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Field Trip B Post-Congress

The Alpi Alpi Apuane Metamorphic Complex

Field Trip Guide

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European Geosciences Union

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Contents

Foreword

The aim of this excursion is to give a concise but complete picture of the evolution of the Alpi Apuane Metamorphic Complex.

This guide-book includes a short outline of the stratigraphic and tectonic evolution of units outcropping in the Alpi Apuane area and in the Italian Northern Apennines, and 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.
- 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.
- 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.
- Conti P., Conticelli S., Cornamusini G. & Marroni M. (2022) - *Toscana*, Guide Geologiche Regionali, vol. 15. Società Geologica Italiana, Roma, 375 pp.

The excursion is divided in two days:

a) the first day is dedicated to the tectonics of the central Alpi Apuane area;
b) the second day will focus on the stratigraphy and tectonics of the northern Alpi Apuane area, and relationships with upper tectonic units (Tuscan Nappe and Ligurian units).

We wish you an interesting excursion!

Paolo Conti
Giancarlo Molli

September 2024

Part I

Geological overview

1

The Northern Apennines

1.1 Introduction

The Northern Apennines (Fig. 1) is a fold-thrust belt formed during the Miocene by thrusting from W to E of the Ligurian units onto the external Tuscan-Umbria domain.

The Ligurian units are characterized by the presence of an ophiolite sequence covered by deep water sediments, and represent part of the Ligurian-Piemont Ocean (or Alpine Tethys). According to most authors these units also suffered the Cretaceous-Paleogene tectonics phases well documented in the Alps. The Tuscan-Umbria domain represents the continental margin of the Adria (Apulia) plate and consists of an Hercynian basement with its Permo-Mesozoic to Tertiary cover. A palinspastic reconstruction for the European-Apulia margin in the Triassic and Late Jurassic is illustrated in Fig. 2 and in Fig. 3. A present-day geological cross section is presented in Fig. 2g.

Eastward motion (in present day coordinates) of the Corsica-Sardinia microcontinent formerly belonging to the European-Iberia plate, led to collision and deformation in the Apulia margin in the Late Oligocene. During the Oligocene-Miocene evolution of the Northern Apennines subduction of the Apulia lithosphere occurred below the Corsica-Sardinia (Briançonnais). Later on back-arc rifting due to slab retreat led to oceanic crust formation first in the Algero-Provencal basin and then in the Tyrrhenian Sea, contemporaneous with eastward migration of subduction, collision zone and deformation. In the Northern Apennines slab rollback led to extension in the more internal area, with basin formation, and contemporaneous shortening in the more external area (Fig. 4).

1.2 Stratigraphy

A palinspastic reconstruction of the Apulia continental margin in the Late Jurassic is illustrated in Fig. 2.

We distinguish the ocean-derived *Ligurian Domain*, a remnant of the Alpine Tethys (?Elter & Pertusati, 1973; Elter, 1975; Bortolotti *et alii*, 2001; Marroni *et alii*, 2001), furthermore separated in:

a) *Internal Ligurian Domain*, characterized by the presence of Jurassic ophiolites and their Upper Jurassic-Cretaceous sedimentary cover (cherts, Calpionella limestone and Palombini shales) associated with a Cretaceous-Paleocene siliciclastic turbidite sequence (Lavagna shales, Gottero sandstones and Bocco/Colli-Tavarone shaly-chaotic complex);
b) *External Ligurian Domain*, characterized by the presence of Cretaceous-Eocene calcareous-dominant flysch sequences (Helminthoid flysch) associated with shaly complexes or pre-flysch formations called "basal complexes" in local literature. The pre-Cretaceous substrate is represented in part by ophiolites and probably its external part consists of transitional crust, a domain that joined the oceanic area to the Apulia continental margin (Ocean-Continent Transition - OCT).

In the Apulia continental margin can be recognized, from W to E (in present day coordinates) the following paleogeographic domains, now outcropping in different tectonic units: the *Tuscan Domain*, the *Umbria Domain*, the *Lazio-Abruzzi platform*. In the Tuscan Domain we can further recognize (see palinspastic reconstruction in Fig. 2):

a) The *Internal Tuscan Domain* (Tuscan Nappe), non - metamorphic (to low-grade metamorphic) formations of Late Triassic to Early Miocene age, completely detached at the level of Triassic evaporites.
b) The *External Tuscan Domain* ("Autochthon" *Auctt.* tectonic unit, or Alpi Apuane tectonic unit), affected by greenschist facies metamorphism, with a Mesozoic-Tertiary succession covering a Paleozoic basement with Hercynian deformation. These rocks crop out in the Alpi Apuane Metamorphic Complex. This unit now outcrops lies tectonically below the Tuscan Nappe.
c) The Massa Unit, structurally interposed between the Tuscan Nappe and the "Autochthon" Auctt. unit, consists exclusively of rocks from Paleozoic to Triassic age and could represent the original substratum of the Tuscan Nappe or derive from an intermediate domain.

The continental origin of the Tuscan Domain is testified by the pre-Mesozoic rocks, the Tuscan Paleozoic basement, substrate of the Tuscan successions (see review in Conti *et alii*, 1991a and Pandeli *et alii*, 1994). This Paleozoic basement is characterized by metasedimentary and metavolcanic sequences showing similarities with the successions observable in nappe- and axial zones of the Variscan chain in Sardinia (Conti *et alii*, 1993). The main pre- Mesozoic deformation and metamorphism in the basement rocks occurred during the Variscan orogeny (Early Carboniferous) with structures developed in greenschist facies in the Alpi Apuane.

During Late Carboniferous/Permian a trans-extensional regime characterized the Tuscan Domain with development of

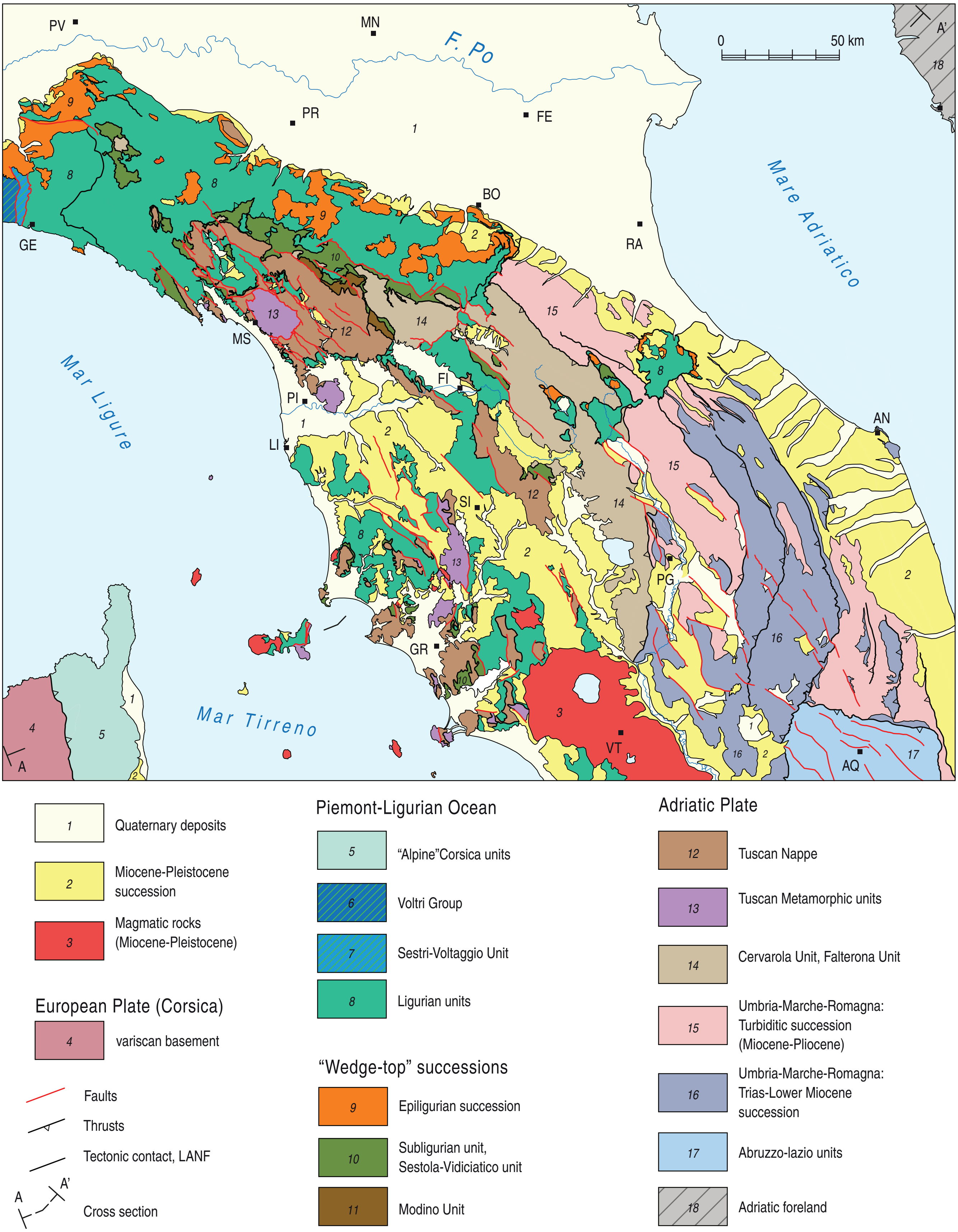

Fig. 1 – Tectonic map of the Northern Apennines, Italy.

