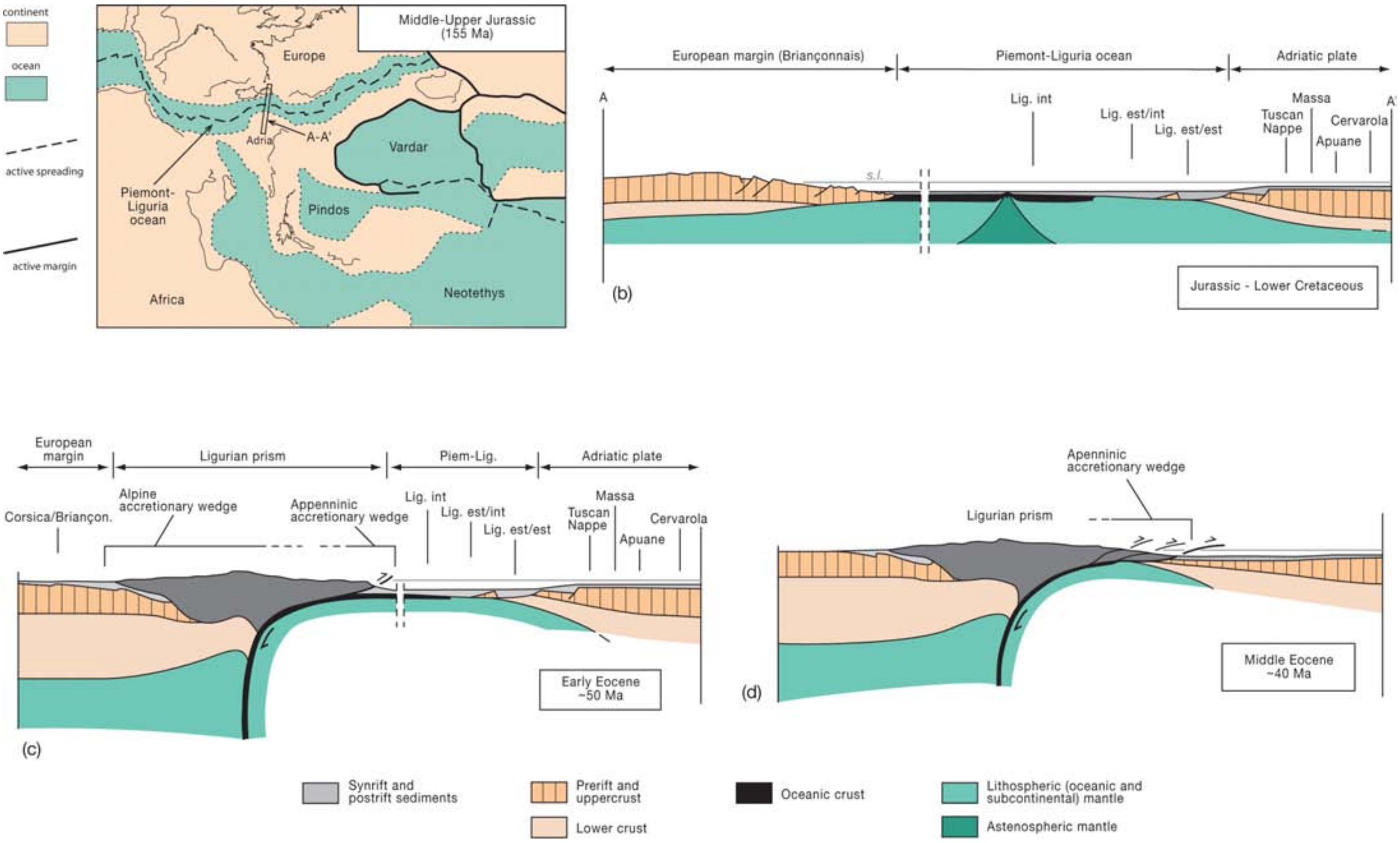


Fig. 6 – Evolution of tectonic units in the Emilia-Tuscany Norther Apennines, see text for discussion.

the Adria margin and its deformation; all these tectonic events are collectively indicated here as "Tuscan phase".

In Fig. 7b are indicated the main thrust planes developing during this tectonic phase:

a) a main tectonic contact developed at the base of the Ligurian Units (thrust plane "a" in Fig. 7b). 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 Petrignacola fms) 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 sandstone 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" thrust a stratigraphic 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" thrust 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".

During the Tuscan phase main regional tectonic transport occurred along the thrust planes "b" and "d" of Fig. 7b. 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 alii*, 2007; Vannucchi *et alii*, 2008). Along the thrust plane "d" the Tuscan Nappe is emplaced above more external units and the Alpi Apuane succession is subducted and reach the depth of about 20 km, where experienced conditions for greenschists facies metamorphism.

Fig. 8a shows the geometry at the end of the Tuscan phase.

Libro Aperto phase (~16 Ma?)

Middle Burdigalian is documented in the central Cervarola Unit, therefore 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 16 Ma Fig. 8b. 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, 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

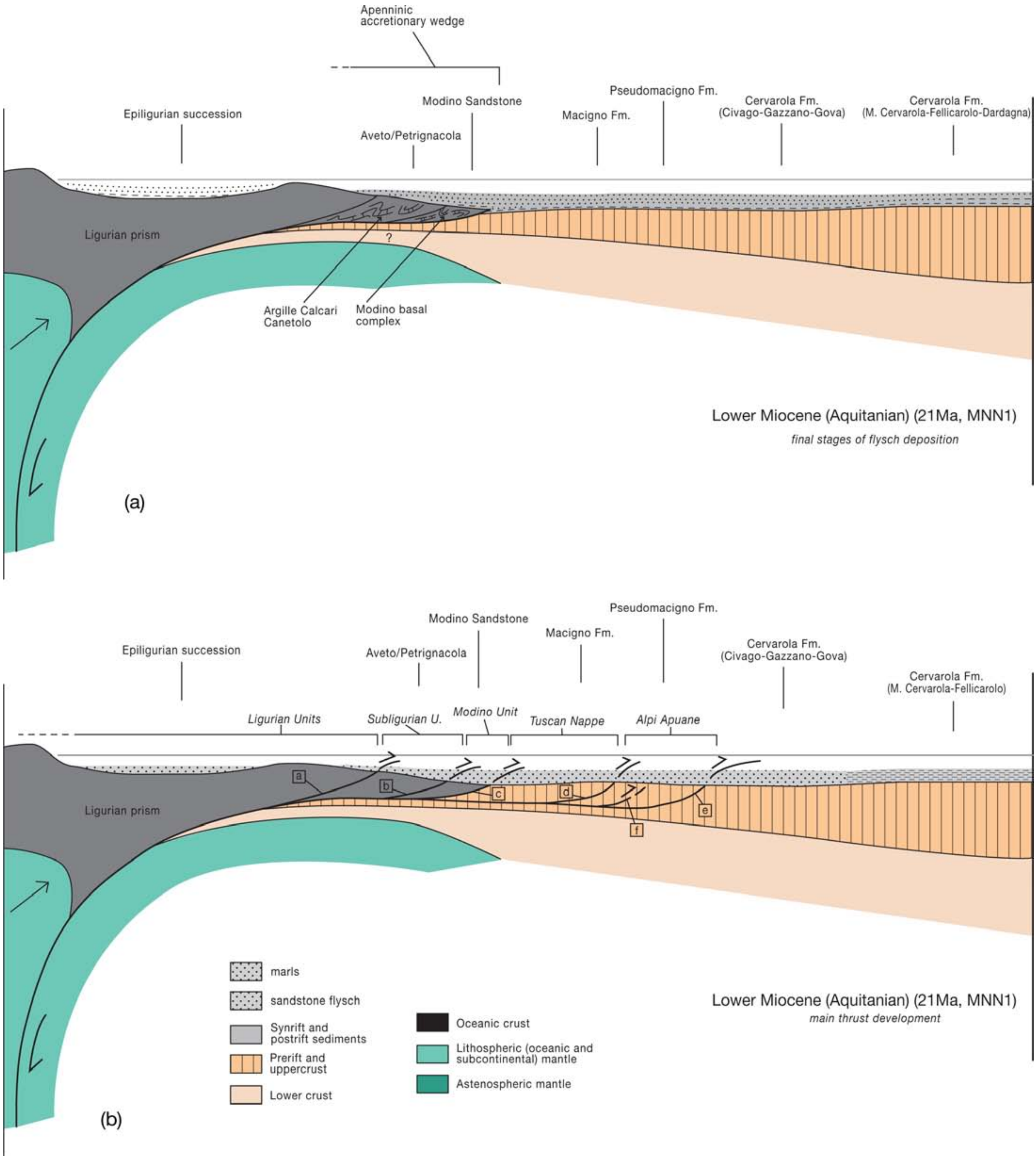


Fig. 7 – Evolution of tectonic units in the Emilia-Tuscany Norther Apennines, see text for discussion.

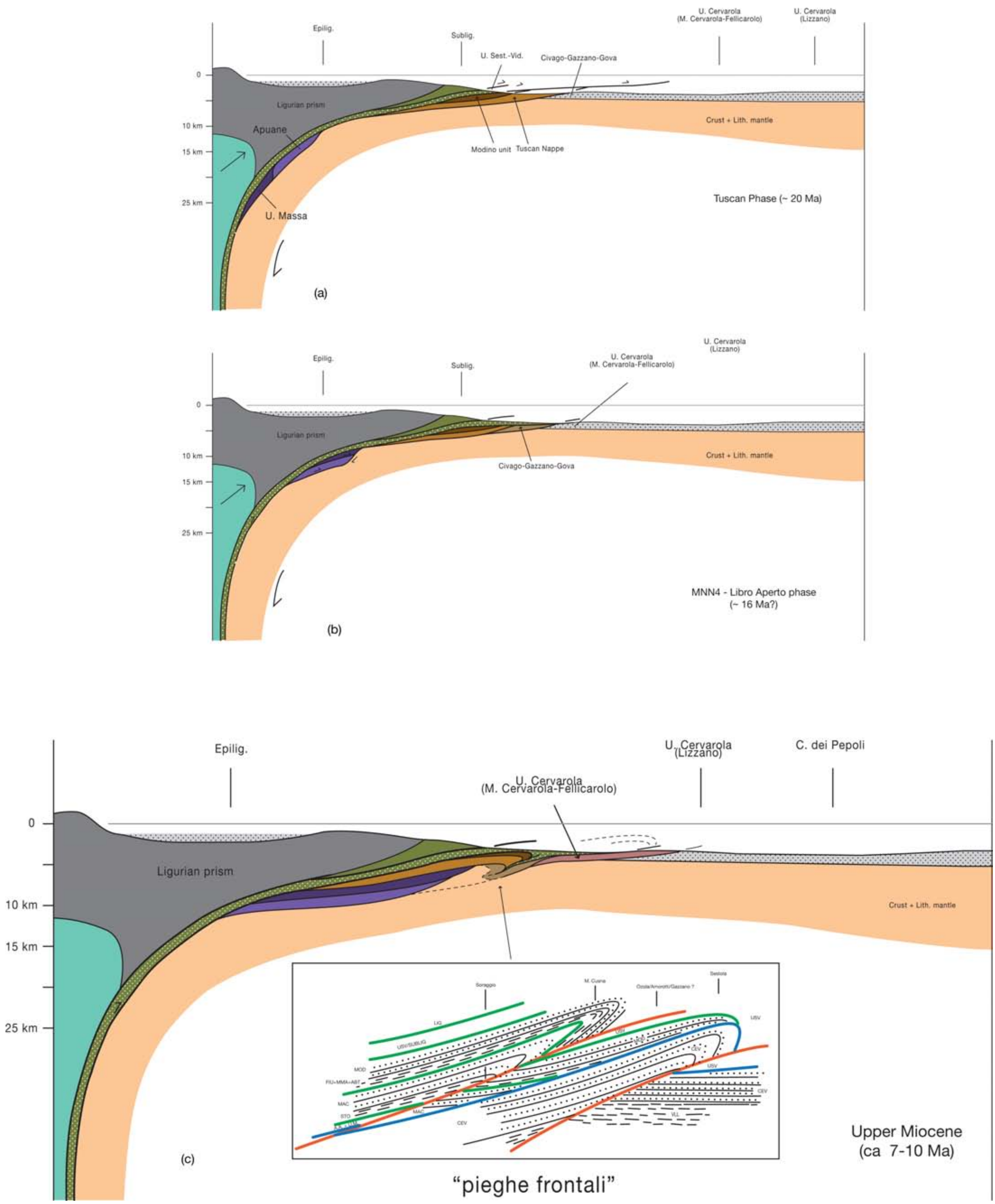


Fig. 8 – Evolution of tectonic units in the Emilia-Tuscany Norther Apennines, see text for discussion.

recognize the nappe structure of the Northern Apennines (Baldacci *et alii*, 1967). This superposition 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 confirm 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 alii* (2013), and that final deformations in the Sestola-Tectonic unit postdate activity along the Libro Aperto shear zone.

Later thrusting

In the Pracchia-Lizzano area 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 later than turbiditic sandstone sedimentation in the external Cervarola Unit (Castiglione dei Pepoli fm.: Langhian), i.e. Serravallian or younger in age, these thrust are indicated as “Later thrusts” in 3 (Fig. 8c).

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 fm. and deformed Ligurian units along the Sillaro Line: these recent features are not discused here.

2

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. 9). 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 & GIGLIA, 1975; CARMIGNANI & KLIGFIELD, 1990):

- the Tuscan Nappe;
- the Massa unit;
- the "Autochthon" *Auctt.* unit (also "Alpi Apuane unit").

2.1 The Tuscan Nappe

The Tuscan nappe (Fig. 10) consists of a Mesozoic cover detached from its original basement along the decollement level of the Norian anidrites and dolostones now totally transformed into cataclastic rocks called "Calcare Cavernoso" ("cellular" limestone).

The succession continues upward with Rhaetian to Hettangian shallow water limestones (Rhaetavicula Contorta, Portoro and 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 (Late Oligocene-Early Miocene).

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 Ligurian ocean closure.

Peak metamorphic conditions does not exced the anchizone/subgreenschist facies conditions with estimated temperature around 250-280 °C on the basis of vitrinite reflectance, illite cristallinity, isotope studies and fluid inclusion analysis (CERRINA FERONI *et alii*, 1983; REUTTER *et alii*, 1983; CARTER & DWORKIN, 1990; MONTOMOLI *et alii*, 2001).

2.2 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. 5). The pre-Mesozoic basement is formed by ?Upper Cambrian-?Lower Ordovician phyllites and quarzites, Middle Ordovician metavolcanics and metavolcanoclastic sediments (porphyroids and porphyric schists) associated to quartzic metasandstones and phyllites and rare Silurian Orthoceras-bearing metadolostones and black phyllites.

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

The metasedimentary sequence is formed by quartzose clast-supported metaconglomerates associated with metasandstones, metasiltstones and black phyllites that are overlain by marine deposits (Ladinian crynoidal marbles, carbonate metabreccias, calcschists and phyllites) intercalated with alkaline metabasalts (prasinites and green schists). Upwards the succession ends up with a transgressive continental cycle consisting of coarse-grained quarzitic metarudites (anageniti), quarzites 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 alii*, 1986; JOLIVET *et alii*, 1998; FRANCESCHELLI & MEMMI, 1999; MOLLI *et alii*, 2000b).

2.3 The "Autochthon" *Auctt.* unit

The Autochthon *Auctt.* unit is made up by a Paleozoic basement unconformably overlain by the Upper Triassic-Oligocene meta-sedimentary sequence (Fig. 10).

The Paleozoic basement is formed by the same rocktypes of the basement in the Massa unit, but here they are exposed in larger and more clear outcrops: ?Upper Cambrian-

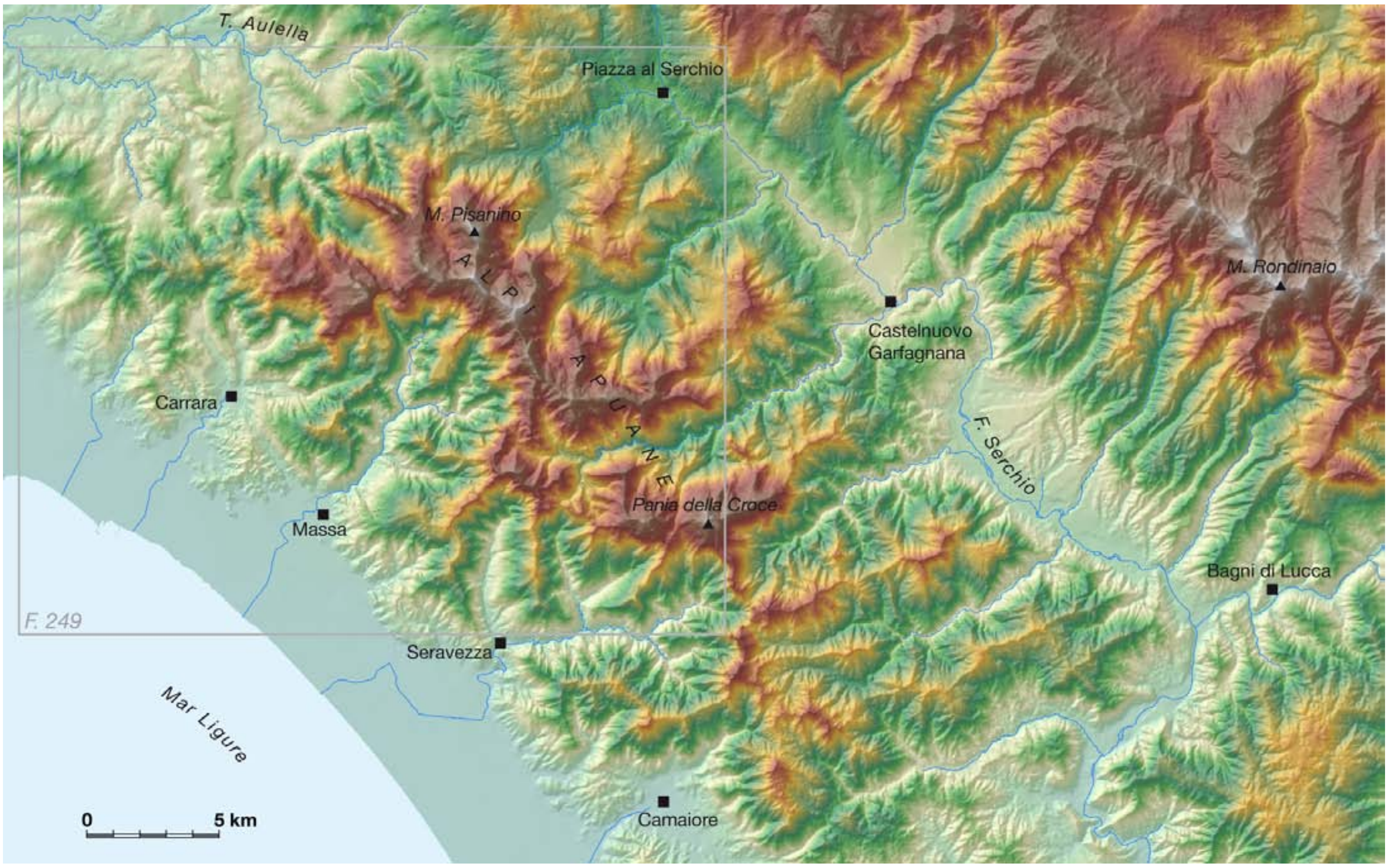


Fig. 9 – The Alpi Apuane region, northern Apennines.

?Lower Ordovician phyllites and quarzites, ?Middle Ordovician metavolcanics and metavolcanoclastics, ?Upper Ordovician quartzic metasandstones and phyllites, Silurian black phyllites and Orthoceras bearing metadolostones,?Lower Devonian calcschists; moreover the ?Upper Cambrian-?Lower Ordovician phyllites/quarzites 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 & Meccheri, 1987; Conti *et alii*, 1993).

Also basement rocks in the Autochthon *Auctt*. unit recorded a pre-Alpine deformation and greenschist facies metamorphism as the Massa unit (Conti *et alii*, 1991), for which the most striking evidence is the regional angular unconformity at the basis of the oldest Mesozoic formation (Triassic Dolomite) stratigraphycally lying on almost all the Paleozoic formations.

The Mesozoic cover (Fig. 10) include thin Triassic continental to shallow water Verrucano-like deposits followed by Upper Triassic-Liassic carbonate platform metasediments comprised of dolostones (”Grezzoni”), dolomitic marbles and marbles (the “Carrara marbles”), which are followed by Upper Liassic-Lower Cretaceous cherty metalimestone, cherts, calcschists. Lower Cretaceous to Lower Oligocene sericitic phyllites and calcschists, with marble interlayers, are related to deep water sedimentation during downdrowning 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 alii*, 1986; Di Pisa *et alii*, 1987; Jolivet *et alii*, 1998; Molli *et alii*, 2000b). Di Pisa *et alii* (1985) first recognized through a Calcite/Dolomite investigation temperature variations from southwest (Ca/Do temperature up to 450 °C) to central and northeast part (Ca/Do of 380-350 °C). Such data have been recently confirmed and used to interpret some of the microstructural variability in marbles.

2.4 Tectonics

The regional tectonic setting of the Alpi Apuane area is well known and generally accepted by researchers belonging to different geological schools (Fig. 11). On the contrary, different and often contrasting opinions do persist in interpreting the context of development of some deformation structures and the Tertiary geological history responsible for such a setting; the most recent debate focus on the exhumation mechanisms and their geodynamic context (Carmignani & Giglia, 1977; Carmignani *et alii*, 1978; Carmignani & Giglia, 1979; Carmignani & Kligfield, 1990; Storti, 1995; Cello & Mazzoli, 1996; Jolivet *et alii*, 1998; Molli *et alii*, 2000b).

In the Alpi Apuane metamorphic units two main polyphasic

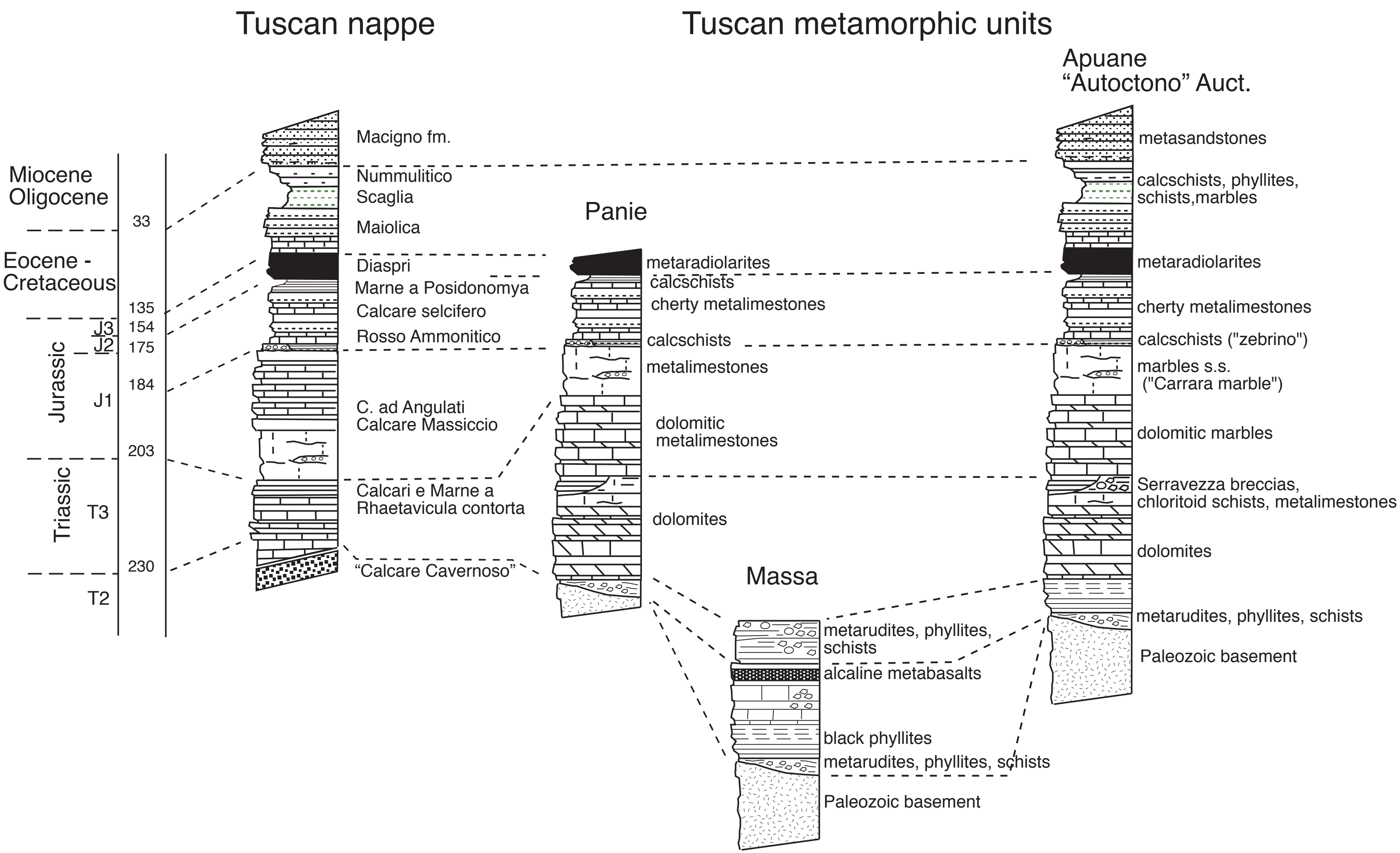


Fig. 10 – Stratigraphic sequence of the Tuscan units (Tuscan Nappe and metamorphic units) in the Alpi Apuane area, after Molli (2002).

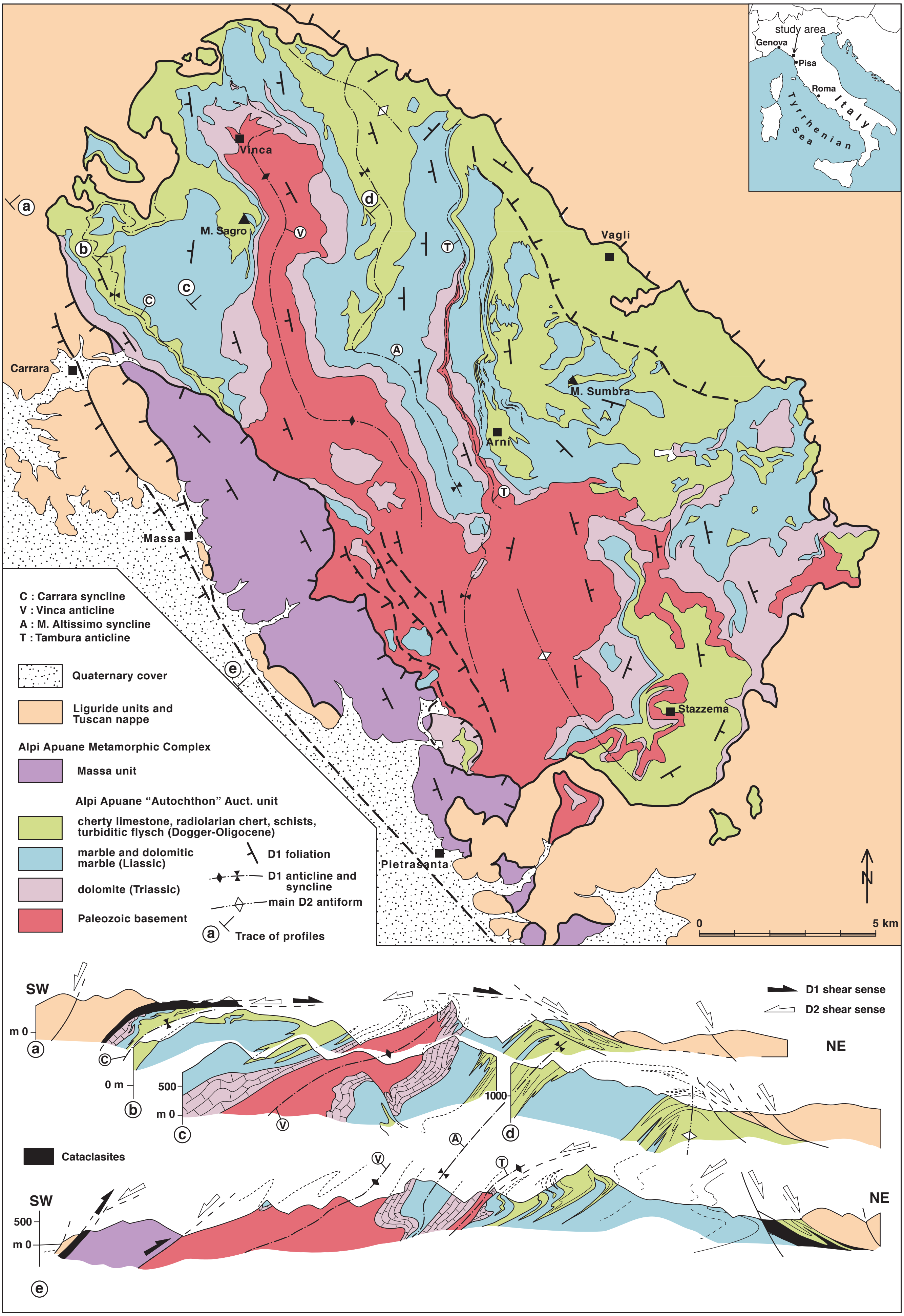


Fig. 11 – Geological sketch map of the Alpi Apuane area.

tectono-metamorphic events are recognized: the D1 and D2 events (CARMIGNANI & KLIGFIELD, 1990), which are classically regarded as a progressive deformation of the internal Northern Apenninic continental margin during collision (D1) and late to post-collisional processes (D2).

During D1 nappe emplacement occurred with 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 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, leading to progressive unroofing and exhumation of the metamorphic units toward higher structural levels. Late stages of D2 are associated with brittle structures.

2.4.1 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. 12).

Foliation bears a WSW-ENE trending mineral and extension lineation (Fig. 13) 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 alii*, 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.Tambura anticline. The two main antiform-anticline structures are cored by Paleozoic basement rocks, whereas Mesozoic metasediments are present in the core of synclines (Fig. 11).

A nearly 90° change in orientation of D1 fold axes is described from the WSW to ENE across the Alpi Apuane (CARMIGNANI & GIGLIA, 1977; CARMIGNANI *et alii*, 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-cilindric sheath folds appear (CARMIGNANI & GIGLIA, 1984; CARMIGNANI *et alii*, 1993). This relationship has been proposed as an example of passive rotation of early formed folds into the extension direction during progressive simple shear.

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. 14b); (2) "antiformal stack phase" in which further shortening and a crustal scale duplex are realized (Fig. 14b). The development of D1 structures is strongly controlled by the original paleotectonic setting and its lateral heterogeneities.

2.4.2 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 folds mainly associated with a low dipping to sub-horizontal axial planar foliation (S2), of crenulation type (Fig. 15). Late D2 structures are mainly represented by upright kinks and different generations of brittle faults, that accomodate the most recent tectonic history.

According to classical interpretations (CARMIGNANI *et alii*, 1978; CARMIGNANI & GIGLIA, 1979; CARMIGNANI & 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. All around the antiform, second order asymmetric folds facing away from the dome crests are described and, at scale of the whole Alpi Apuane, reverse drag-folds 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 and structural position within the folded multilayer but also from the orientation and intensity of development of D1 structures.

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) hanginwall collapse during overthrusting on a deeper ramp (CARMIGNANI *et alii*, 1978); b) interference patterns between two folding phases at high angle (CARMIGNANI & GIGLIA, 1977) or two high angle synchronous folding produced through one directional contraction in a multilayer with different mechanical properties (CARMIGNANI & GIGLIA, 1977); c) domino-like rigid blocks rotations with antithetic shear during progressive eastward thrusting (JOLIVET *et alii*, 1998);
- they produced as reverse drag folds overprinting complex highly non-cylindric D1 sheath folds during late rebound by vertical isostatic reequilibration of former thickened crust (CARMIGNANI & GIGLIA, 1979);
- they developed as passive folds related to distributed shear within kilometric scale shear zones accomodating crustal extension (CARMIGNANI & KLIGFIELD, 1990; CARMIGNANI *et alii*, 1994).

Possibly different folding mechanisms were contemporaneously active during D2 deformation.

Fig. 12 – D1 folds in marbles, Carrara, Alpi Apuane.

Fig. 13 – Strongly boudinaged cherty limestone during D1 deformation, Capanne di Careggine, Alpi Apuane.

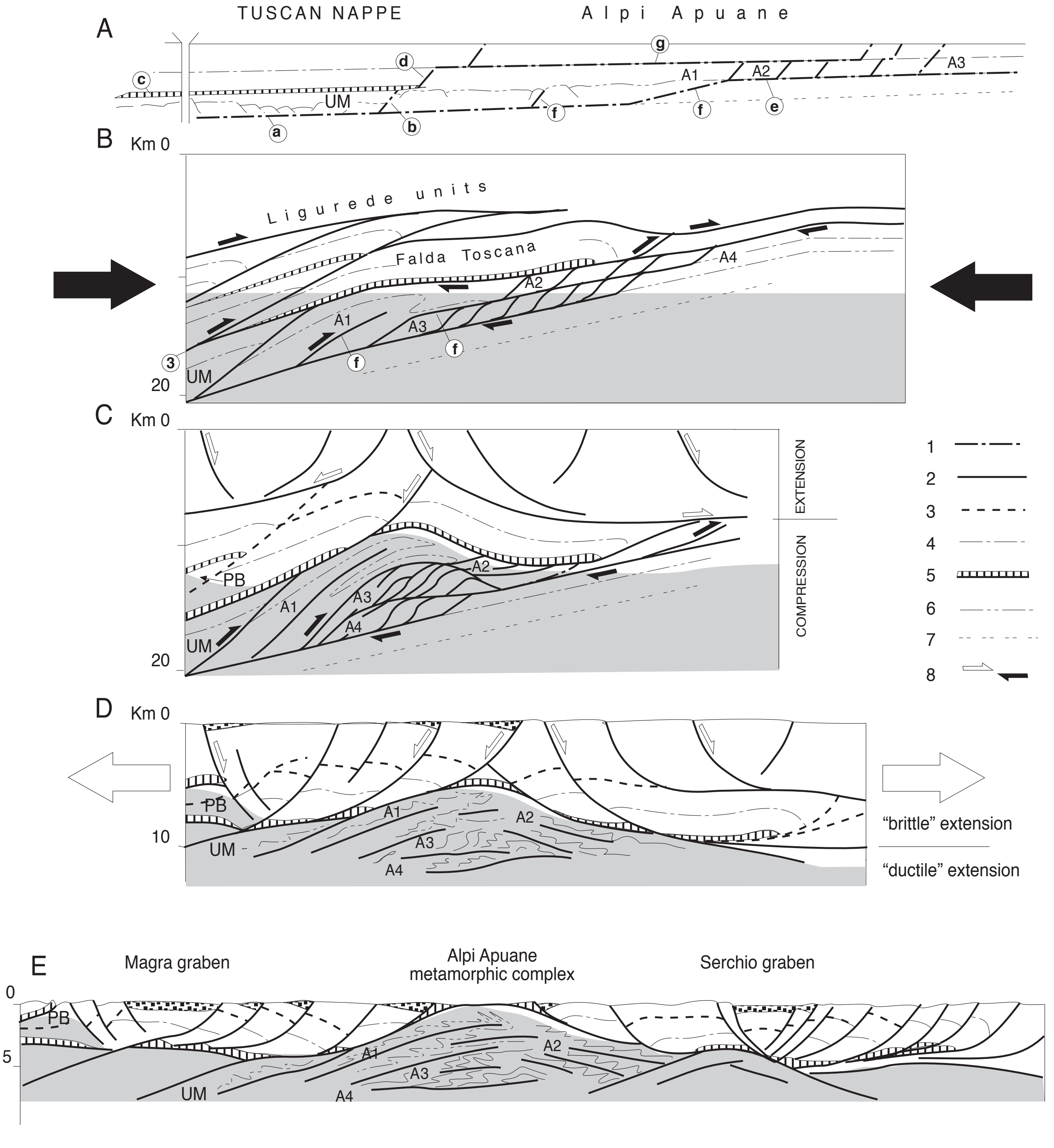


Fig. 14 – Tectonic evolution of the Alpi Apuane Metamorphic Complex and adjoining areas (after CARMIGNANI & KLIGFIELD, 1990, modified). (a) Pre-collisional geometry showing restored state traces of principal thrust faults and ramp-flat geometry. (b) Development of Alpi Apuane duplex structure. Metamorphic rocks shown 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-crustallevels, 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 Paleozoic 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-crustallevels (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-plate nonmetamorphic rocks and lower-plate metamorphic rocks is aided by the adoption as a detachment horizon of the evaporite-beariog 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.