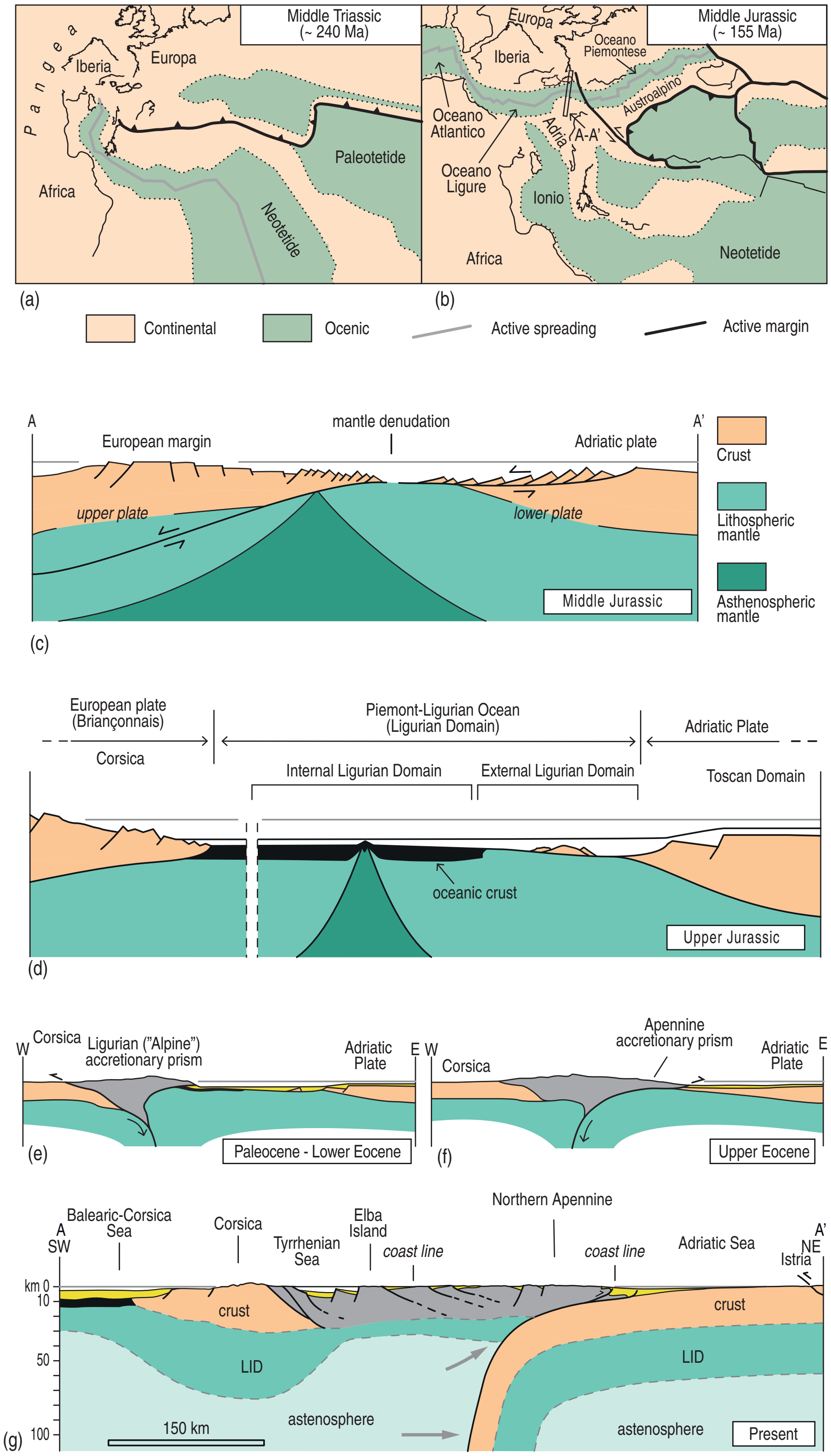

Fig. 2 – (a) Paleogeography of the Piemont-Ligurian Ocean and adjacent areas during the Middle Triassic. (b) Paleogeography during the Middle Jurassic. (c) Section through the European continental margins, the Adriatic and the Piemont-Ligurian Ocean in the Middle Jurassic, the approximate location of the section is given in (b). (d) Upper Jurassic reconstruction. (e) Paleogene reconstruction, with E-directed (in present day coordinates) subduction of the European plate. (f) Late Eocene reconstruction, with W-directed subduction of the Adria Plate. (g) Section through the Northern Apennines, see (a) for trace of section. From Lemoine *et alii* (1987), Stampfli *et alii* (1991, 1998), Marroni *et alii* (2010), Molli & Malavieille (2011), Carminati & Doglioni (2012), modified.

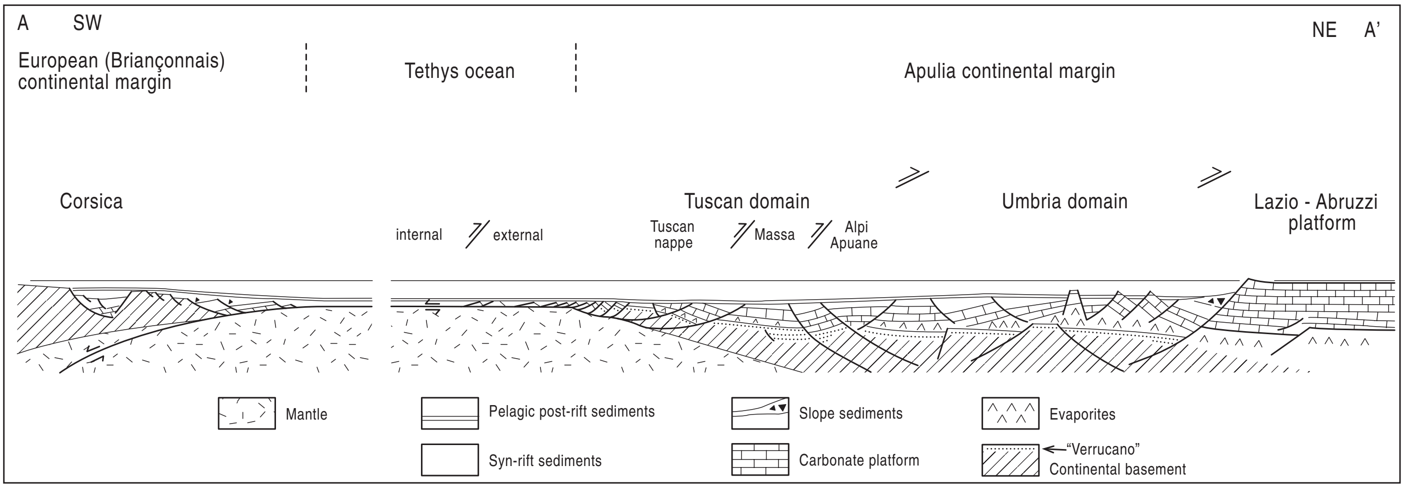

Fig. 3 – Reconstruction of the western continental margin of Apulia, Tethys ocean and adjoining European margin during the late Jurassic; after Marroni *et alii* (1998) and Bernoulli (2001).

narrow continental sedimentary basins (coal-measures, red fanglomerate deposits and acid magmatism, e.g. Monti Pisani and southern Tuscany) bounded by faults and characterized by unconformity and abrupt change in sedimentary facies (Rau & Tongiorgi, 1974; Molli *et alii*, 2020).

During the Middle Triassic evidence of further crustal attenuation is provided by the Anisian-Ladinian extensional basins (Punta Bianca/ Brugiana sequence) in which marine platform sediments (Diplopora-bearing marbles) are associated with alkaline basaltic flows and breccias. This sequence testifies that a Triassic aborted rifting stage affected the Tuscan Domain (Martini *et alii*, 1986).

The continental sedimentation was later re-established through the deposition of the Upper Ladinian (?)-Carnian Verrucano sediments, grading upward to shallow water carbonates (Norian Dolomites "Grezzoni") or evaporites (Calcare Cavernoso) during the renewal of the rifting process. Shallow water carbonate deposition occurred all over the continental margin (Calcare Massiccio platform) during the Rhaetian to early Liassic, locally interrupted by uplift, emersion and development of slope breccias (Rhaetian-Liassic boundary).

Early to Middle Jurassic block faulting and progressive subsidence of the continental margin were associated with the dismembering of the carbonate platforms and the oceanization of the Ligurian Tethys (Malm) far west. Drowning of carbonate platform is testified by Middle Jurassic-Cretaceous to Cenozoic pelagic carbonates and shales grading upward to Oligocene-lower Miocene sandstones and shales (Macigno and Pseudo-Macigno). As a whole, the Mesozoic to Cenozoic stratigraphic evolution of the Tuscan Domain reflects deposition in a rifted continental margin which evolved into convergence with development of a clastic foredeep before being involved in the Miocene Apenninic tectonics.

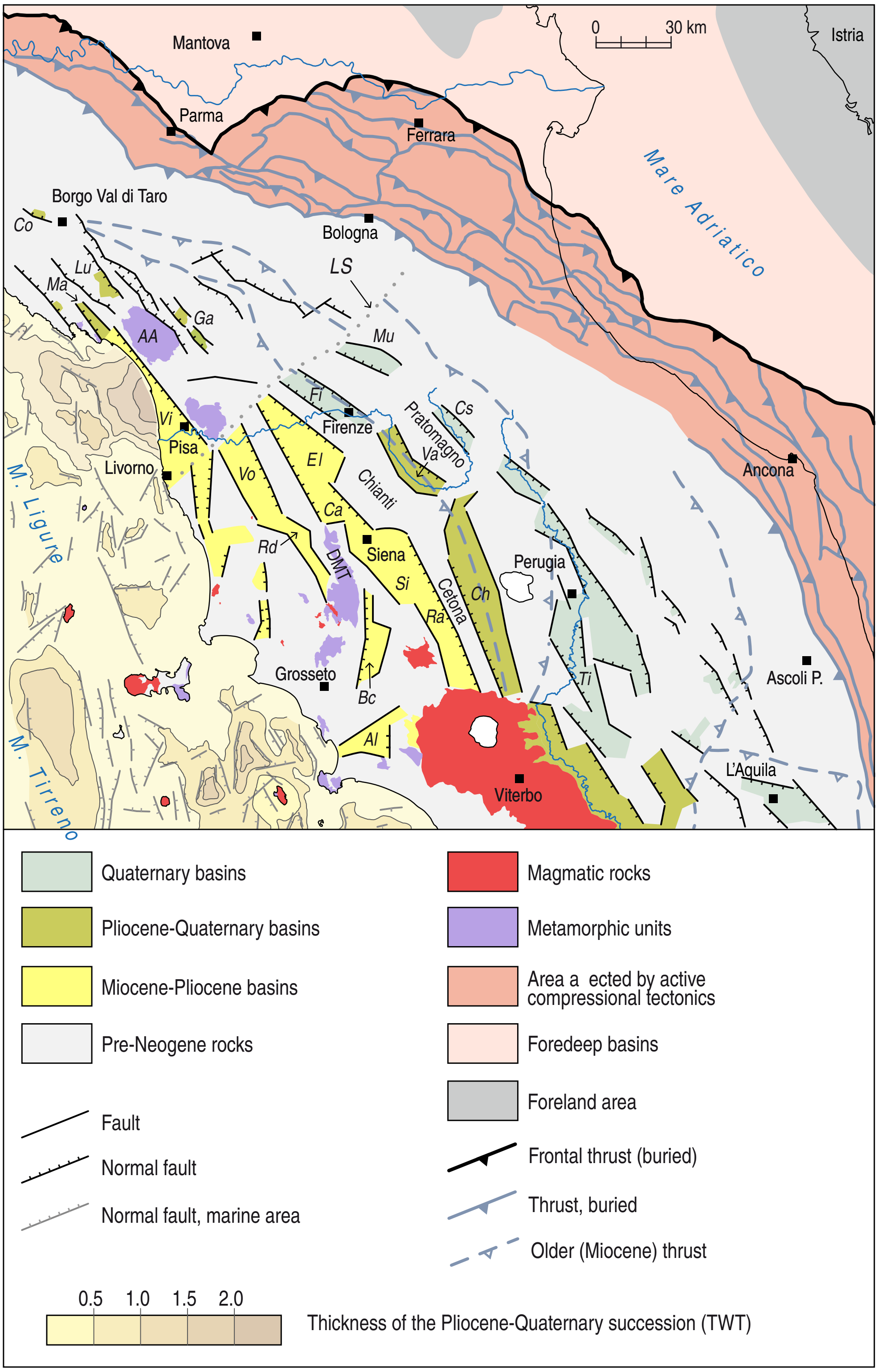

Fig. 4 – Cenozoic-Quaternary basins in the Northern Apennines, after Pascucci *et alii* (2007) and Conti *et alii* (2022). AA–Alpi Apuane, Al–Albegna, Bc–Baccinello, Ca–Casino, Ch–Val di Chiana, Co–Compiano, Cs–Casentino, DMT–Dorsale Medio–Toscana, El–Valdelsa, Fi–Firenze, Ga–Garfagnana, Lu–Lunigiana, Ma–Val di Magra, Mu–Mugello, Ra–Radicofani, Rd–Radicondoli, Si–Siena, Ti–Tiberino, Va–Valdarno, Vi–Viareggio, Vo–Volterra. LS–Livorno–Sillaro line.