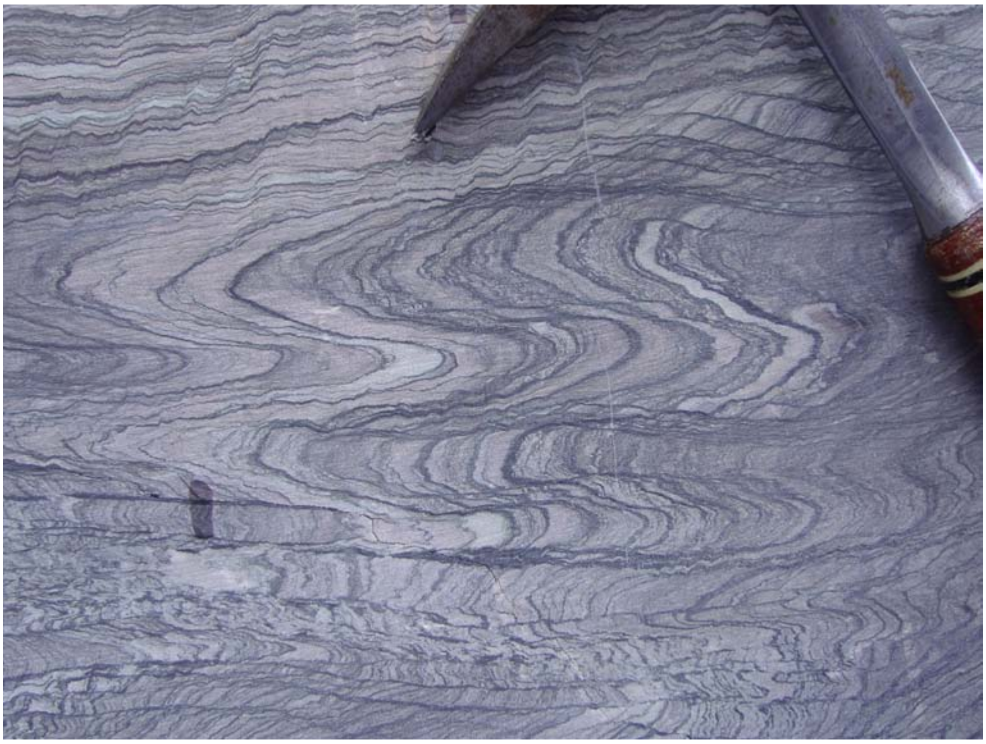


Fig. 15 – D2 folds in Cretaceous calcschists, Valle Turrite, Alpi Apuane.

2.4.3 Deformation - metamorphism relationships

The presence of index minerals (chlorithod and kianite) in suitable rock-types 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 alii*, 1997) can be observed in syn- to post tectonic relationships with the D1 foliation. The chloritoid mainly predates the D2 crenulation (who meccanically rotates it) in the uppermost geometrical levels of the unit, e.g. at Campo Cecina. 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.

2.4.4 Age of deformation

In the metamorphic unts of the Alpi Apuane the youngest sediment involved in the syn-metamorphic deformation is the Pseudomacigno Fm. containing microfossils of Oligocene age (Dallan Nardi, 1976). Moreover available K-Ar and Ar-Ar dates (Kligfield *et alii*, 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 younger history can be constrained using apatite fission tracks suggesting that between 5 and 2 Ma (Abbate *et alii*, 1994; Fellin *et alii*, 2007) the metamorphic units passed through 120 °C, approximately at a depth of 4-5 km depending on the coeval thermal gradient (Carmignani & 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-Middle Pliocene conglomerates with metamorphic clasts derived from the Alpi Apuane metamorphic units (Bartolini & Bortolotti, 1971; Federici & Rau, 1980; Bernini & Papani, 2002; Argnani *et alii*, 2003; Balestrieri *et alii*, 2003).

3

The Alpi Apuane marbles

In the Alpi Apuane region marbles derive from stratigraphically different levels, the Liassic marbles however are the thickest succession and represents 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 alii*, 1978; SPIERS, 1979; SCHMID *et alii*, 1980, 1987; WENK *et alii*, 1987; FREDRICH *et alii*, 1989; DE BRESSER, 1991; RUTTER, 1995; COVEY-CRUMP, 1997; PIERI *et alii*, 2001; DE BRESSER *et alii*, 2005; BRUIJN *et alii*, 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. 16). 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 alii*, 1977; DI PISA *et alii*, 1985; COLI, 1989).

3.1 Marble types and their microstructures

In the Alpi Apuane three main groups of marbles can be distinguished according to their mesoscopic features (Fig. 17 and Fig. 18):

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 alii*, 2007b; BLASI & RAGONE, 2010).

Taking into account the main microstructural features and relationships with mesoscopic field structures (foliations, folds and shear zones), we have been able to divide the marbles into three main group-types whose microstructures are interpreted respectively as the product of (Fig. 19):

a) static recrystallization (type A microfabric);
b) dynamic recrystallization (type B microfabric, further subdivided into two types B1 and B2);
c) reworking during the late stage of deformation (type C microfabric).

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 & HEILBRONNER PANOZZO, 1999 and MOLLI *et alii*, 2000a).

3.1.1 Annealed microfabric (type-A microfabric)

This type of microfabric is characterized by equant polygonal grains (granoblastic or "foam" microstructure, Fig. 20a), 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 levels 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 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 & 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.

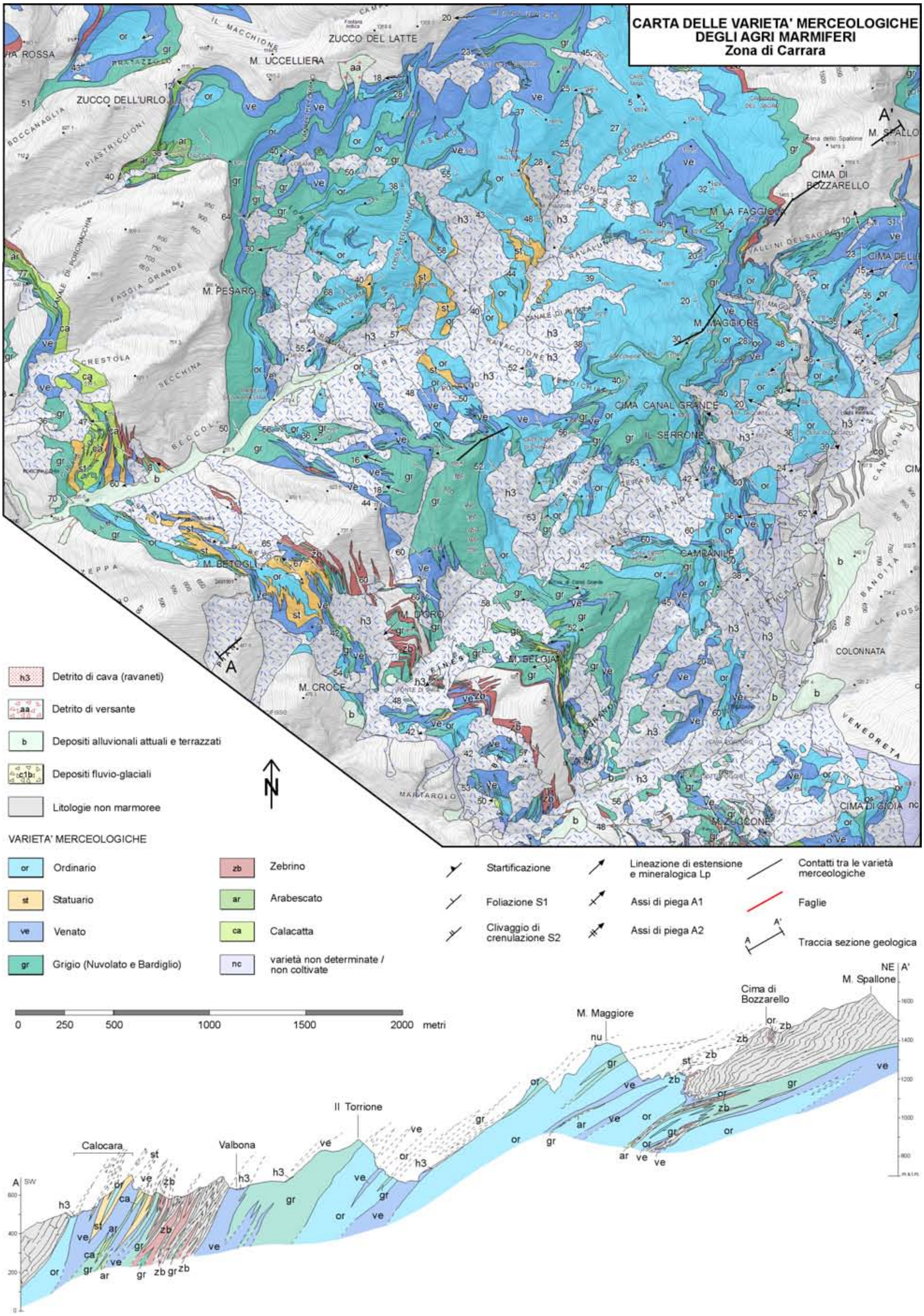


Fig. 16 – Map of marble types in the area north of Carrara.

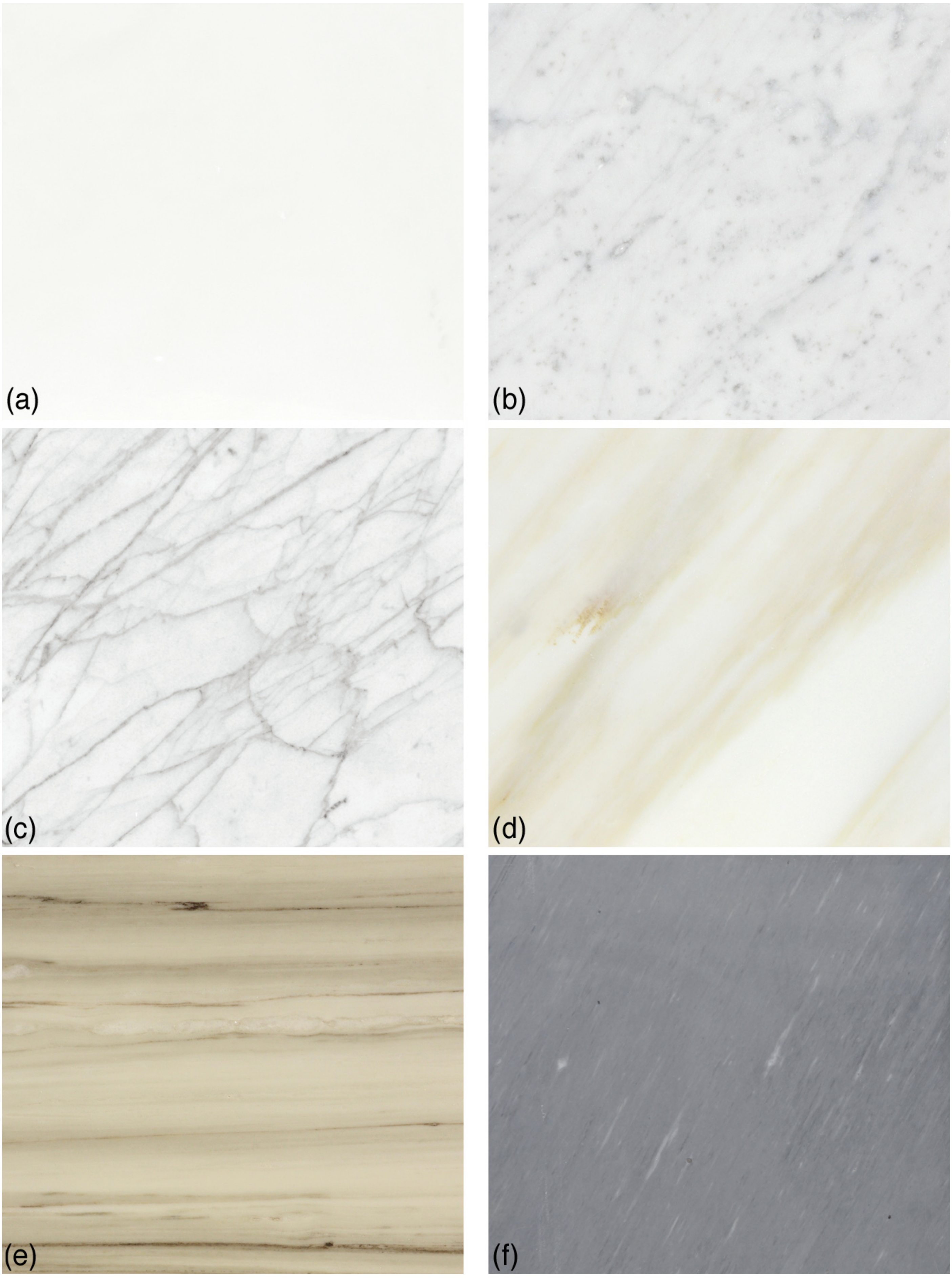


Fig. 17 – Some marble types from the Alpi Apuane: (a) “Statuario”. (b) “Bianco. (c) “Venato”. (d) “Calacatta”. (e) “Zebrino”. (f) “Bardiglio”.

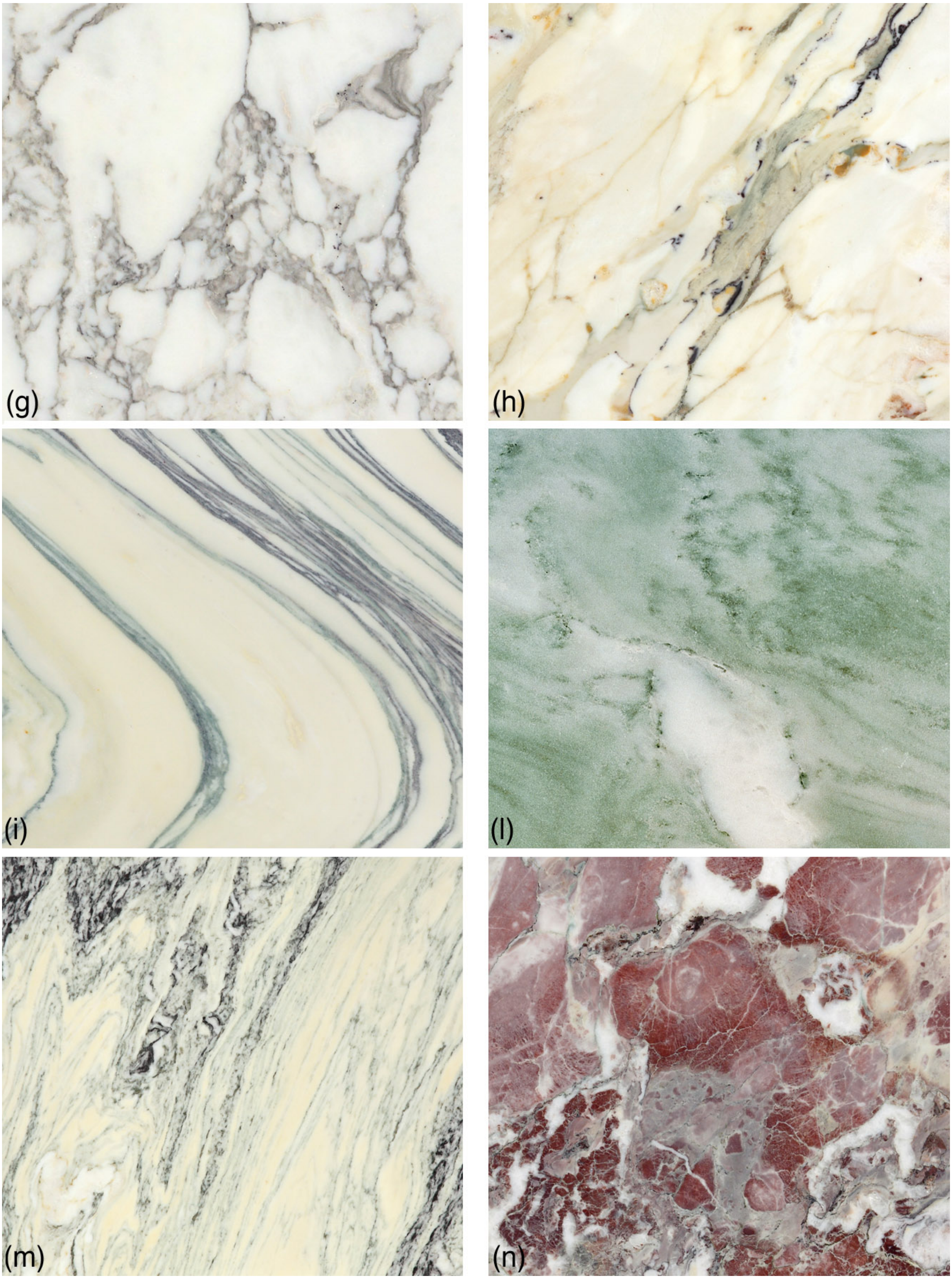


Fig. 18 – Some marble types from the Alpi Apuane: (g) "Arabescato". (h) "Breccia Capraia". (i) "Fantastico". (l) "Cipollino". (m) "Cremo". (n) "Fior di Pesco".

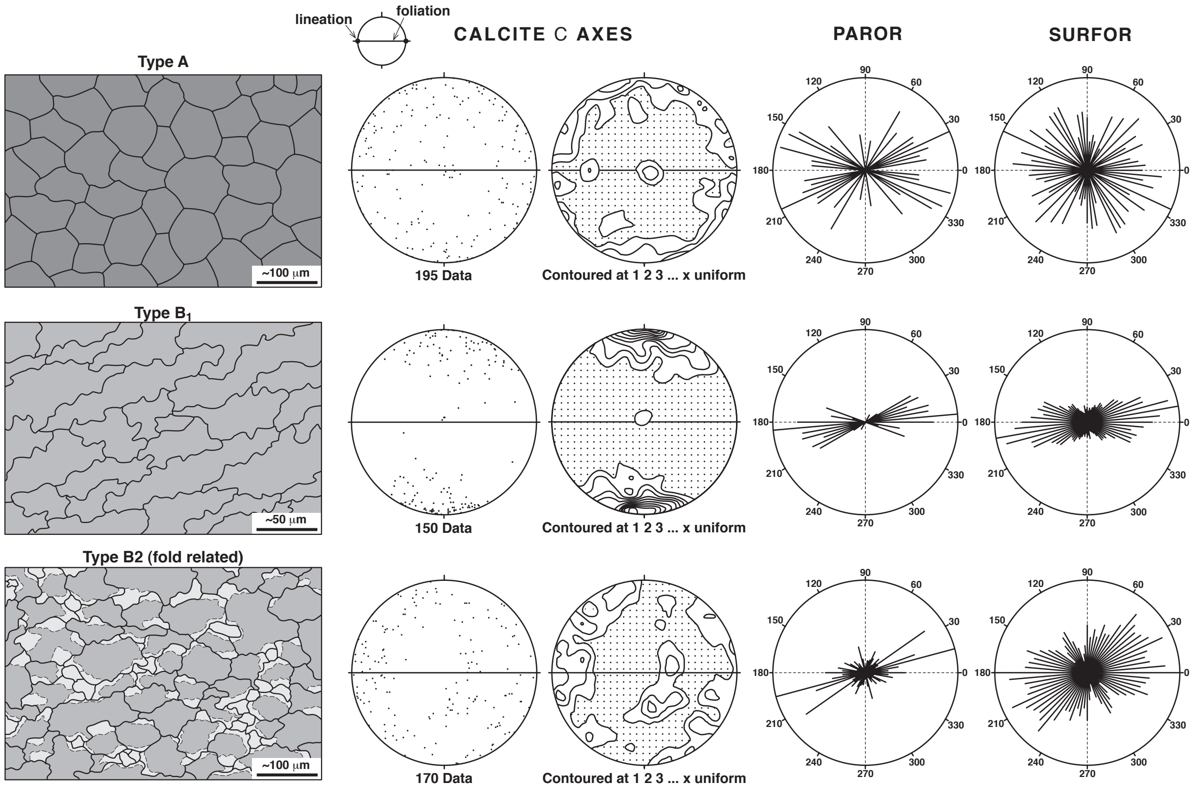


Fig. 19 – Line drawing of microstructures, c-axis orientation (from universal stage measurements) and results of PAROR and SURFOR analysis for calcite microfabric of type-A and type-B. Number of grains analysed with PAROR and SURFOR routines is more than 200 (from MOLLI *et alii*, 2000a).

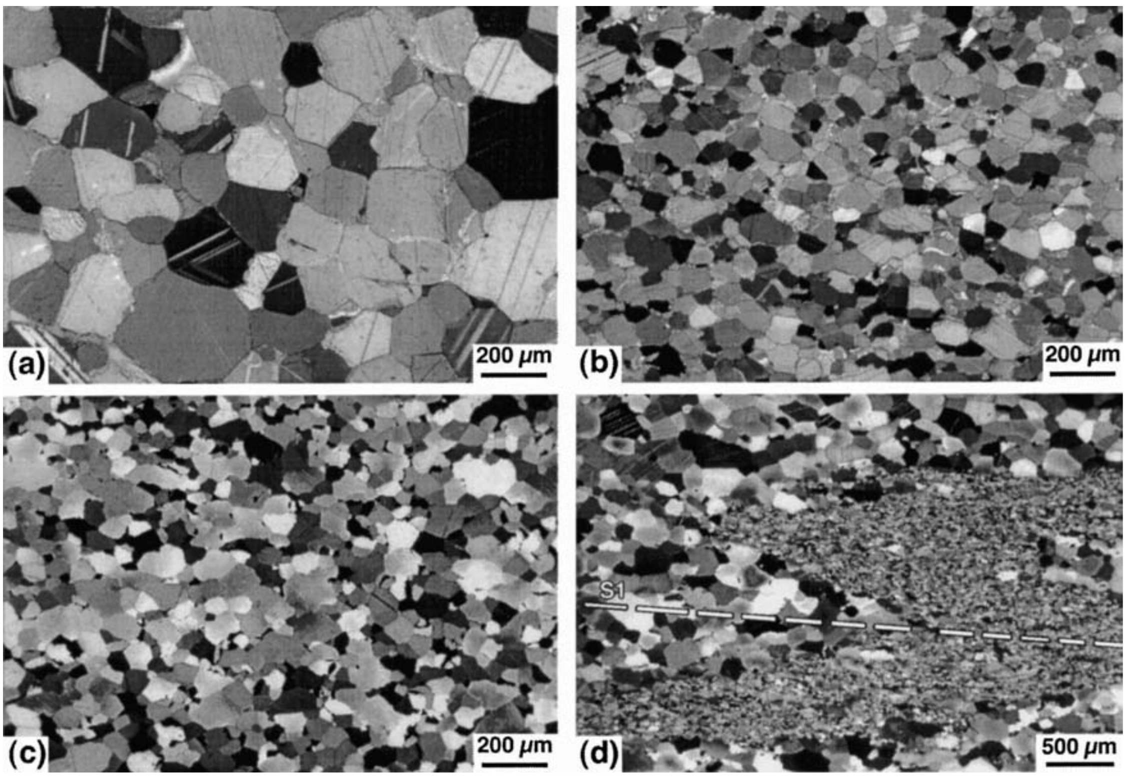


Fig. 20 – Annealed microstructures in Alpi Apuane marbles: (a) Sample 34 (western Alpi Apuane). (b) Sample 39. (c) Sample 180 (eastern Alpi Apuane). (d) D1 fold overgrown by granoblastic microstructure (locality Belgia, western Alpi Apuane). The folded level, made up of fine-grained, calcite dolomite and phyllosilicates, represents a former stratigraphic layer. From MOLLI *et alii* (2000a).

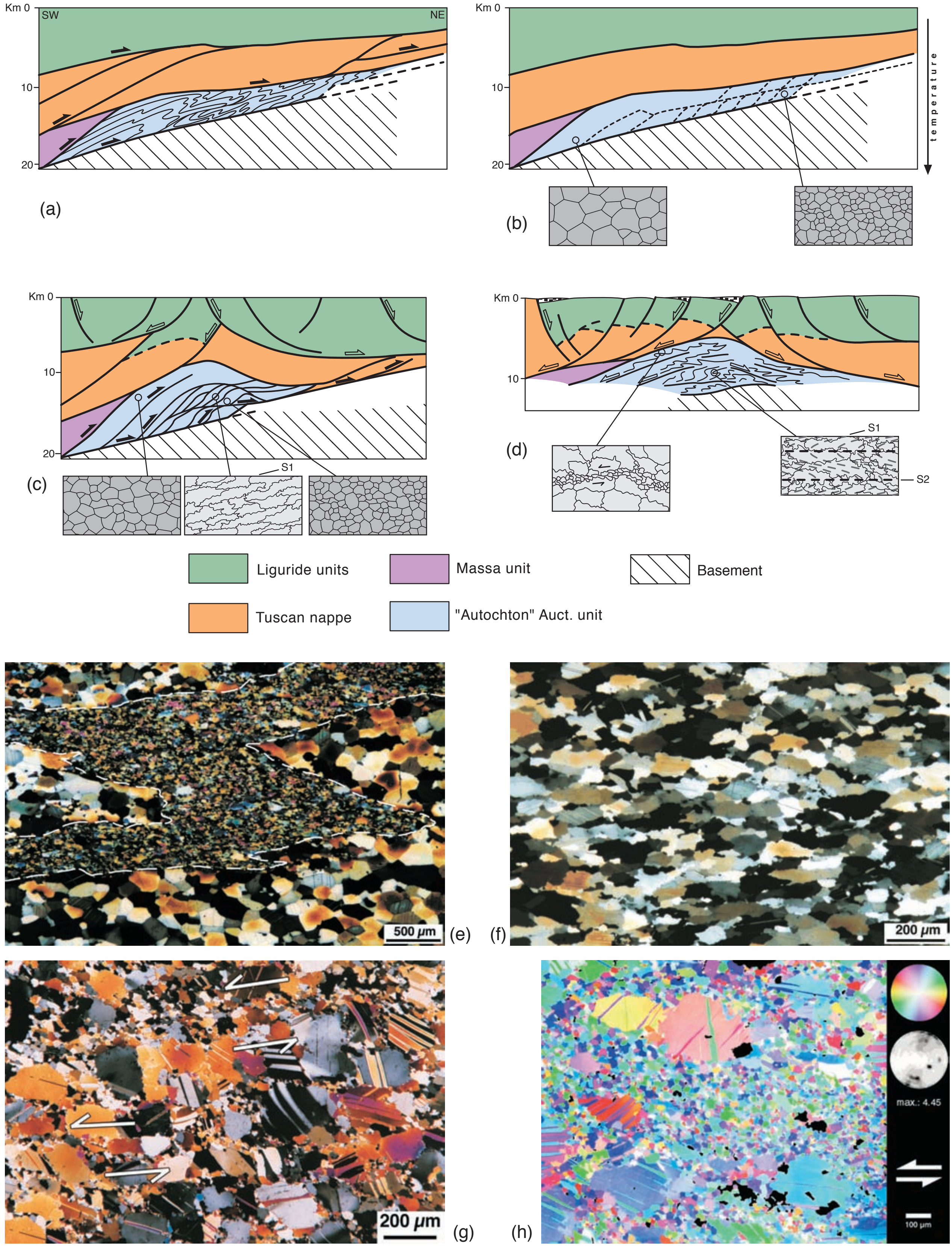


Fig. 21 – Microfabrics in Alpi Apuane marbles (after Molli *et alii*, 2000a). (a) D1 phase, with main foliation and km-scale isoclinal folds developed. (b) After D1 main folding phase annealing occurred, with static recrystalliszation and complete obliteration of earlier microfabrics. (c) During final 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 & 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 show a strong crystallographic preferred orientation oriented normal to the shear zone boundary

3.1.2 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. 19 shows representative examples of the two types of microfabrics. These two types of microstructures are both interpreted as related to high strain and high 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.

3.1.3 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.

3.2 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. 21a), nappe emplacement, km-scale NE-facing isoclinal folds, stretching lineations and main 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. 21b). 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 the D1 event (antiformal stack phase, Fig. 21c), 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 accomodate 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. 21d). During this event, narrow millimeterto 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. 21d). 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.

Part II

Field Trip

Day 1 : Emilia–Tuscany Northern Apennines

Field Trip Route

San Giovanni Valdarno - Pistoia - Abetone - Pievepelago - Passo delle Radici - Corfino.

Topics

Tectonics of the Emilia-Tuscany Northern Apennines. Relationships between the Tuscan Nappe/Cervarola Unit/Modino Unit. Kinematic evolution of tectonic units.

Stop 1.1

Locality: Pianosinatico.
Coordinates: 44°7'10.01"N – 10°43'43.06"E
Topics: Relationships between Tuscan Nappe and Cervarola Unit. The Libro Aperto shear zone.

We stop in a large wide road bend above Pianosinatico village, about 8 km before the Abetone pass.

Panoramic view (Fig. 23) from south of the Libro Aperto – Cima Tauffi ridge. We observe the wide Libro Aperto Shear Zone, formed of several tectonic slices stacked top-E shearing Fig. 22. Tectonic elements of Mt. Modino Sandstone, Marmoreto Marl, Fiumalbo Shale, Ligurian/Subligurian shale/limestone lithosomes as Abetina Reale Flysch and the Chaotic Complex, Serpiano Sandstone and Mt. Cervarola Sandstone are incorporated in the shear zone.

The shear zone is limited to the west by the thrust of the Macigno of the Libro Aperto (Tuscan Nappe), with overturned sandstone beds, and to the east by 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

Locality: M. 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. 25).

From bottom upwards, first outcrop disrupted limestone blocks within chaoticized grey shale belonging to the Ligurian Rotari Flysch (Fig. 26a) 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 Fm. (Fig. 26b).

The Marmoreto Marl fm. 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 represents a channel-filling body onlapping onto the Fiumalbo Shale. Above another pebbly mudstone horizon few meters 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 Fm. passes through a sharp but parallel boundary to thin bedded sandstones, the the base of the Mt. Modino Sandstone Fm. This horizon, 10 meters thick, is built of turbidite sandstones showing typical sedimentary structures. 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.

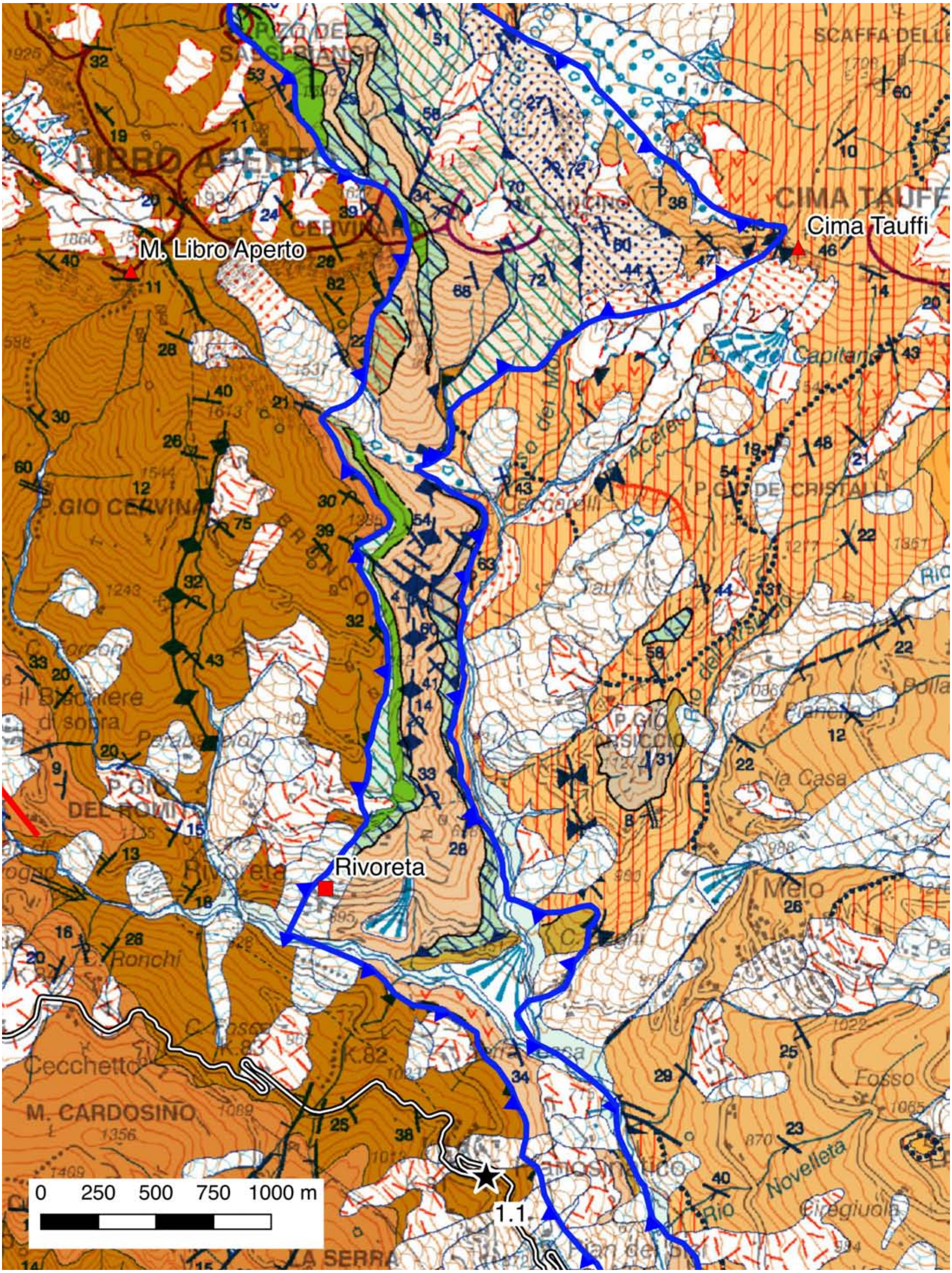


Fig. 22 – Geological map of the area of Stop 1.1, after BOTTI *et alii* (2011).