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. 5). The maximum height is M. Pisanino, with 1947 m a.s.l.

The Alpi Apuane region is a tectonic window (Fig. 6) 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. 7) consists of a Mesozoic cover detached from its original basement along the décollement level of the Norian anhydrites 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 silici-clastic 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 exceed the anchizone/subgreenschist facies conditions with estimated temperature around 250-280 °C on the basis of vitrinite reflectance, illite crystallinity, 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. 7). The pre-Mesozoic basement is formed by ?Upper Cambrian-?Lower Ordovician phyllites and quartzites, 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 quartz clast-supported metaconglomerates associated with metasandstones, meta-siltstones and black phyllites that are overlain by marine deposits (Ladinian crinoid marbles, carbonate meta-breccias, calcschists and phyllites) intercalated with alkaline meta-basalts (prasinites and green schists). Upwards the succession ends up with a transgressive continental cycle consisting of coarse-grained quartzitic metarudites (*Anageniti*), quartzites and muscovite phyllites.

The basement rocks in the Massa unit show evidence of a pre-Alpine greenschist-facies metamorphism which has been ascribed to the Variscan (Hercynian) orogeny. The Alpine metamorphism (as investigated in the Mesozoic cover rocks) is characterized by kyanite+chloritoid+ phengitic muscovite assemblages in metapelites. Peak conditions have been estimated in the range of 0,6-0,9 GPa and 420-500 °C (Franceschelli *et alii*, 1986; Jolivet *et alii*, 1998; Franceschelli & Memmi, 1999; Molli *et alii*, 2000b, 2018; Di Vincenzo *et alii*, 2022; Papeschi *et alii*, 2023).

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. 7).

The Paleozoic basement is formed by the same rock types of the basement in the Massa unit, but here they are exposed in larger and more clear outcrops: ?Upper Cambrian-?Lower Ordovician phyllites and quartzites, ?Middle Ordovician metavolcanics and metavolcanoclastics, ?Upper Ordovi-

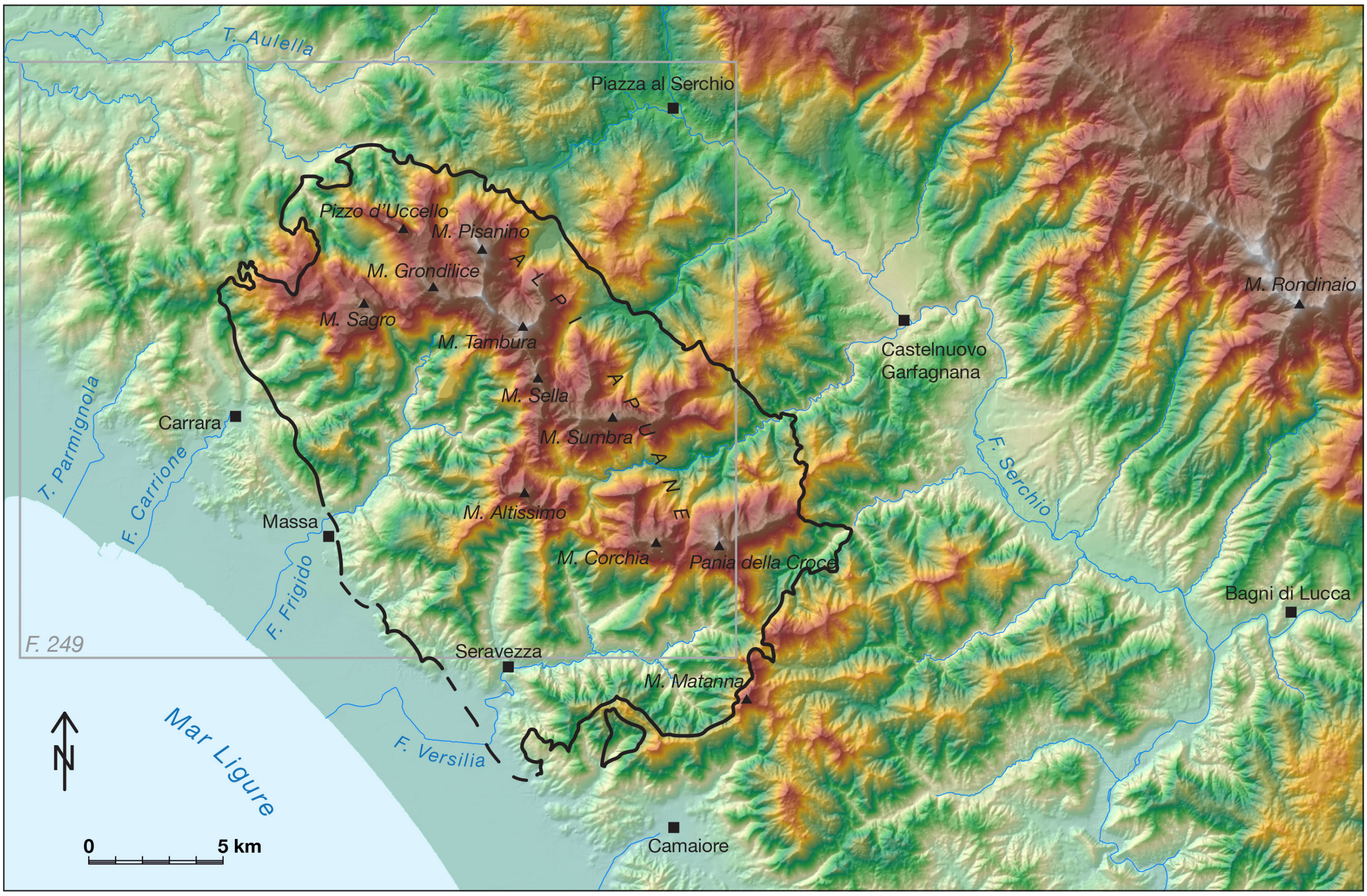

Fig. 5 – The Alpi Apuane region, Northern Apennines. The black line is the area of outcrop of the metamorphic rocks.

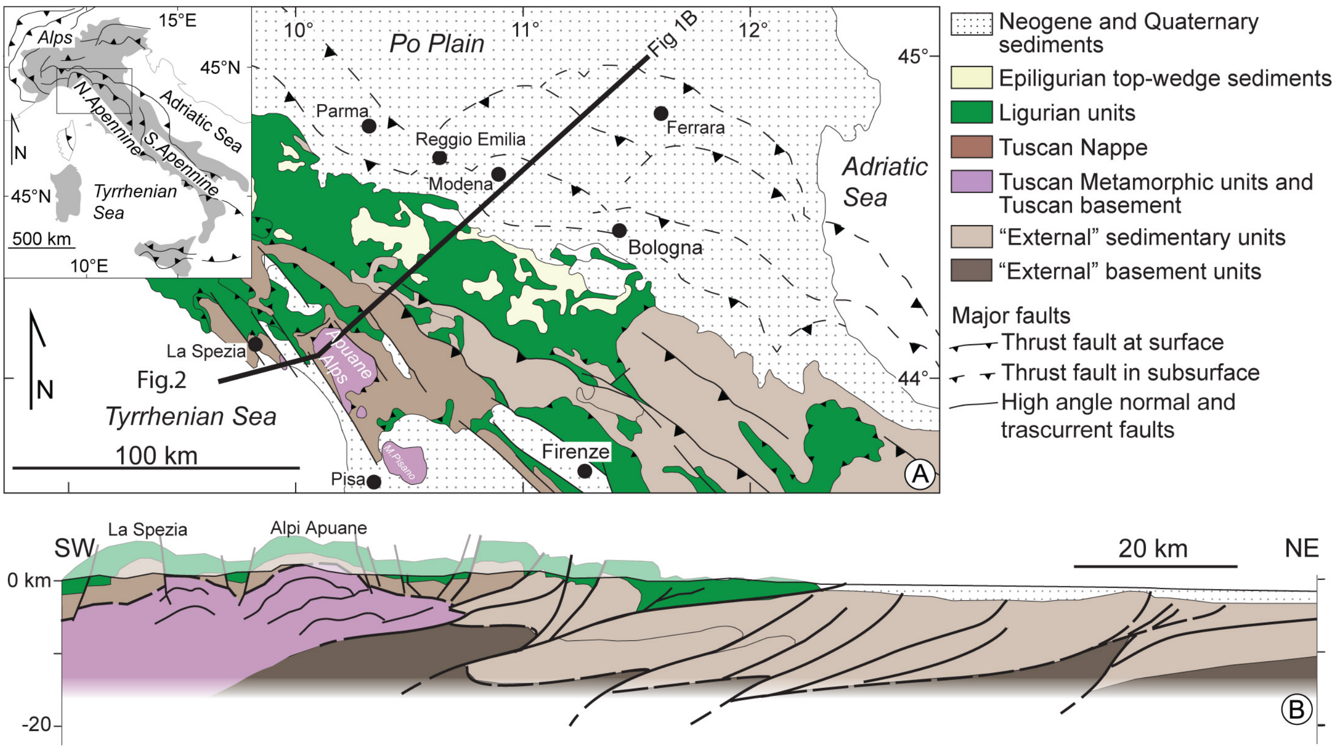

Fig. 6 – Tectonic map of the Northern Apennines, with cross section. After Molli (2008).