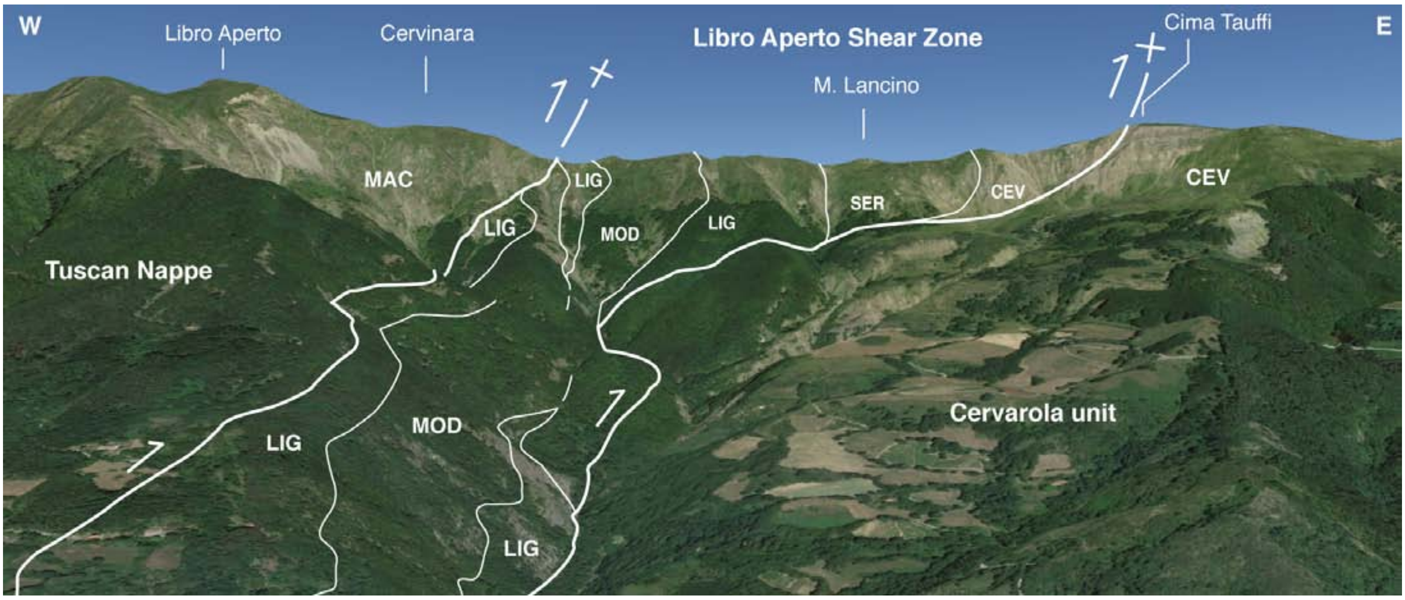
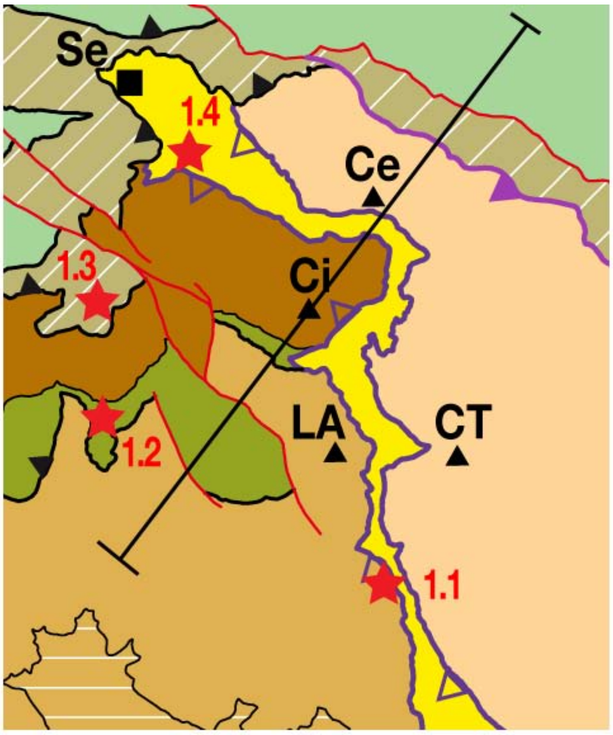


Fig. 23 – Panoramic view from Pianosinatico, Stop 1.1. Geology after BOTTI *et alii* (2011).



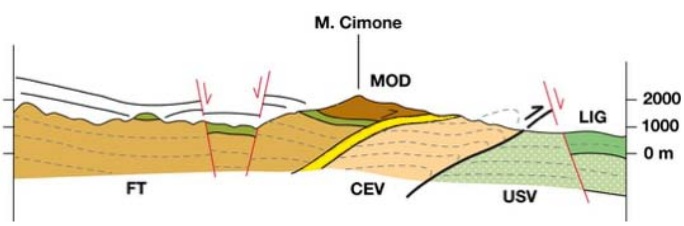


Fig. 24 – Relationships between the Modino unit, Tuscan Nappe, and Cervarola unit in the Cimone-cervarola area. See Plate 3 for legend.

A complete panoramic view is observable from Mt. Modino (Fig. 27). 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 upwards sharp reduction in bed thickness, that BRUNI *et alii* (1994b, and references therein) interpreted as the stratigraphic boundary between the Macigno Fm. and the Mt. Modino Sandstones, lacking of the chaotic unit in between. Looking to WSW we'll see the Mt. Nuda showing the prolongation of the Mt. Modino settings.

The Mt. Modino Succession has two main different interpretations in the Northern Apennine geological framework. The Florence school and others (BRUNI *et alii*, 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 alii*, 2006). Following this interpretation the submarine slide should be placed conformably at the top of the Macigno Fm. 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 alii*, 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 Fm. We'll discuss this topic in terms of structural framework, relationships 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 Riolunato and then turn right again along a small road parallel to the Scoltenna Creek, leading to the San Michele ENEL power station.

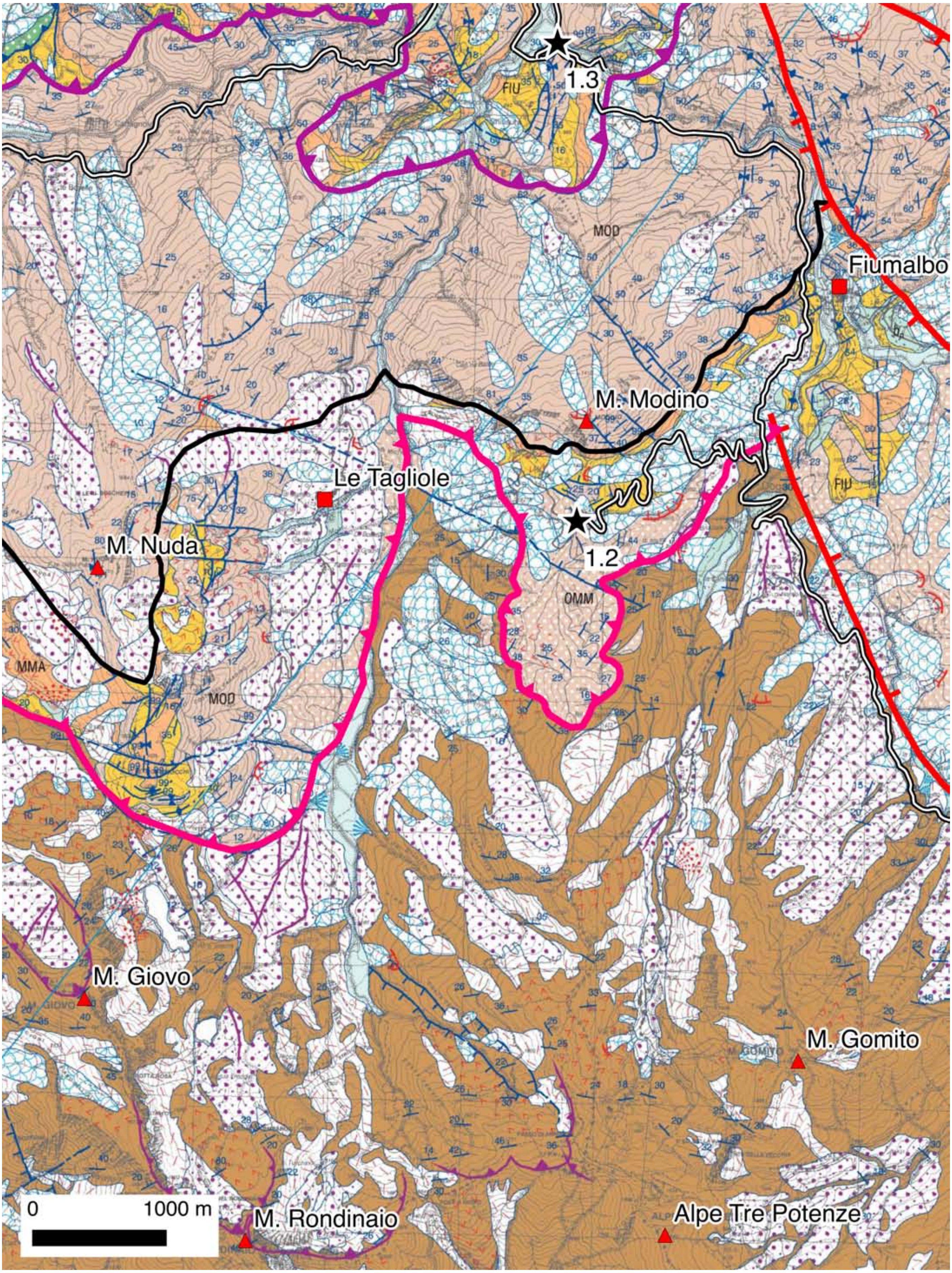


Fig. 25 – Geological map of the area of Stop 1.2, after PUCCINELLI *et alii* (2010) and BOTTI *et alii* (2011).

Fig. 26 – Stop 1.2, M. 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.

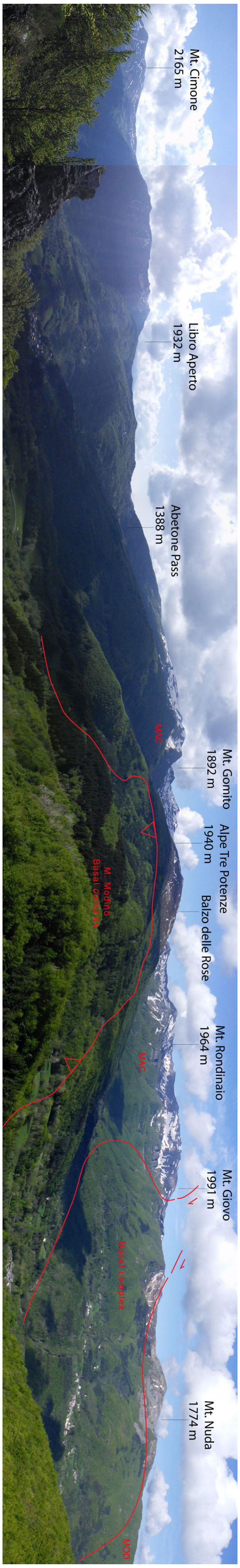


Fig. 27 – Panoramic view from M. Modino (Stop 1.2).

Stop 1.3

Locality: 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. 28).

Along the road beautifully exposed sandstones outcrop, with beds dipping 60° toward NE. The sandstones show alternation of thin to thick beds with typical turbidite structures and a slump horizon of about 1 m thickness. The sandstones pass downwards to strongly deformed and foliated marlstones, referable to the Marmoreto Marl Fm. The internal structure and deformation style of Marmoreto Marl are well exposed along the cliff above the San Michele ENEL Power station (Fig. 29a).

A steep cliff along the Scoltenna valley (Fig. 29b,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 affecting the rock mass.

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-relate 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 alii*, 2004, 2007, 2011, 2013; Vannucchi *et alii*, 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 alii*, 2002, , among the others), tectonically of stratigraphically located above the Mt. Modino Sandstone.

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

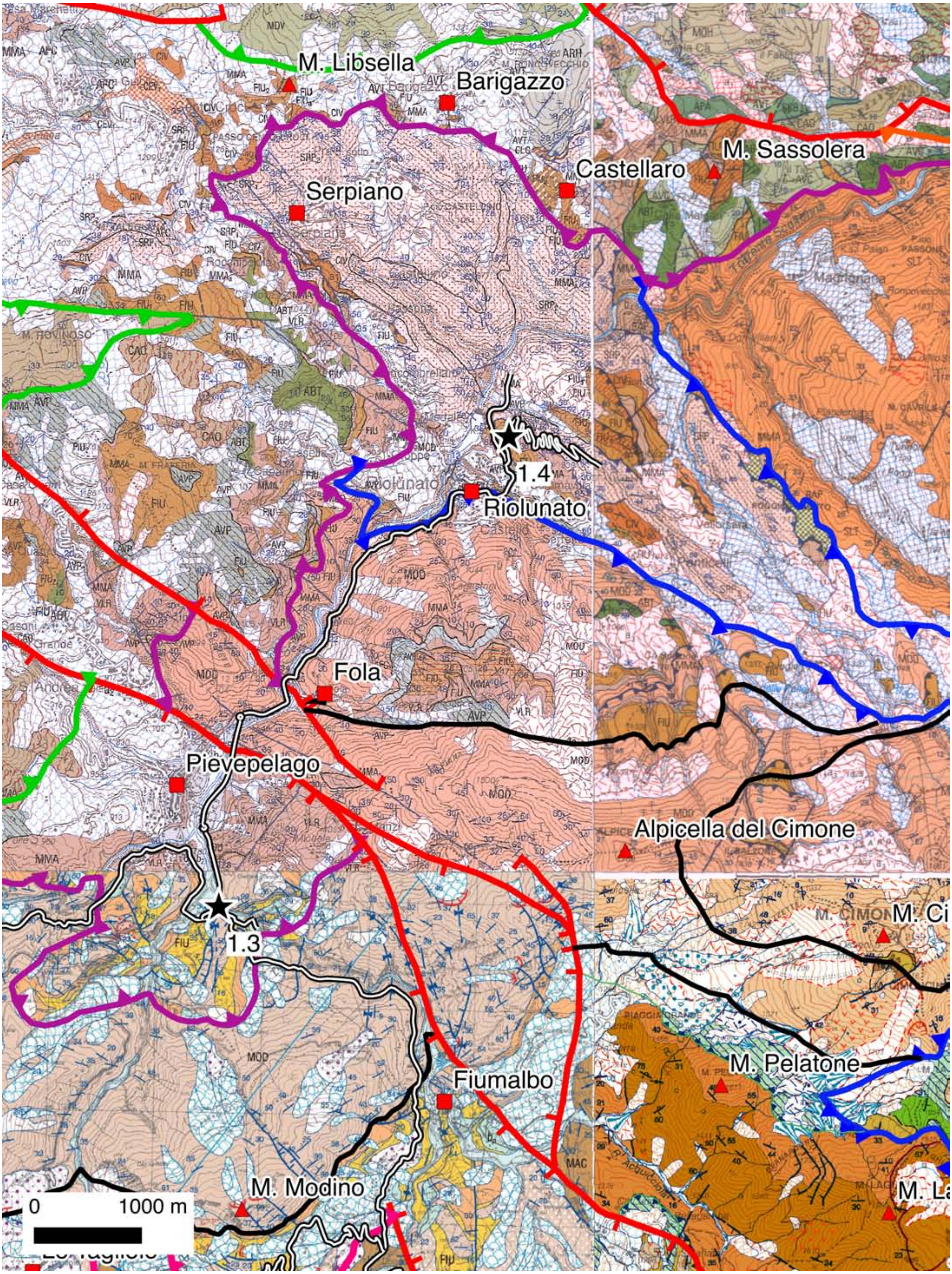


Fig. 28 – Geological map of the area of Stops 1.3 and 1.4, after BETTELLI *et alii* (2002); PLESI (2002); PUCCINELLI *et alii* (2010); BOTTI *et alii* (2011).

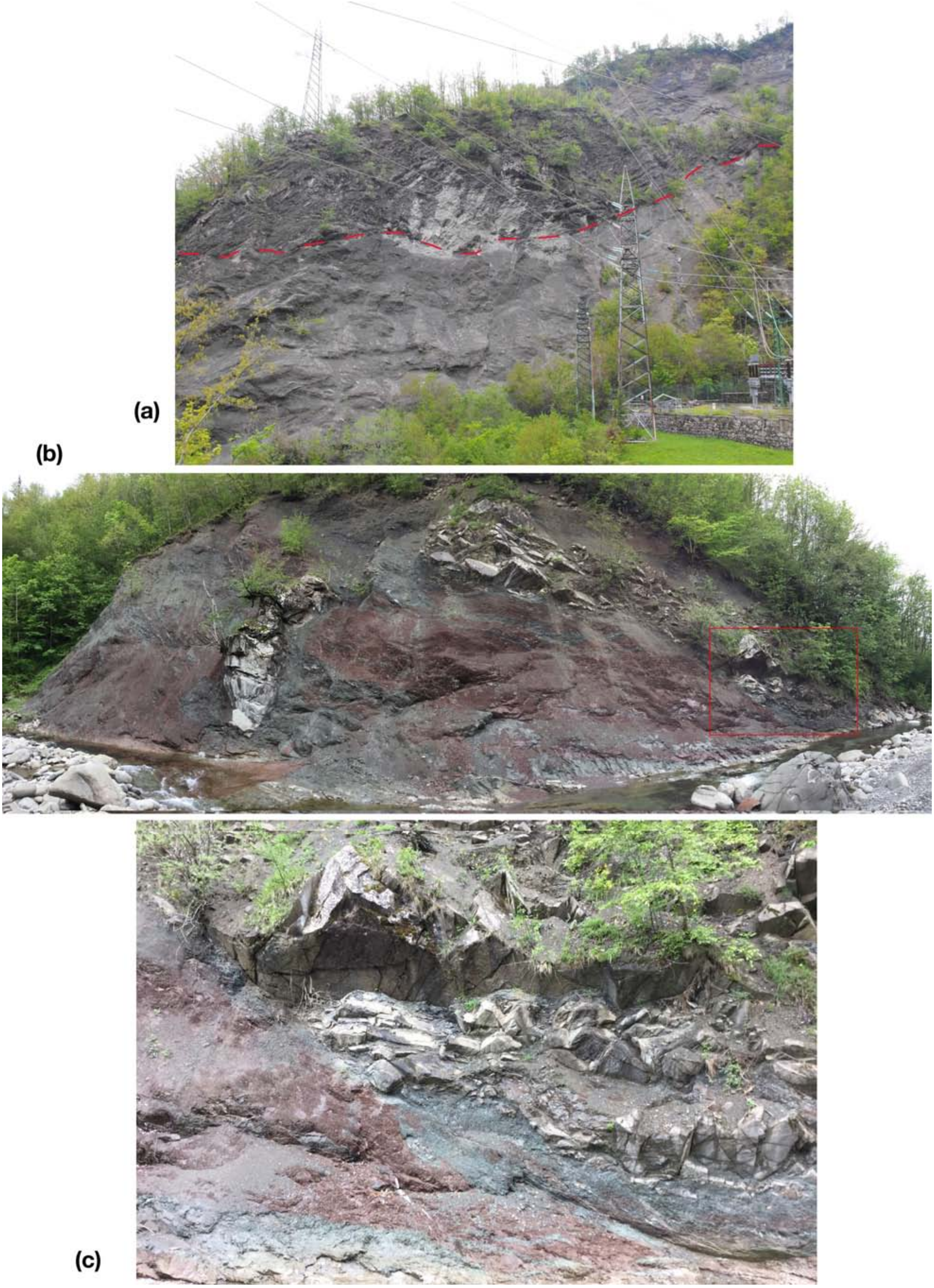


Fig. 29 – The Sestola-Vidiciatico Unit at Ponte Modino, Scoltenna Valley (Stop 1.3). (a) San Michele ENEL Power Station: tectonic contact between sandstones and marlstones. (b) Outcrop of sandstones and marlstones slivers, strongly deformed. (c) Detail of (b), red box.

Stop 1.4

Locality: Riolunato – 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.

Riolunato: park in front of the cemetery.

Here we'll have a look at the internal structure of the Libro Aperto Shear Zone (Fig. 28, Fig. 30), 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 allows us to observe thin-bedded turbidite sandstones lying tectonically below the marlstones, called Serpiano Sandstone correlated 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. These 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. 30a). More in detail (Fig. 28), 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 outcrops the tectonic contact with the above-lying Sestola-Vidiciatico Unit here represented by deformed rocks of the Modino Unit and Ligurian basal complex terms. 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.

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

Locality: San Pellegrino in Alpe.
Coordinates: 44°11'27.73"N – 10°29'59.73"E
Topics: Deformation in the frontal parte 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. 31).

Along the slope to La Cimetta overturned steep inclined sandsdtone beds of the Macigno Fm. 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 Fm. 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 trasport direction, outcrops 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 belongin 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 Fm. 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.

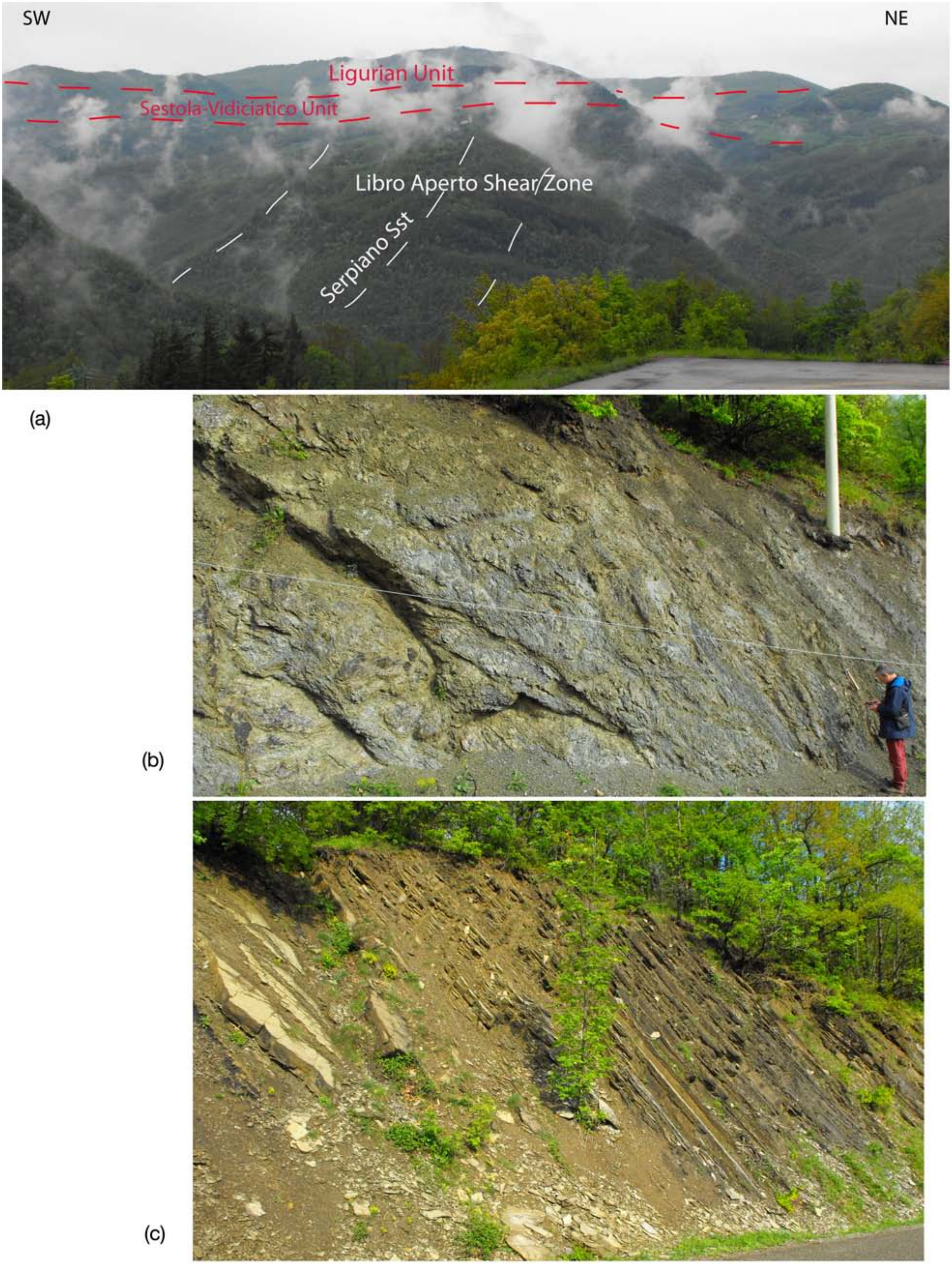


Fig. 30 – Stop 1.4. (a) Relationships between the Libro Aperto Shear Zone and the Sestola-Vidiciatico Unit. (b) Deformed Marmoreto Marls in the Libro Aperto Shear Zone. (c) Overturned Serpiano Sandstones in the Libro Aperto Shear Zone.

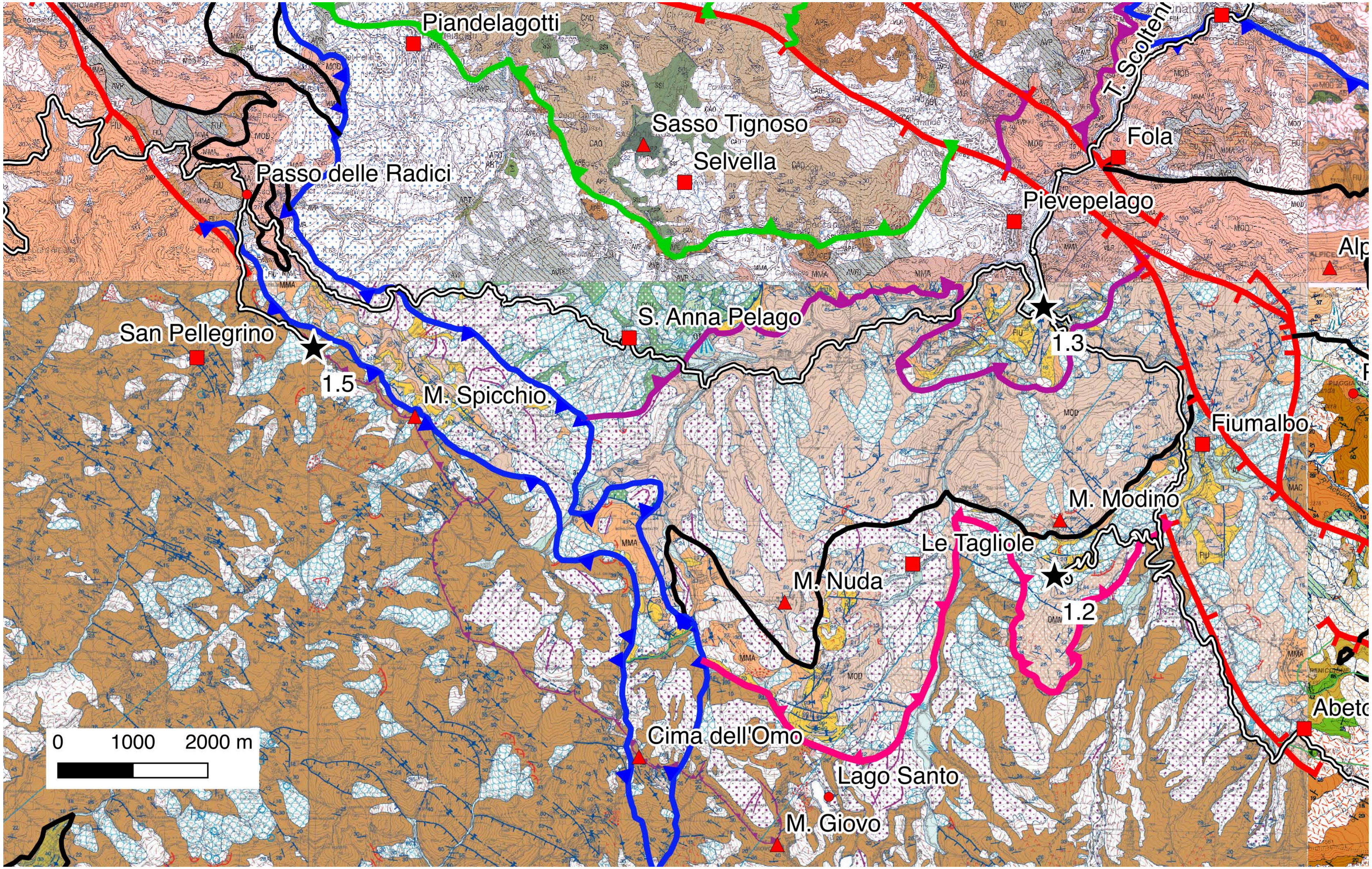


Fig. 31 – Geological map of the area of Stop 1.5, after PLESI (2002) and PUCCINELLI *et alii* (2010).

Day 2 : 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

Locality: Turrite Secca

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

Topics: The Calcare Cavernoso fm: cataclastic rocks 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. 32).

In this small outcrop we can observe, although not very well exposed, the Calcare Cavernoso fm. 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, rauhwacke), with dolomite/calcite clasts and an overall brecciated structure (Fig. 33). 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

Locality: 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 (Figs. 2 and 3). 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 Formation).

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 Formation, D2 folds with wavelengths of decimeters to half of meters are associated with a sub-horizontal axial planar foliation. The metasediments are affected by welldeveloped 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-theeast kinematics. At the top of folded domain, a meter-thick layer of cohesive, fragmented metasediments of the Pseudomacigno Formation can be recognized. This cataclastic domain is in contact with a meters-thick fault gouge, with evidence for confi ned fl uid infi ltration 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 noncylindrical 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 S0, 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 Formation in the footwall and Macigno Formation (sample 03RE20) in the hangingwall of the fault may be found in Fellin *et alii* (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 (sample 03RE20) yielded a ZHe

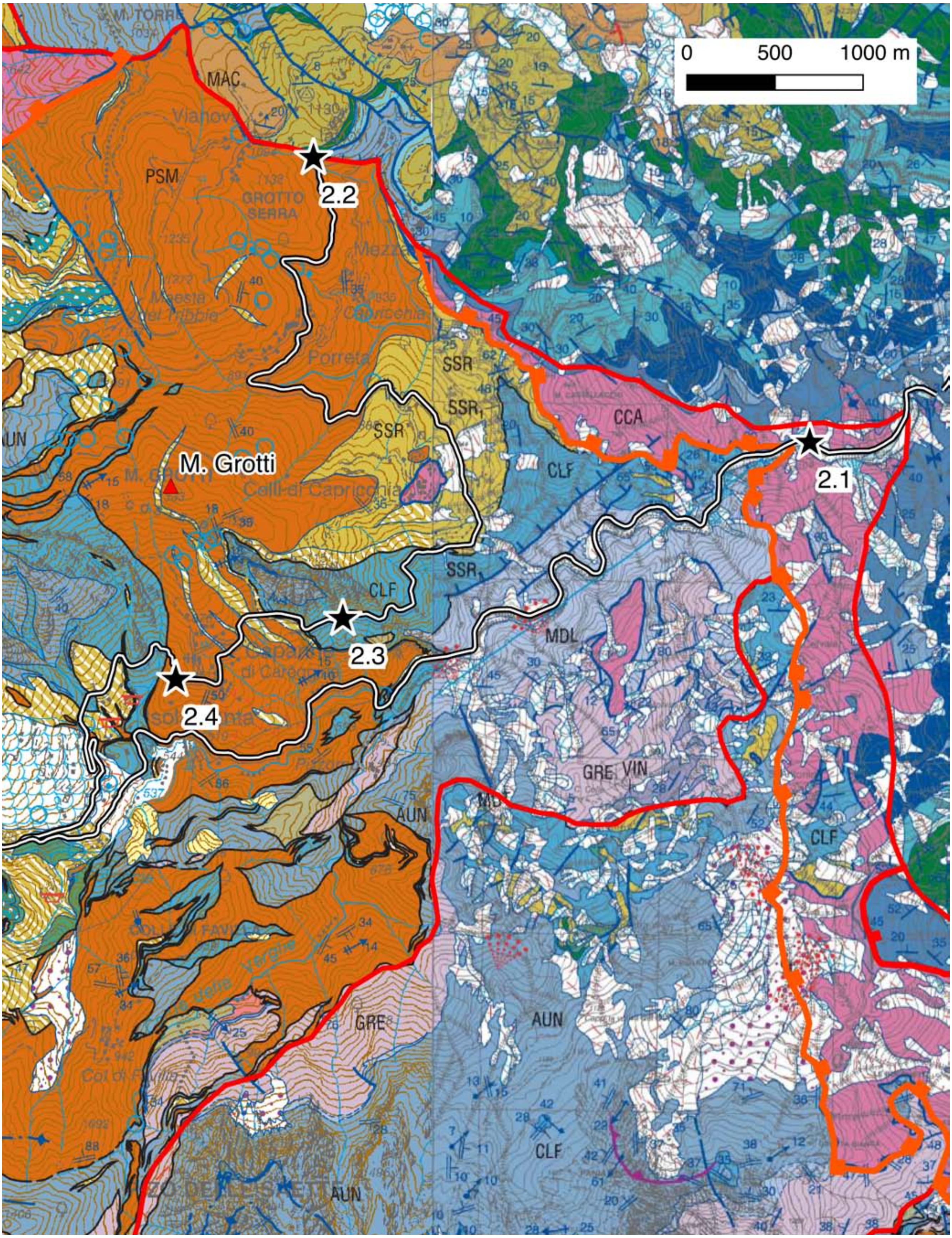


Fig. 32 – Geological map of the area of Stops 2.1, 2.2, 2.3 and 2.4, after PUCCINELLI *et alii* (2010) and CONTI *et alii* (2018).

Fig. 33 – Cataclastite (Calcare Cavernoso fm.), Stop 2.1, Turrite Cava.

age of 12.5 ± 1 Ma, which may be only a partially reset age. 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 alii*, 2007).

Stop 2.3

Locality: E 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.) outcrops (Fig. 32). In this area severe shear deformation affect Late Jurassic - Early Miocene rocks. Cherty limestones, calcschists (metamorphic "Scaglia Toscana") and phyllites and metasandstones (Pseudomacigno fm.) are here strongly foliated and bedding is completely transposed along S1 foliation. S1 foliation bear a L1 stretching lineation NE-SW oriented.

We stop where the "Calcari selciferi" fm. outcrops (Fig. 35). 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 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

Locality: Capanne di Careggine
Coordinates: 44° 4'8.69"N – 10°18'50.83"E
Topics: Deformation in the Pseudomacigno fm.

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

In this outcrop the Pseudomacigno fm. is represented by metasandstones and phyllites strongly foliated (Fig. 36). 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.

Stop 2.5

Locality: Passo del Vestito
Coordinates: 44° 3'51.85"N – 10°13'24.02"E
Topics: Panoramic view toward the northern Alpi Apuane.