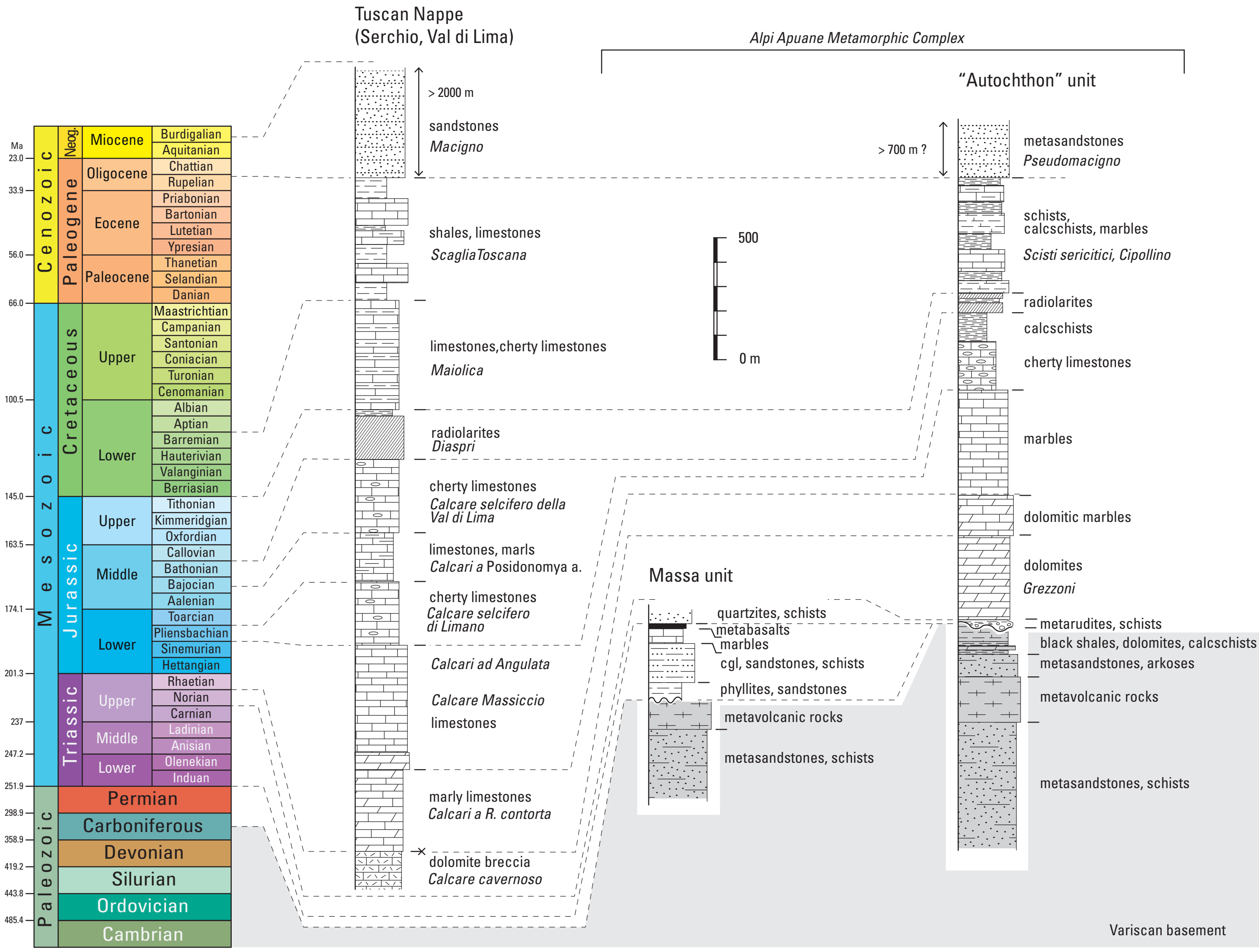

Fig. 7 – Stratigraphy of the Tuscan units (Tuscan Nappe and metamorphic units) in the Alpi Apuane area, after Conti *et alii* (2019a).

cian 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*, 1991b), for which the most striking evidence is the regional angular unconformity at the basis of the oldest Mesozoic formation (Triassic Dolomite) lying on almost all the Paleozoic formations.

The Mesozoic cover (Fig. 7) 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 drowning 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 south-west (Ca/Do temperature up to 450 °C) to central and north-east part (Ca/Do of 380-350 °C). These data have been recently refined in Molli *et alii* (2018) by using Raman data.

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. 8). 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 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 decimeter to kilometer scale folds (Fig. 9).

Foliation bears a WSW-ENE trending mineral and extension lineation (Fig. 10) 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. 8).

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. 11b); (2) "antiformal stack phase" in which further shortening and a crustal scale duplex are realized (Fig. 11b). The development of D1 structures is strongly controlled by the original paleotectonic setting and its lateral heterogeneities (Molli & Meccheri, 2012).

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. 12). 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) hangingwall collapse during overthrust 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-cylindrical D1 sheath folds during late rebound by vertical isostatic re-equilibration of former thickened crust (Carmignani & Giglia, 1979);
- they developed as passive folds related to distributed shear within kilometric scale shear zones that accomodate crustal extension (Carmignani & Kligfield, 1990; Carmignani *et alii*, 1994);
- They developed by vertical shortening on the previous antiformal stack during the switch from crustal contraction to crustal extension (Molli *et alii*, 2002; Di Vincenzo *et alii*, 2022).

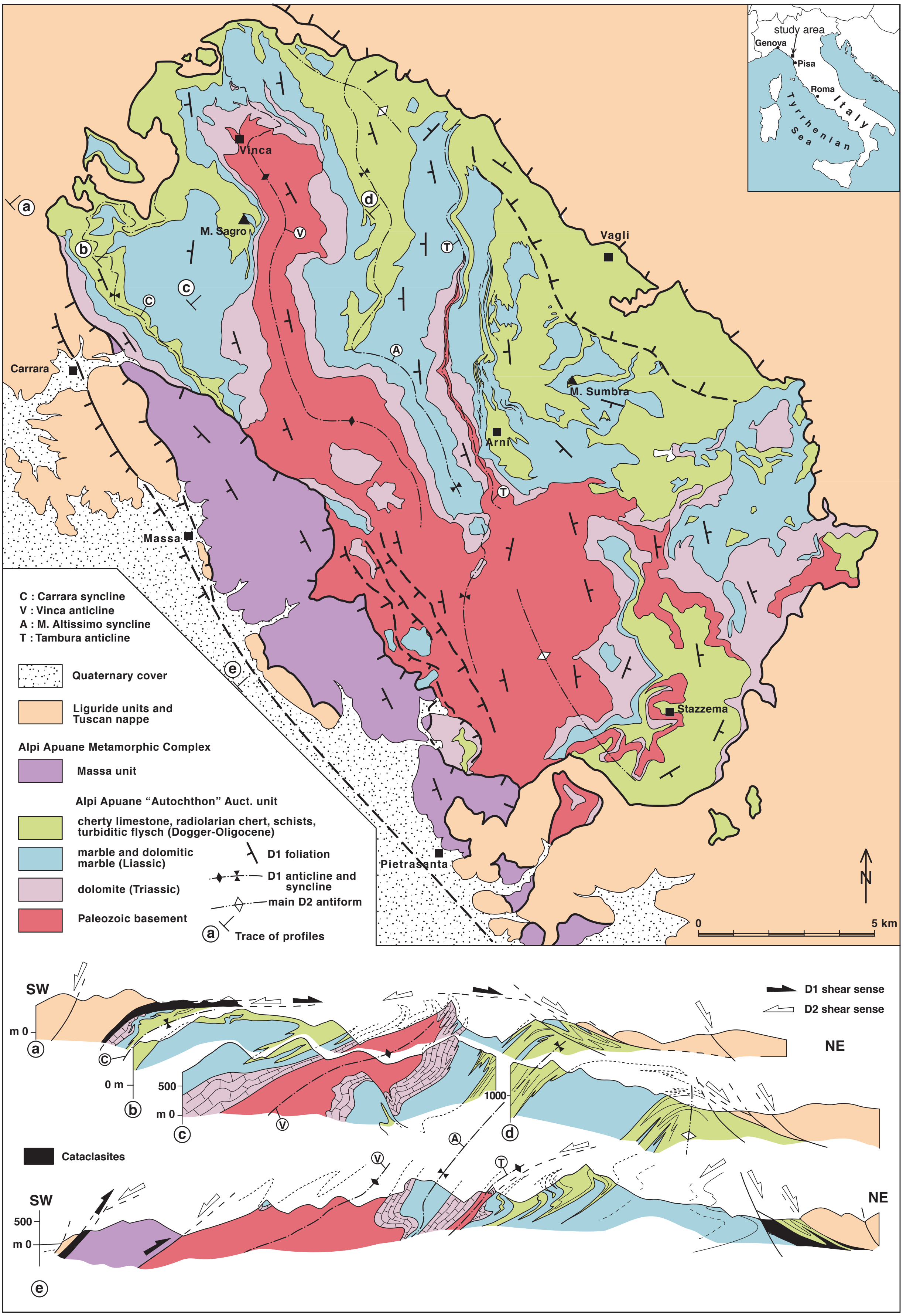

Fig. 8 – Geological sketch map of the Alpi Apuane area.

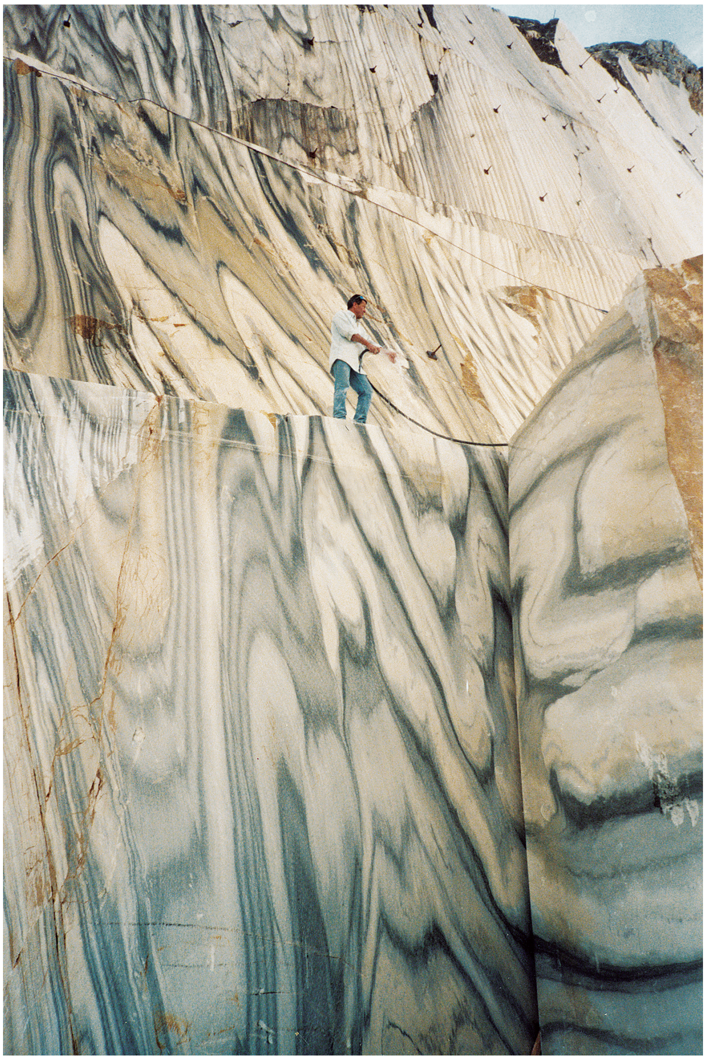

Fig. 9 – D1 folds in marbles, Carrara, Alpi Apuane.