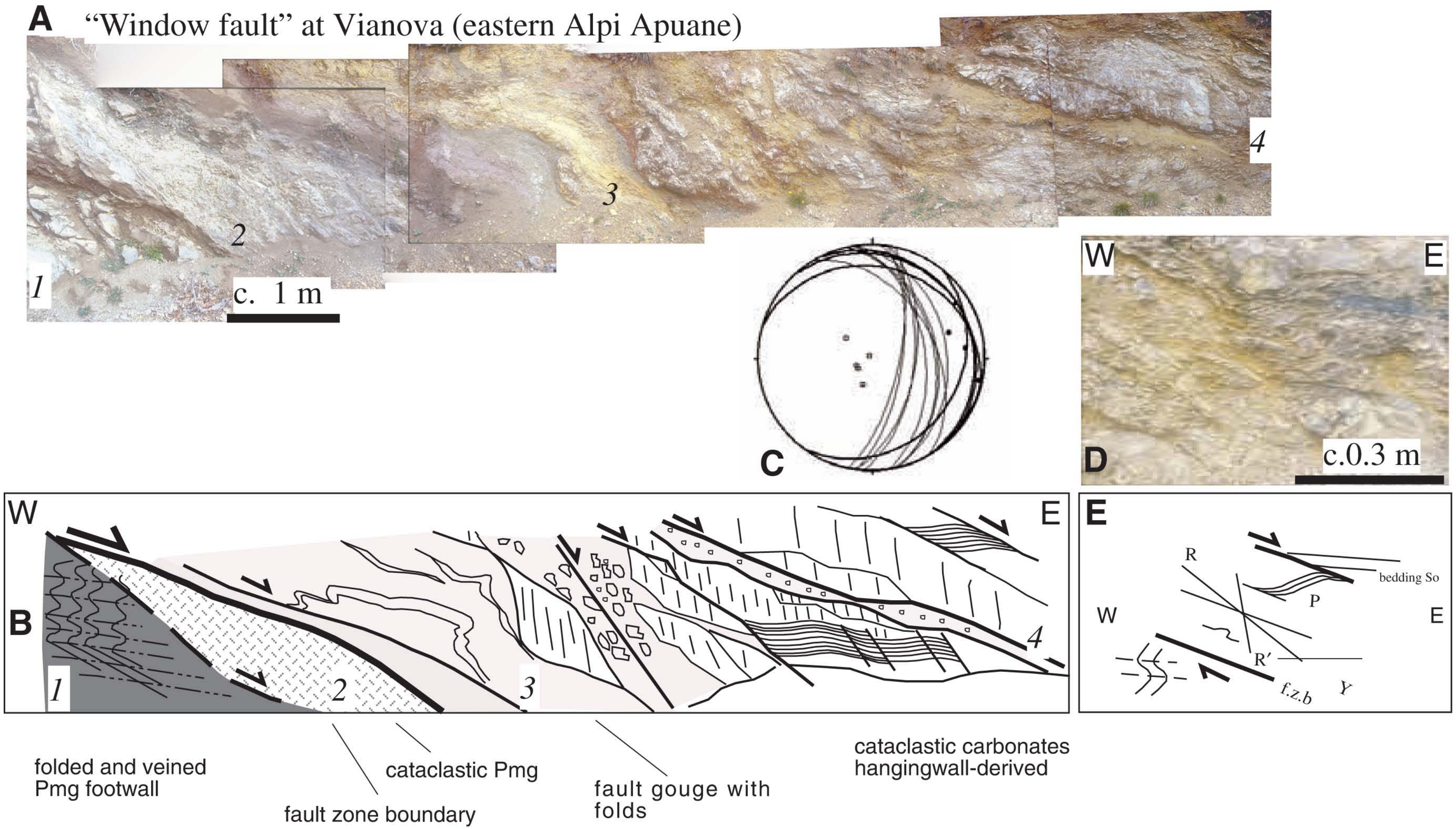


Fig. 34 – Stop 2.2. (A) General view (scale bar 1 m) and schematic representation (B) of the structural elements of the tectonic "window fault" between the unmetamorphic Tuscan Nappe and metamorphic Apuane core, a fault that is observable at Vianova (road toward Capanne di Careggine) eastern Apuane. (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), R′ 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′—Ridel fractures; Y—slip surfaces; P—foliation. After Molli (2002).

Fig. 35 – Mylonitic cherty limestones at Stop 2.3.

Fig. 36 – D2 folds in the Pseudomacigno fm., Stop 2.4.

At this stop (Fig. 37), a panoramic view of the western side of the Alpi Apuane region can be observed from the Tyrrhenian Sea to the eastern Alpi Apuane (Fig. 38, Fig. 39).

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; 6–8 Kb) at the top of the lower grade "Autoctono" unit (350–400 °C; 4–6 Kb).

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, Marbles (east edge of Sagro and M. Spallone) and Cherty limestone (peak of M. Sagro and M. Spallone). The core of the Vinca anticline is made of phyllite and volcanic rocks of the Paleozoic 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, 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 antiform with a core of Liassic marbles (M. Rasori synform and antiform). The complex structure in 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 (Paleozoic phyllites) that superpose and inteference 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 dolomite 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. 40.

Stop 2.6

Locality: 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. 37 and Fig. 39)

Along the road the core of the D1 isoclinal M. Tambura anticline crops out and the "Filladi inferiori" fm. (phyllites) is here exposed. This antiform have an extension of about 10 km in map view. The Grezzoni formation (dolomites) of the overturned limb is reduced to a few metres of cataclastic dolomite, often budinaged, and usually in the area the Paleozoic 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

Locality: 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.

Witha 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

Locality: Cervaiole
Coordinates: 44° 2'21.67"N – 10°14'45.91"E
Topics: Deformed marble breccia; origin of brecciation and structures of the area; Paleozoic basement rock types; quarrying technology.

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

Fig. 37 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 Cervaiole 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 Cervaiole," and minor amounts of "ordinario" and "statuario" marble types (see Meccheri *et alii*, 2007a for a comprehensive overview of the M. Altissimo marble basin). The "ordinario" type in this area

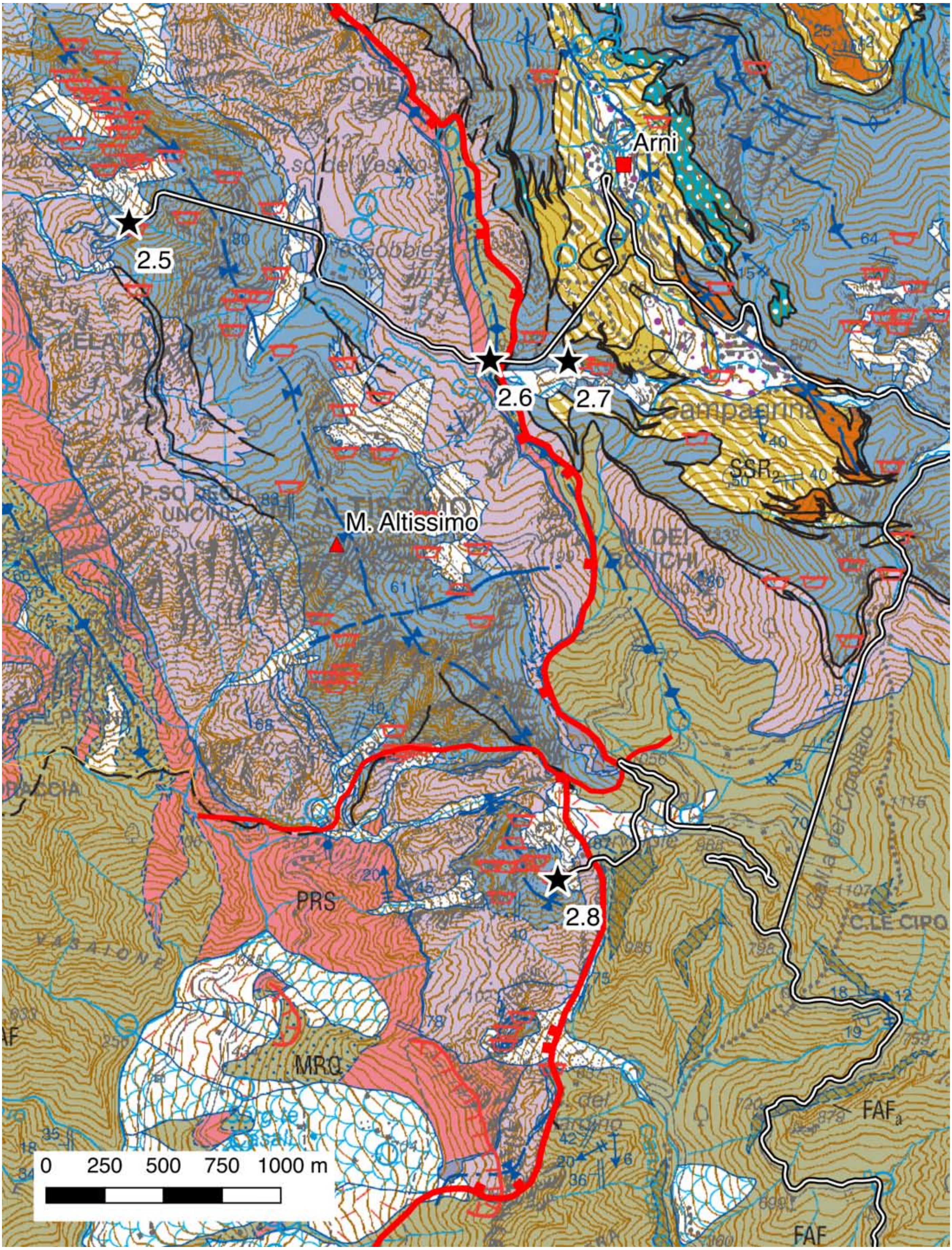


Fig. 37 – Geological map of the Stops 2.5, 2.6, 2.7 and 2.8.

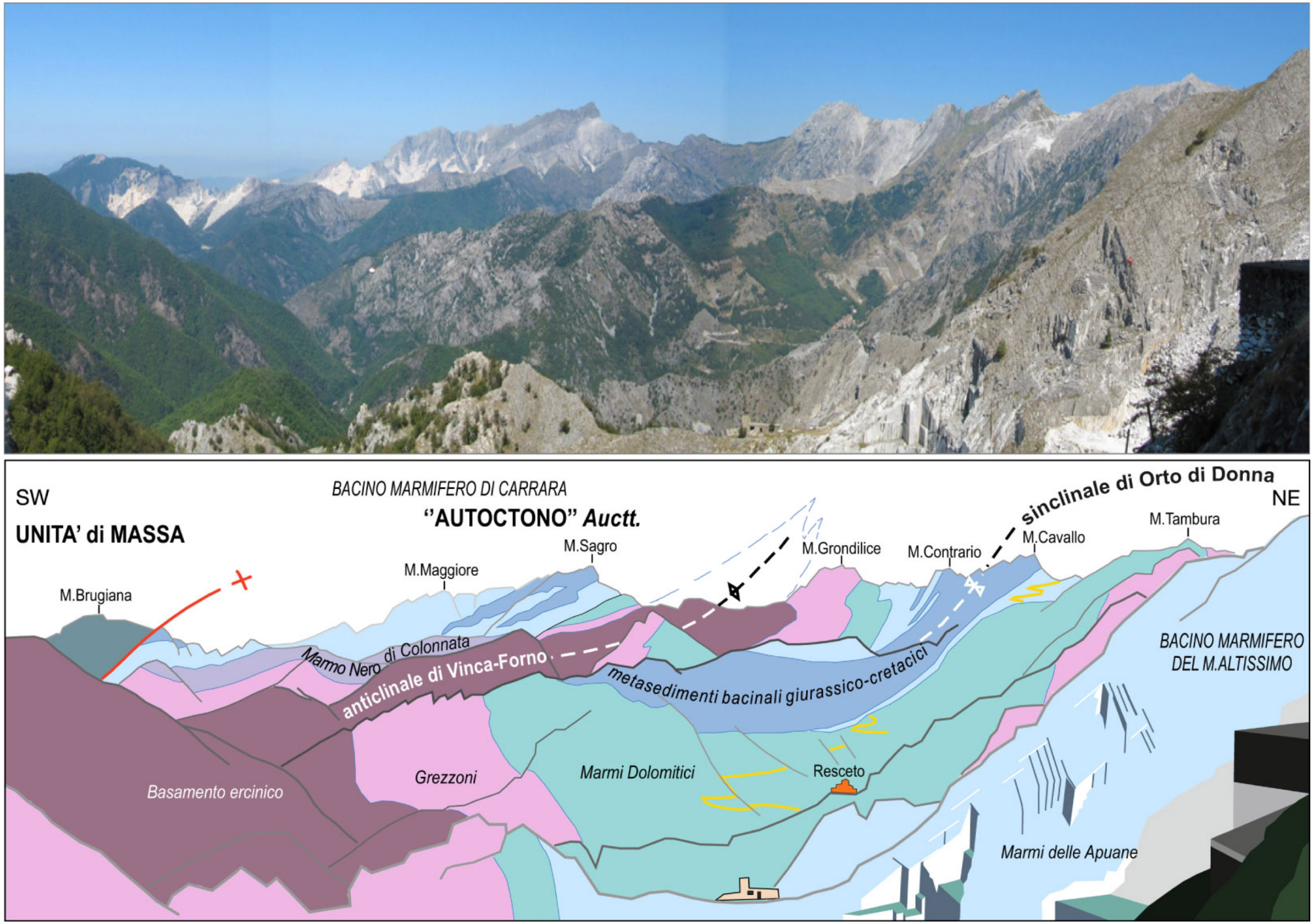


Fig. 38 – Panoramic view of the northern Alpi Apuane, from Stop 2.5, Antona-Arni road, W of the Passo del Vestito tunnel. Line Drawing by E. Patacca and P. Scandone, in CONTI *et alii* (2018).

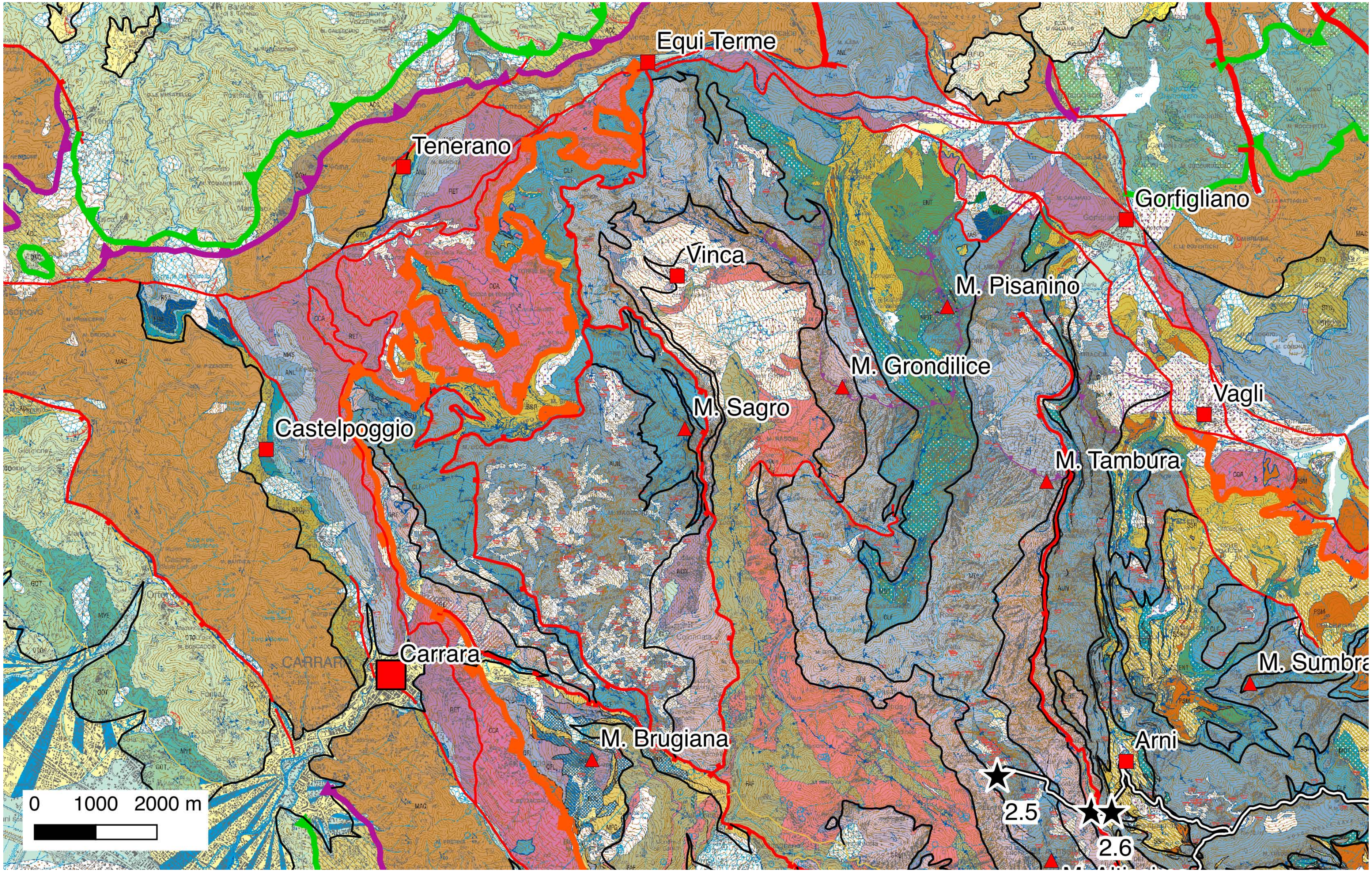


Fig. 39 – Geological map of the northern Alpi Apuane, from CONTI *et alii* (2018).

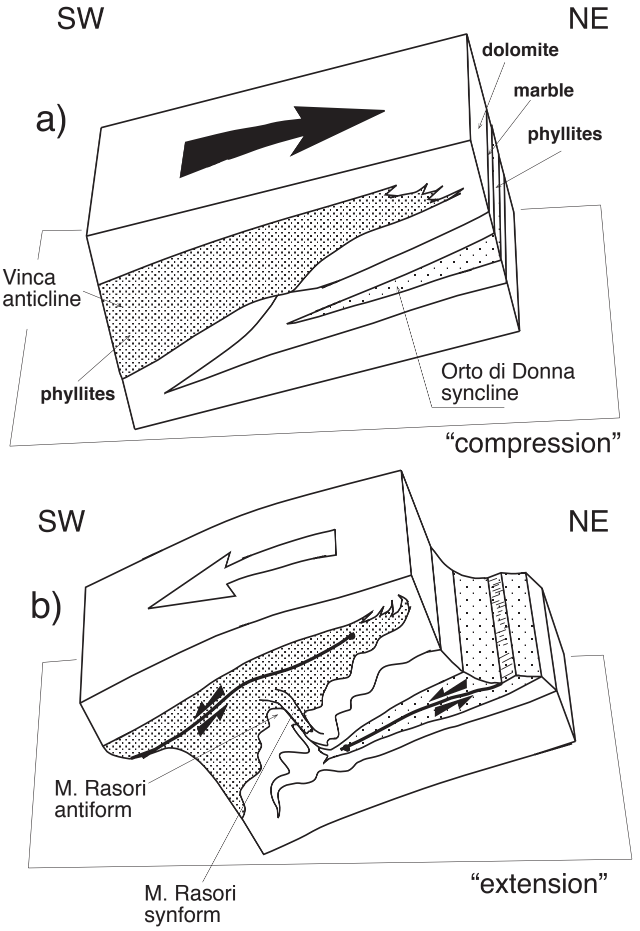


Fig. 40 – D1 and D2 deformation superposition in the Frigido valley (Stop 2.5). Late structures in the inverted limb of the D1 Vinca anticline are interpreted as “transfer folds” between two ductile shear zones.

looks like a regularly stratifi ed 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 Early 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 alii*, 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 Paleozoic phyllites, dolomites and marbles. Dolomite-phyllite and dolomite-marble show evidence for a contrast in competence during deformation that results in a modifi ed cartographic-scale dome and basin interference pattern, with cuspate 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 planar crenulation (D2).

The overall structure of the Mount 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 rations 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 preexisting 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 & Giglia, 1983; Molli & Vaselli, 2006; Meccheri *et alii*, 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 & Meccheri (2012).

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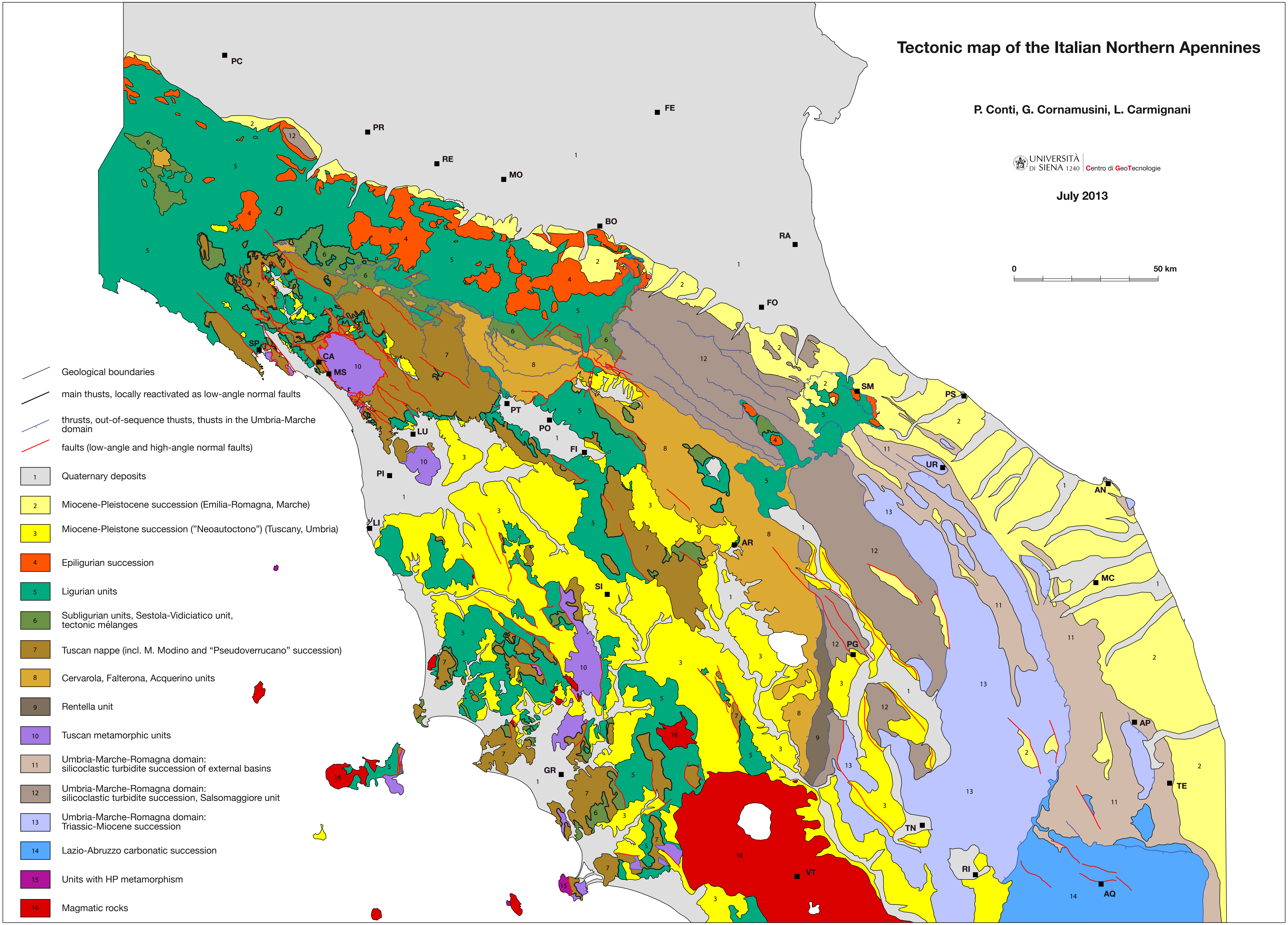


Plate 1 – Tectonic map of the Northern Apennines.

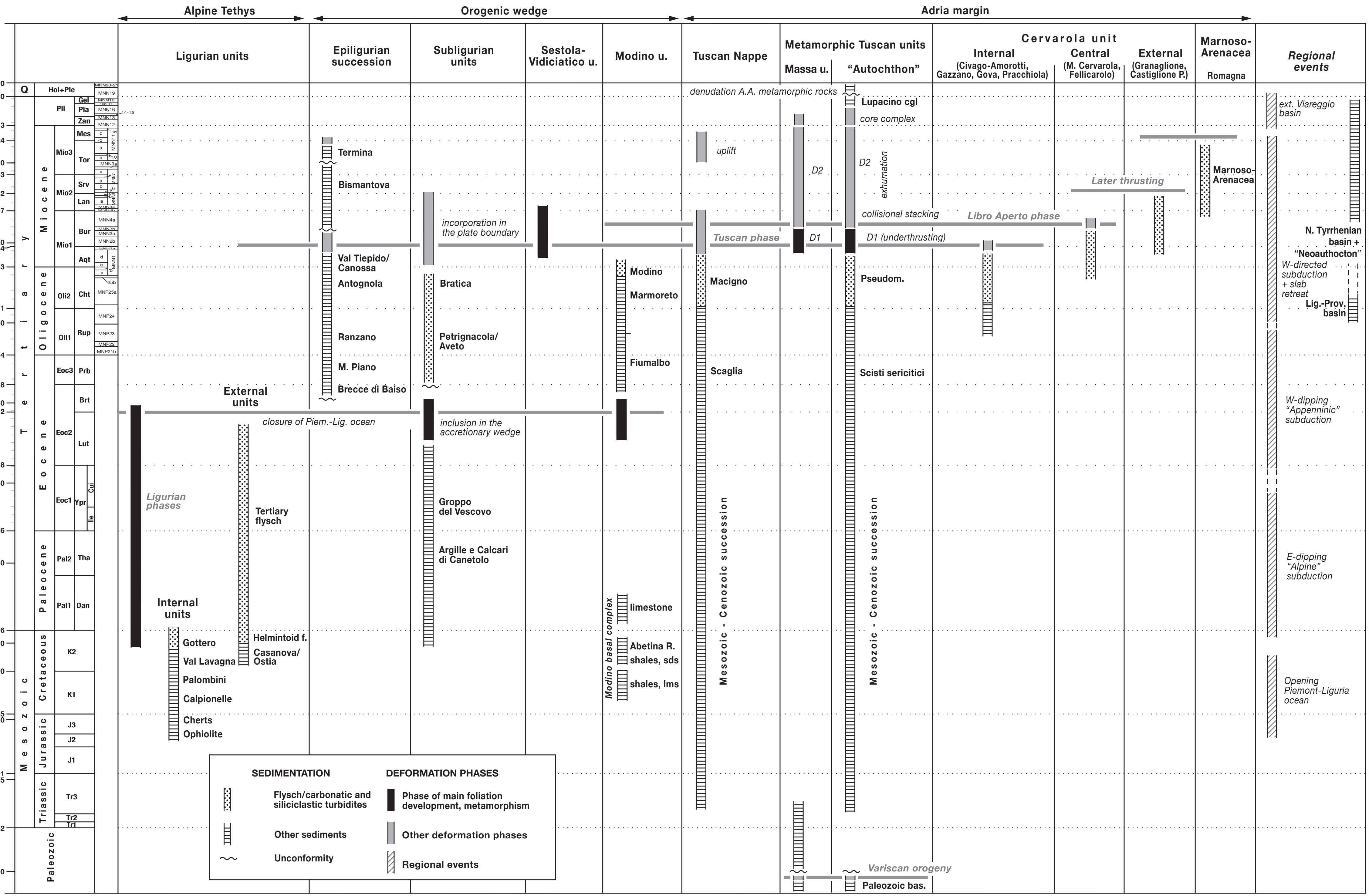


Plate 2 – Chronostratigraphic scheme showing the main sedimentary and tectonic events in the tectonic units of the Northern Apennines.

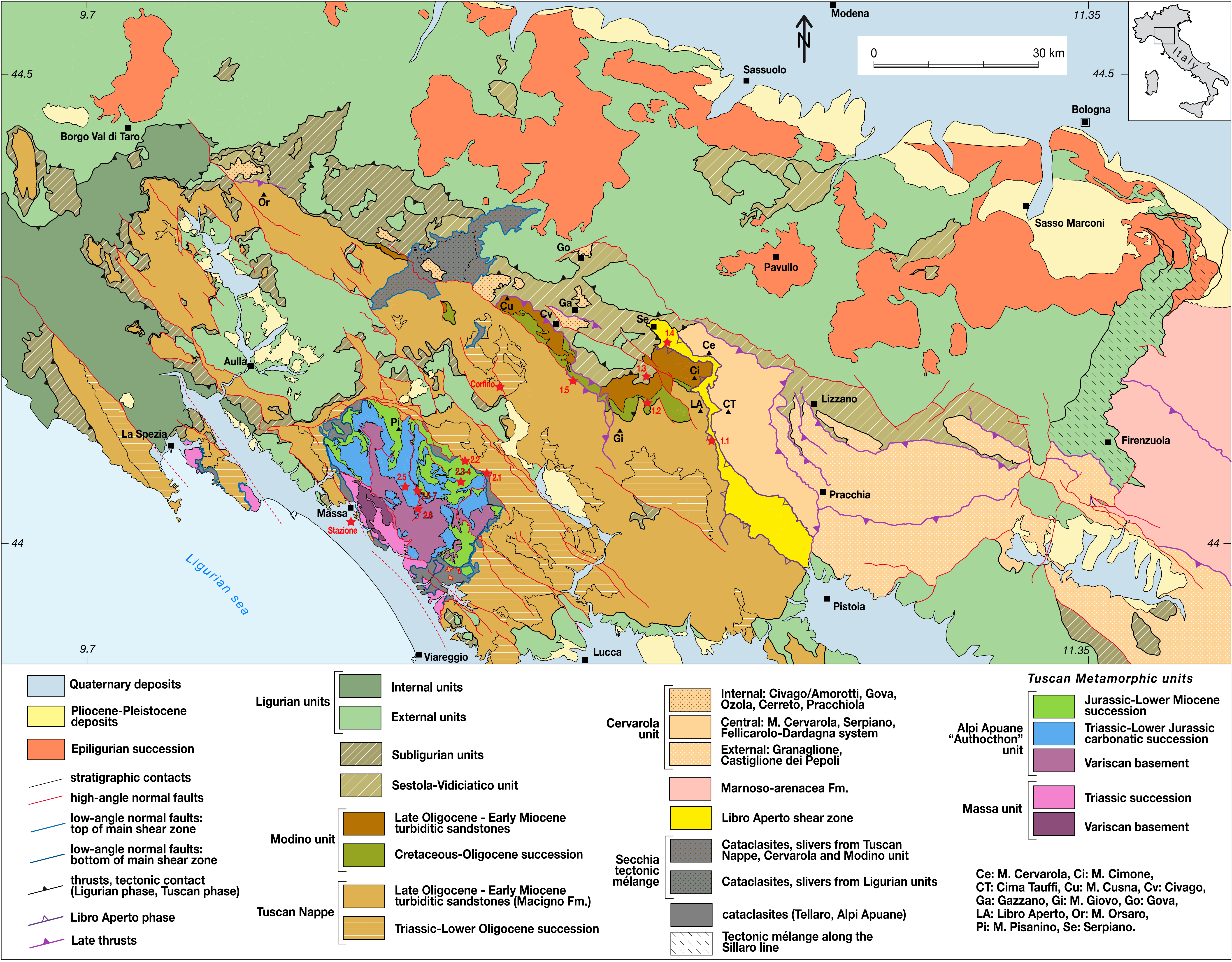
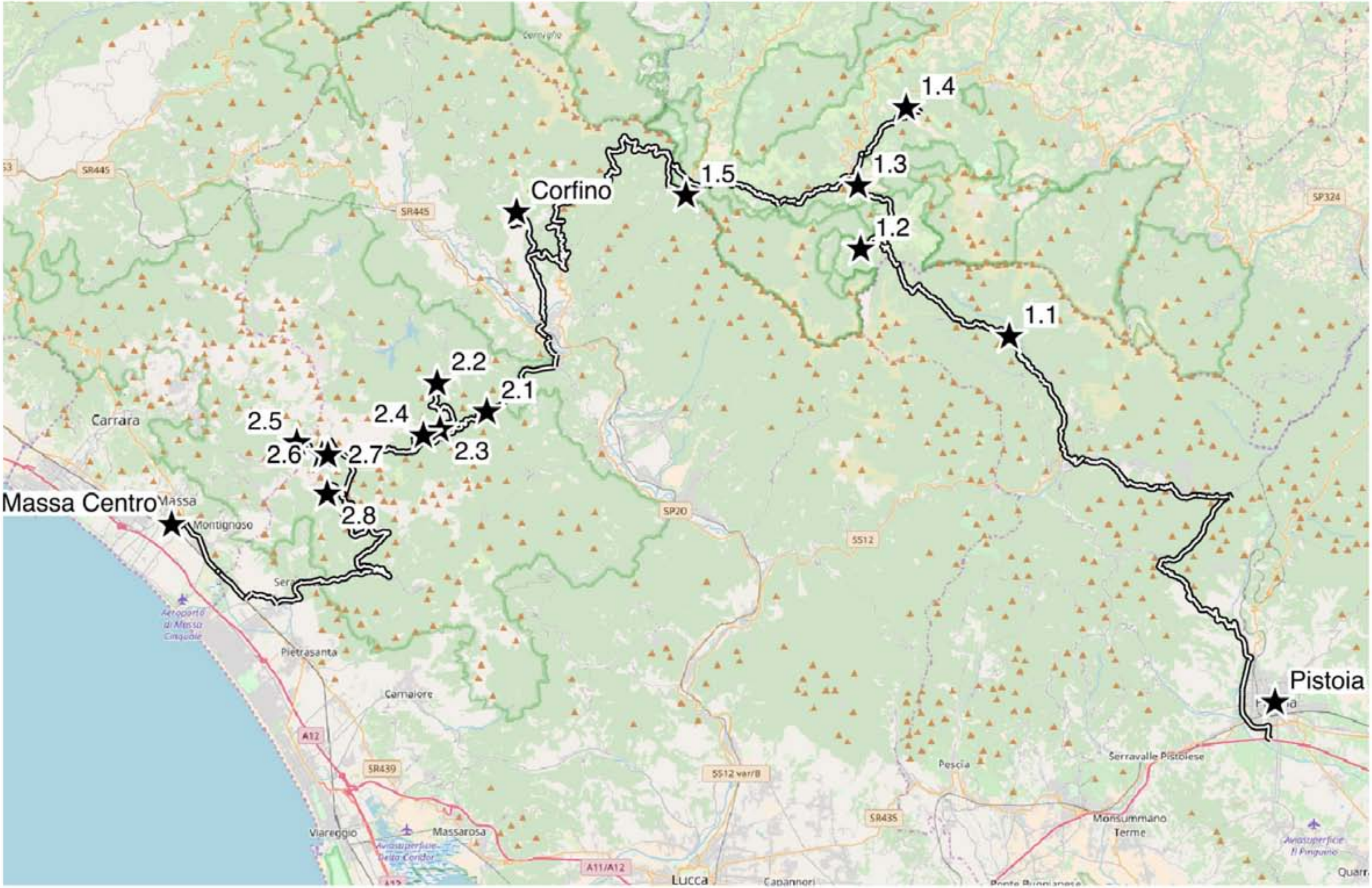


Plate 3 – Tectonic map of the Emilia-Tuscany Northern Apennines, with Stops.



Road Trip with Stops location.