Fig. 10 – Strongly boudinaged cherty limestone during D1 deformation, Capanne di Careggine, Alpi Apuane.

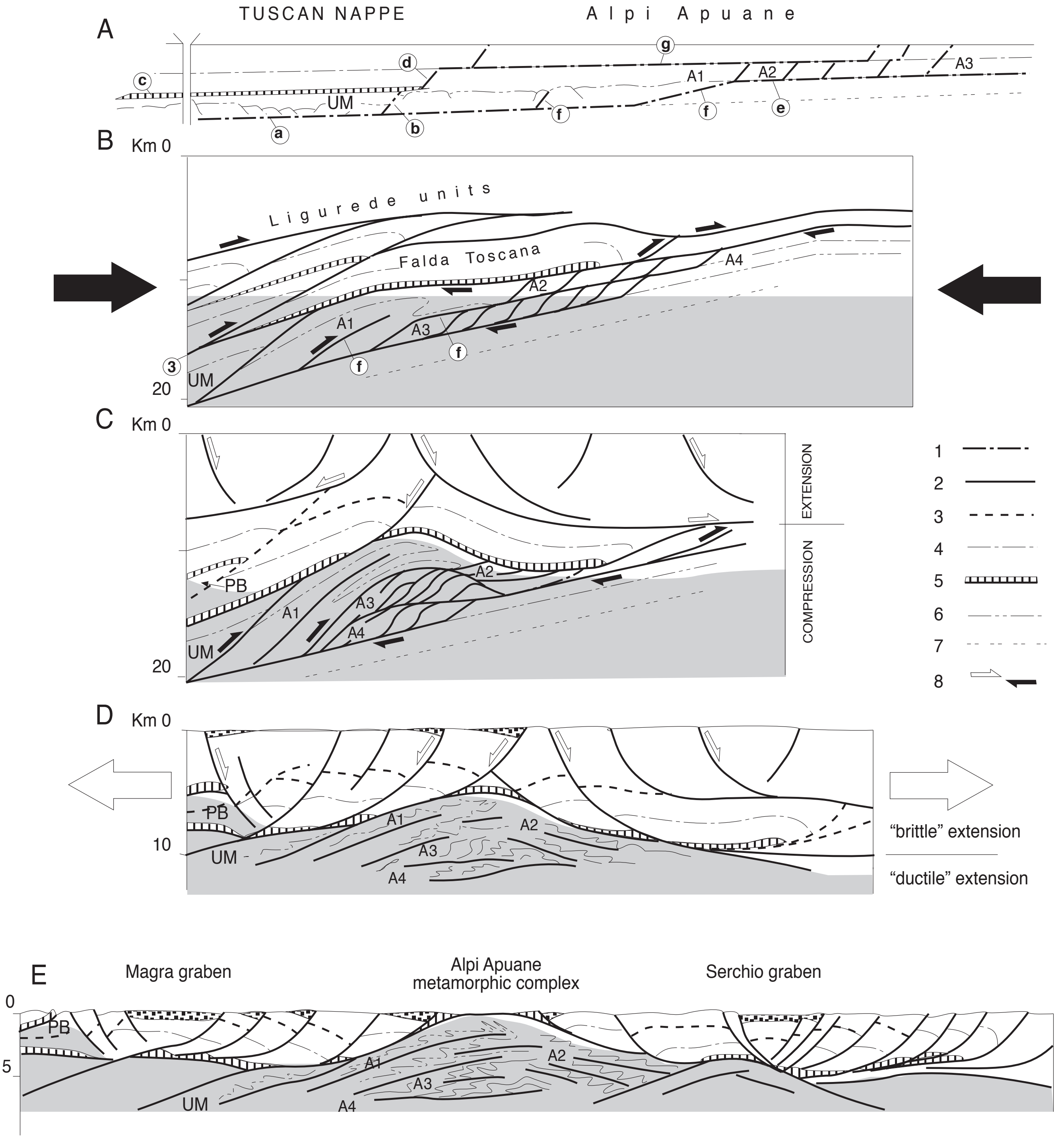

Fig. 11 – Tectonic evolution of the Alpi Apuane Metamorphic Complex and adjoining areas (after Carmignani & Kligfield, 1990, modified). (a) Pre-collisional geometry showing restored state traces of principal thrust faults and ramp-flat geometry. (b) Development of Alpi Apuane duplex structure. Metamorphic 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-crustal levels, respectively. Legend: 1: Thrust fault trace. 2: Active thrusts and normal faults. 3: Inactive thrusts. 4: Base of flysch. 5: Triassic evaporite. 6: Top of 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-crustal levels (Alpi Apuane metamorphic sequences, shown in shaded pattern) and brittle extension at upper-crustal levels (Tuscan Nappe and Liguride units). Metamorphic features associated with tectonic extension at mid-crustal conditions require that significant crustal thinning occurred prior to uplift. Differentiation of the core complex into upper-plate non metamorphic rocks and lower-plate metamorphic rocks is aided by the adoption as a detachment horizon of the evaporite-bearing overthrust faults of the earlier compressional phases. (e) Further crustal thinning, now accompanied by denudation and uplift, results in exposure of Alpi Apuane metamorphic core complex. High-angle brittle normal faults of the surrounding Magra and Serchio graben systems are interpreted to root downward against earlier low-angle normal faults.

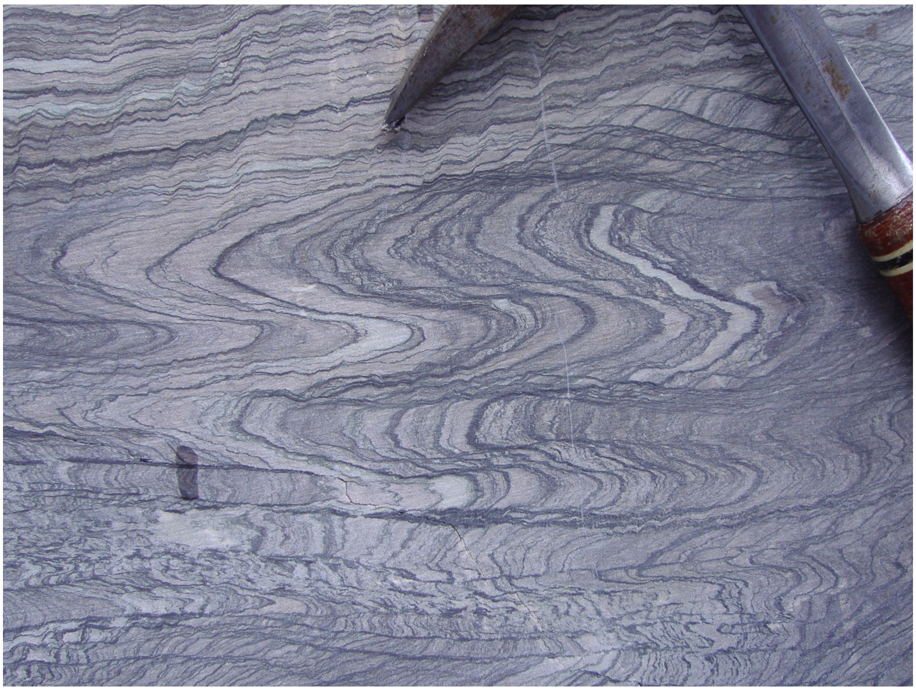

Fig. 12 – D2 folds in Cretaceous calcschists, Valle Turrite, Alpi Apuane.

2.4.3 Deformation - metamorphism relationships

The presence of index minerals (chloritoid and kyanite) 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 Auctt. 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 mechanically 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 units 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). An update view on PTt evolution with still ongoing debated issues may be found in Molli *et alii* (2018) and Di Vincenzo *et alii* (2022), and in Fig. 13.

2.5 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.

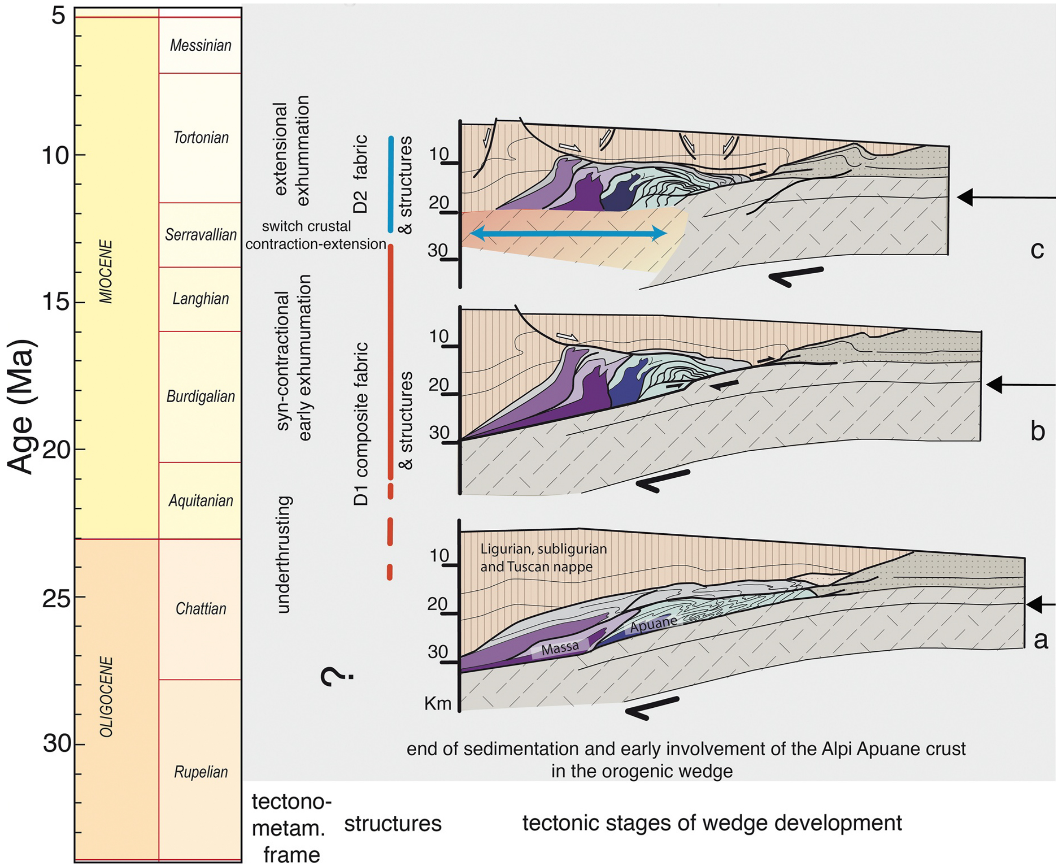

Fig. 13 – Timing of deformation and metamorphism in the Alpi Apuane, after Di Vincenzo *et alii* (2022).

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. 14). 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).

2.5.1 Marble types and their microstructures

In the Alpi Apuane three main groups of marbles can be distinguished according to their mesoscopic features (Fig. 15 and Fig. 16):

the white-light gray, more or less massive marbles (with or without light gray 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 gray 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*, 2007; 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. 17):

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).

2.5.1.1 Annealed microfabric (type-A microfabric)

This type of microfabric is characterized by equant polygonal grains (granoblastic or "foam" microstructure, Fig. 18a), 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

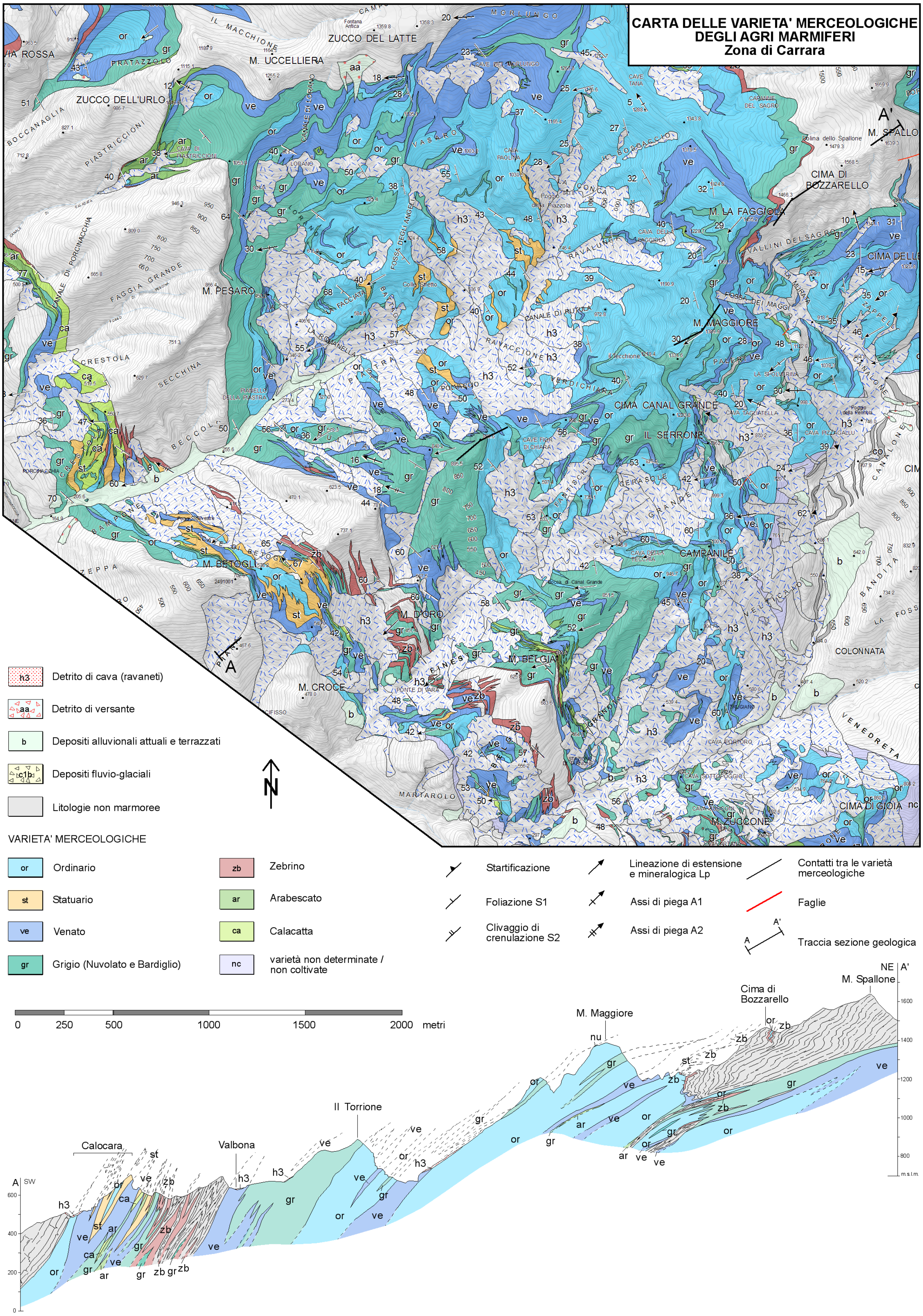

Fig. 14 – Map of marble types in the area north of Carrara.

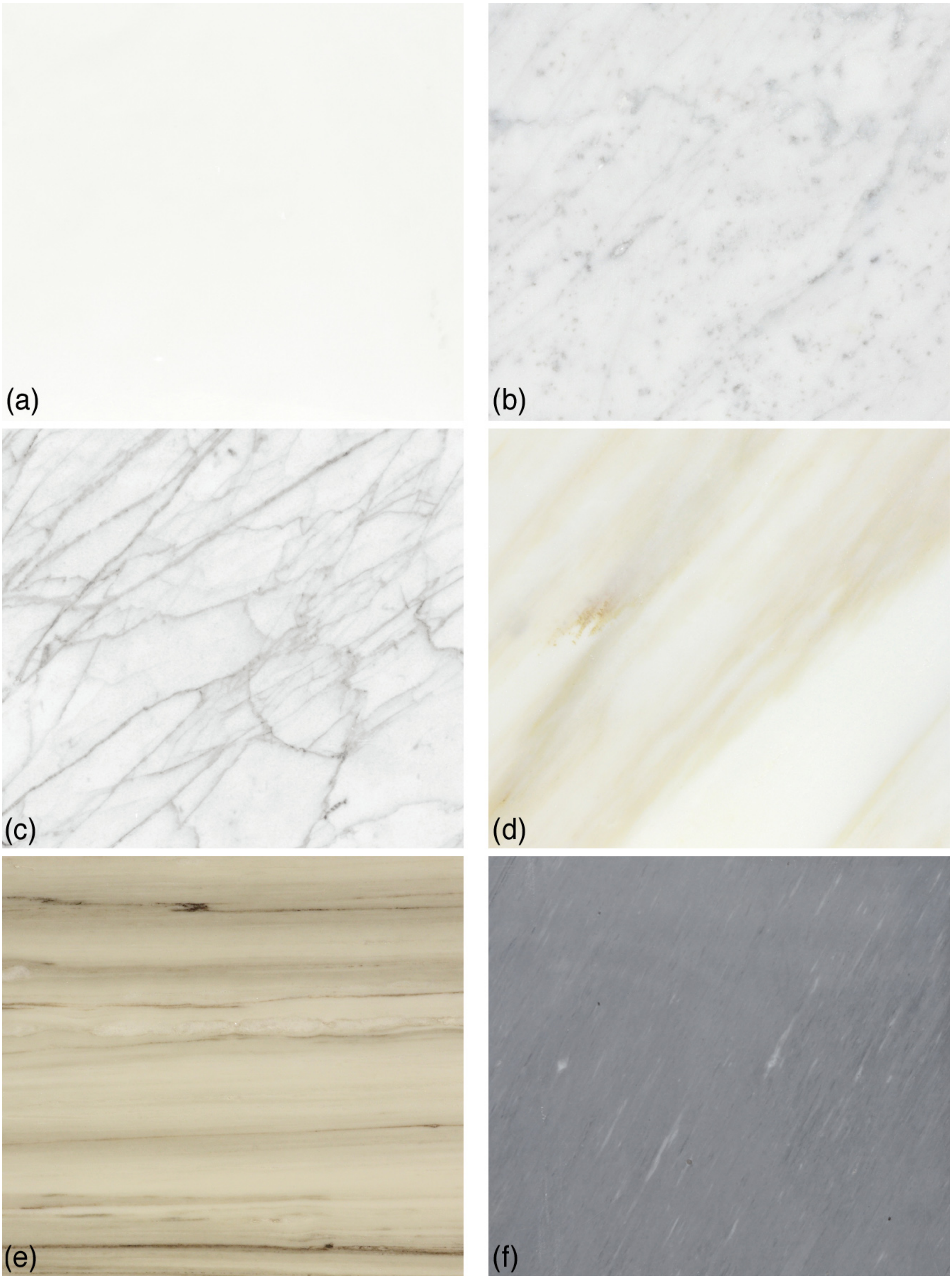

Fig. 15 – Some marble types from the Alpi Apuane: (a) “Statuario”. (b) “Bianco. (c) “Venato”. (d) “Calacatta”. (e) “Zebrino”. (f) “Bardiglio”.

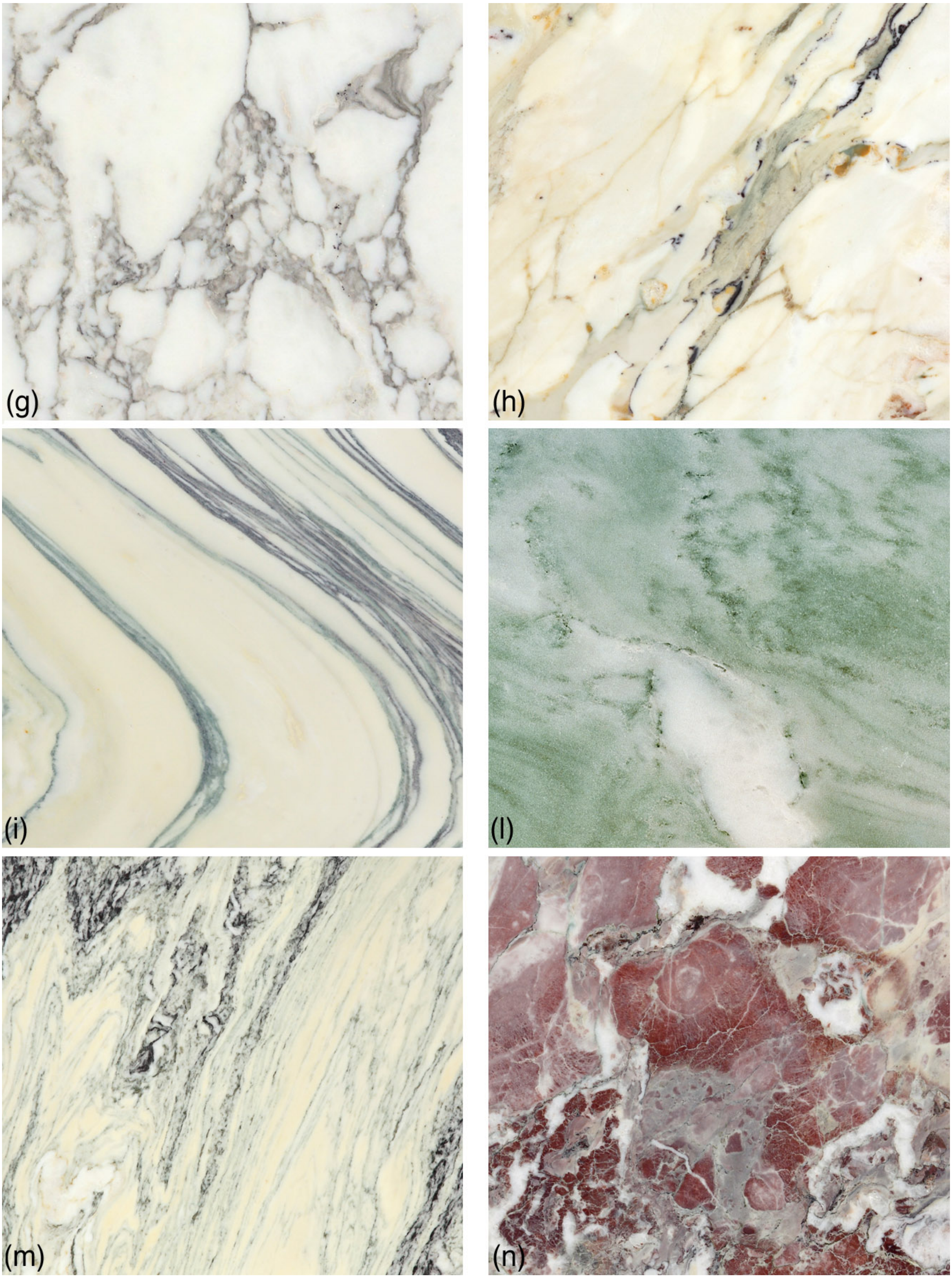

Fig. 16 – Some marble types from the Alpi Apuane: (g) “Arabescato”. (h) “Breccia Capraia”. (i) “Fantastico”. (l) “Cipollino”. (m) “Cremo”. (n) “Fior di Pesco”.

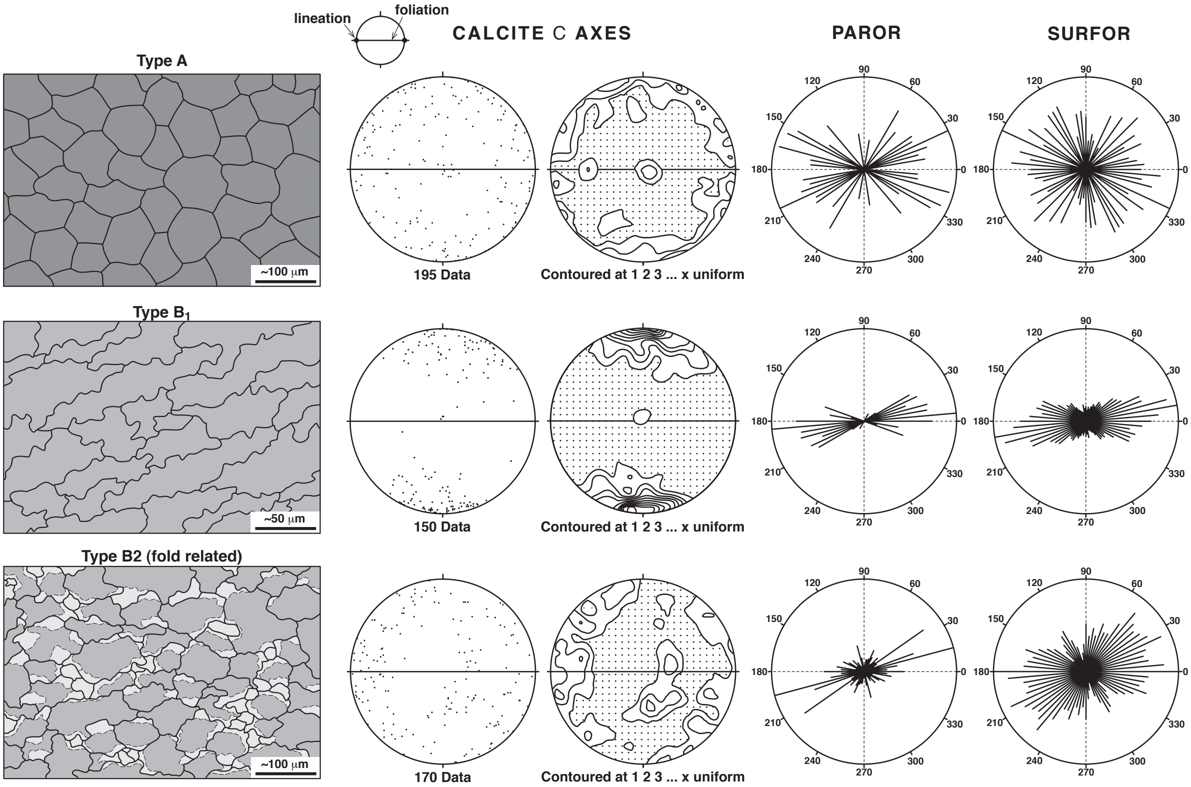

Fig. 17 – Line drawing of microstructures, c-axis orientation (from universal stage measurements) and results of PAROR and SURFOR analysis for calcite microfabric of type-A and type-B. Number of grains analyzed with PAROR and SURFOR routines is more than 200 (from Molli *et alii*, 2000a).

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.

2.5.1.2 Dynamically recrystallized microfabrics (type-B microfabrics)

Within type-B microfabric 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. 17 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.

2.5.1.3 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.

2.5.2 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. 19a), 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. 19b). 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. 19c), further shortening was accomplished. In this phase,

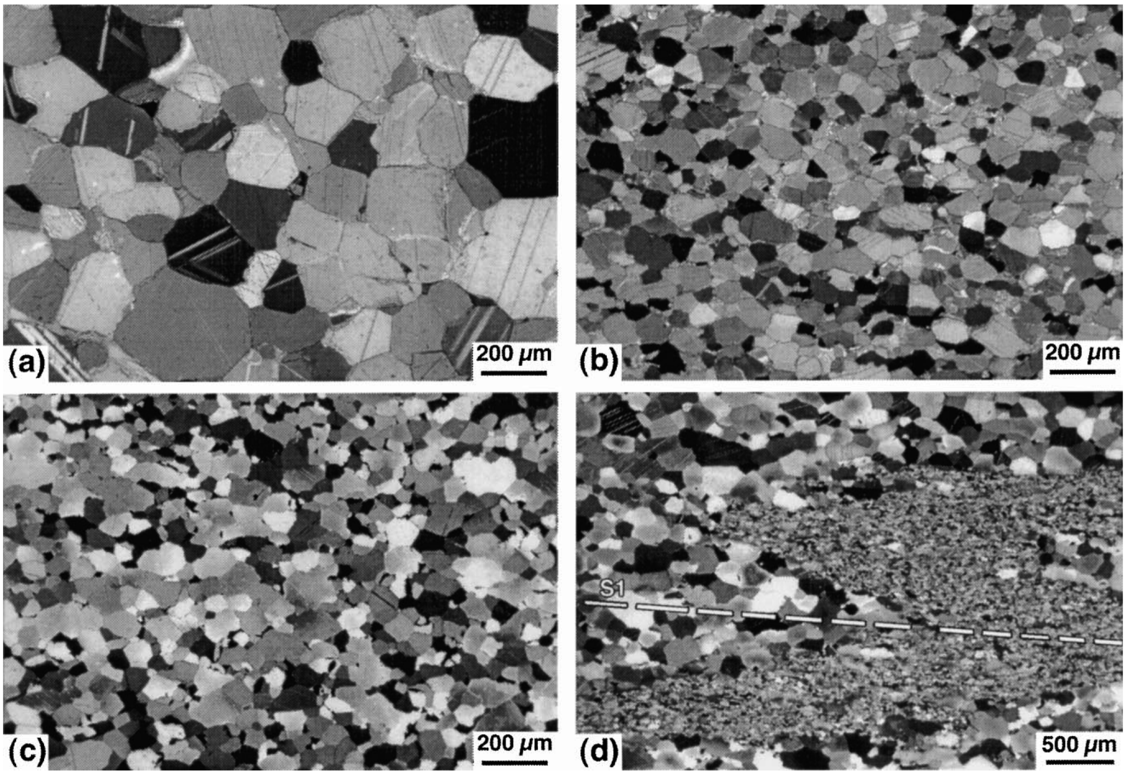

Fig. 18 – Annealed microstructures in Alpi Apuane marbles: (a) Sample 34 (western Alpi Apuane). (b) Sample 39. (c) Sample 180 (eastern Alpi Apuane). (d) D1 fold overgrown by granoblastic microstructure (locality Belgia, western Alpi Apuane). The folded level, made up of fine-grained, calcite dolomite and phyllosilicates, represents a former stratigraphic layer. From Molli *et alii* (2000a).

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. 19d). During this event, narrow millimeter to decimeter-thick shear zones developed in the higher levels of the Alpi Apuane metamorphic complex (Carrara area), whereas folding occurred at lower levels (Arni area). The temperature was lower during D2 deformation than during D1, but high enough to produce syntectonic recrystallization (type B2 microfabric). This is testified by fine-grained calcite in D2 shear zones, and recrystallized calcite grains elongated parallel to the axial surface of D2 folds. The difference in the temperature during the D2 event (380 °C in the east, 340 °C in the west) can be related to the deeper position of rocks from the eastern area relative to rocks from the western area at the beginning of D2 deformation (Fig. 19d). 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.

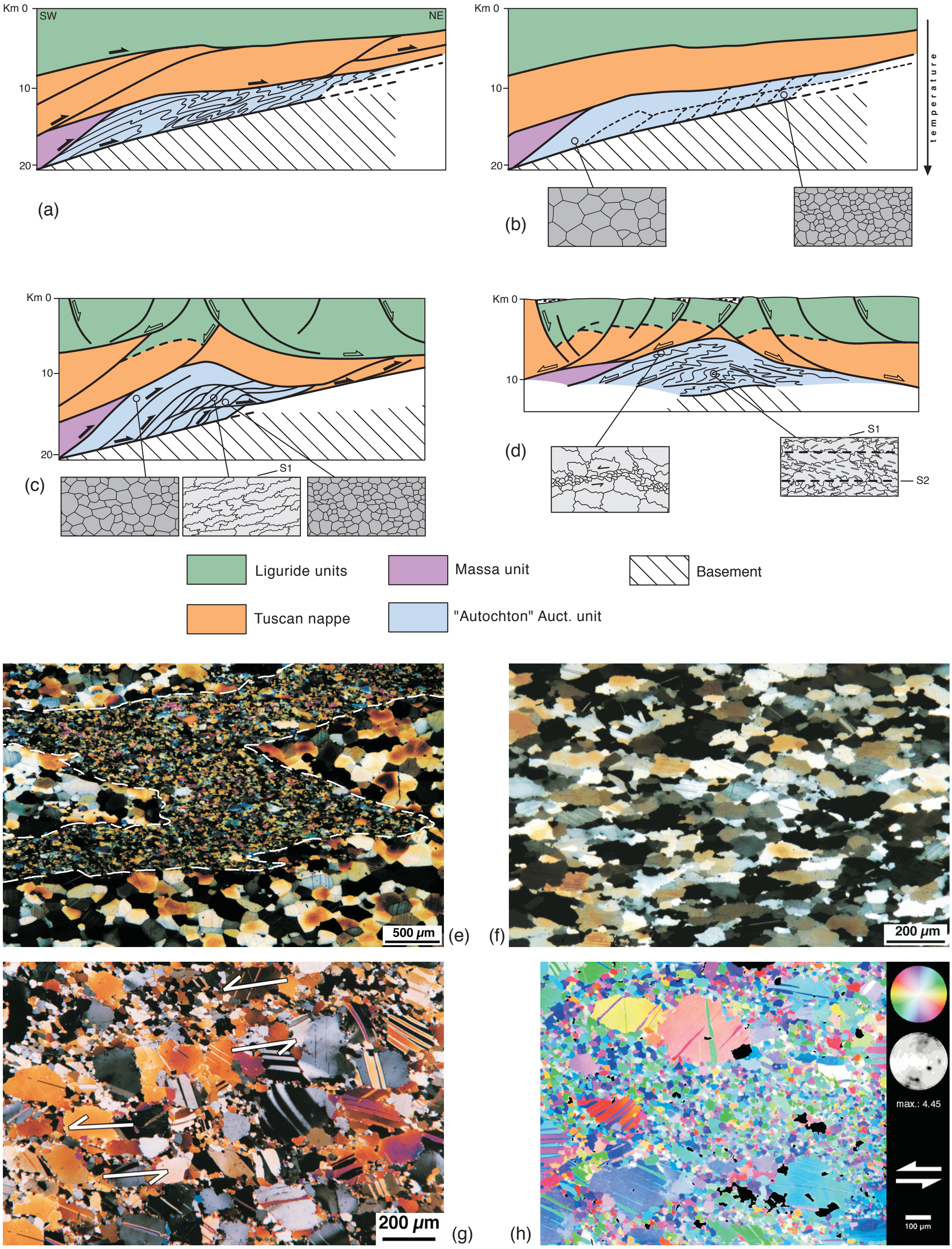

Fig. 19 – Microfabrics in Alpi Apuane marbles (after Molli *et alii*, 2000a). (a) D1 phase, with main foliation and km-scale isoclinal folds developed. (b) After D1 main folding phase annealing occurred, with static recrystallization and complete obliteration of earlier microfabrics. (c) During final D1 NE transport along thrusts annealed microstructures are passively transported toward NE or reworked in shear zones along thrusts. (d) D2 deformation led to fold and shear zones development along low angle normal faults. Earlier microstructures are reworked in D2 shear zones or along D2 fold axial planes. (e) Typical D1 folds, overprinted by annealed microstructure. (f) Shape preferred orientation of calcite grains parallel to axial plane foliation of D2 fold. (g) Dynamically recrystallized microstructures along D2 shear zone. Strain is associated with core-mantle structure, grain size reduction and rotation recrystallization. (h) C-axes orientations image revealed by computer-aided microscopy (Heilbronner Panozzo & 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

Part II

Field Trip

Day 1 : The central Alpi Apuane

Field Trip Route

Massa - San Carlo Terme - Pian della Fioba - Arni - Vianova.

Topics

Tectonics of the central part of the Alpi Apuane Metamorphic Complex. Kinematic evolution of the tectonic units.

Stop 1.1

Locality: San Carlo Terme.
44.0407632,10.1553315
Topic: Panoramic view of Northern Apennines tectonic units superposition.

The Stop is located at the main square of the village of San Carlo Terme, overlooking the town of Massa and the adjacent plain. From this viewpoint it is possible to observe the superposition of the tectonic units of this portion of the Northern Apennines, from the Ligurian to the Tuscan Units (Fig. 21).

Along this profile, the tectonic contacts between all the tectonic units and the bedding and foliation in rocks generally plunge towards the south-west. The first reliefs outcropping from the lowlands are represented by the Helminthoides Flysch formation of the Ligurian units, below follows the Subligurian Unit with the Argille e Calcari di Canetolo fm. Still to the north, thus tectonically below, the Tuscan Nappe outcrops. In this area, the more recent formation of the Tuscan Nappe (the Macigno Formation) is in direct contact with the carbonate cataclasites of the Calcare Cavernoso fm (at the base of the Tuscan Nappe), through a normal fault, the La Foce Fault, which is part of the system of Plio-Quaternary 'edge faults' that delimit the Alpi Apuane Metamorphic Complex.

Still to the north, is the Monte Brugiana relief, made up of Triassic (Anisian-Carnian) formations belonging to the Massa Unit (phyllites, anagenites, metabasites and marbles), lying below the Tuscan Nappe. The Massa Unit is the highest metamorphic grade unit (450-520°C; 0.8-1 GPa) of the Alpi Apuane Metamorphic Complex.

In the distance to the north we can glimpse the summit of Monte Sagro, belonging to the succession of the Autochthonous *Auctt.* unit.

Stop 1.2

Locality: Antona.
44.059379,10.185964
Topic: Variscan basement, Middle Ordovician volcanic rocks.

Along the road to the Passo del Vestito, for a few kilometres we cross rocks belonging to the Alpi Apuane Variscan Basement, the oldest rocks outcropping in the northern Apennines. We first cross the Filladi Inferiori formation (Cambrian-Lower Ordovician) and then the Porfiroidi and Scisti Porfirici formation (Middle Ordovician). The Formation of the Lower Phyllites can be observed in better outcrops in Stop 1.4, while along the road about 3 km after the village of Antona we find an extensive outcrop of Porphyroids and Porphyritic schists. These rocks are light grey-green massive metavolcanic rocks, characterised by the presence of centimetric-sized hyaline quartz and feldspars of volcanic origin (with evidence of magmatic reabsorption and myrmekitic structures), in a quartz-muscovite-chloritic matrix. They represent the result of metamorphism on original volcanic rocks (ignimbrites) and deposits resulting from their erosion. From correlation with similar successions in Sardinia, these volcanic rocks are interpreted as a calc-alkaline volcanic successions of Middle Ordovician age.

The route continues along the road, passing the locality of Pian della Fioba and we stop about 200 metres before the entrance to the Passo del Vestito tunnel, in a small area on the left-hand side of the road.

Stop 1.3

Locality: Passo del Vestito
44.064464,10.223381
Topic: Panoramic view of km-scale tectonic features of the central-northern Alpi Apuane.

At this stop, a panoramic view of the northern part of the Alpi Apuane region can be observed, from the Tyrrhenian Sea to the eastern Alpi Apuane (Fig. 22, Fig. 23).

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

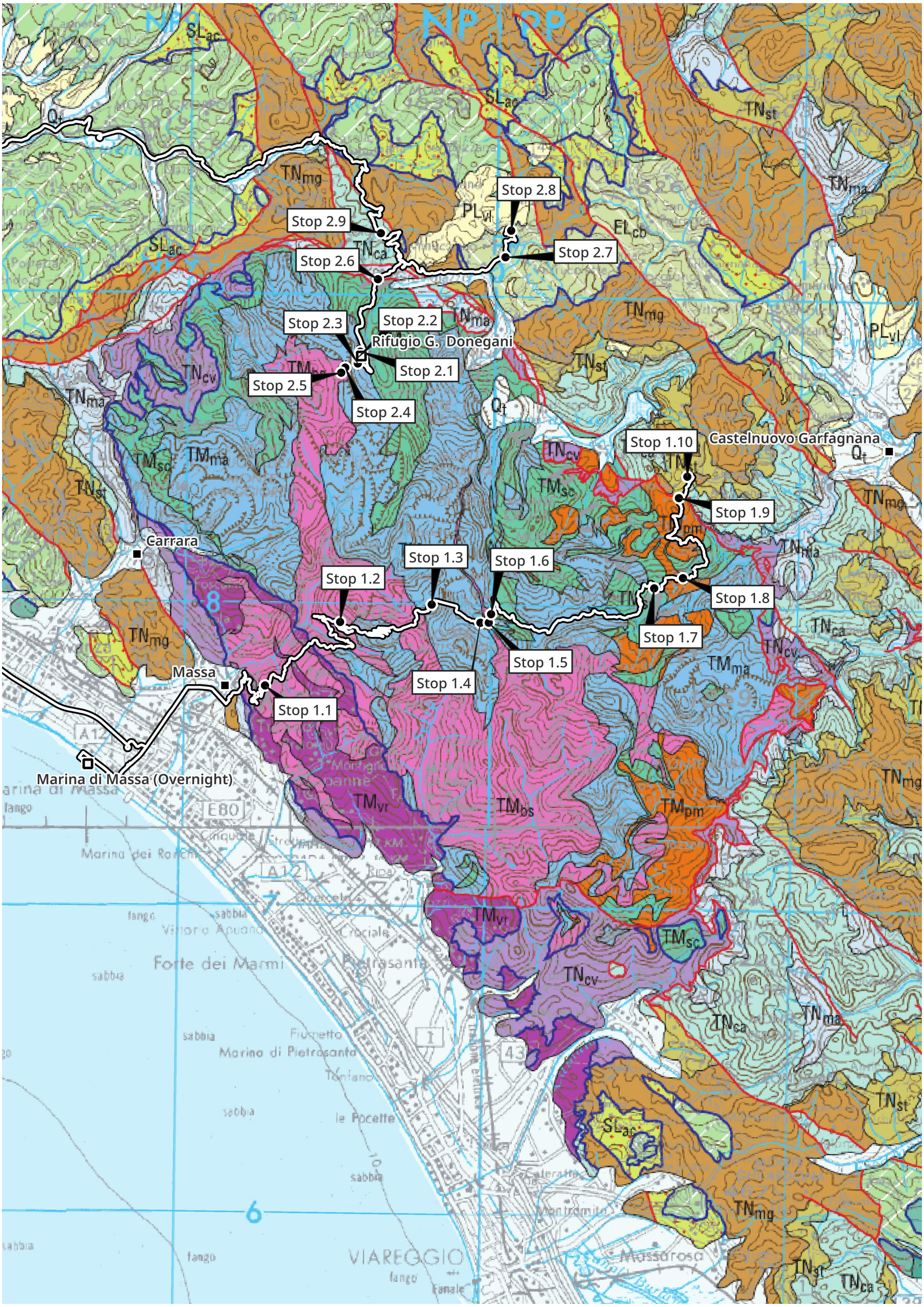

Fig. 20 – Geological map of the Alpi Apuane, after Conti *et alii* (2019b), with Itinerary and Stops.

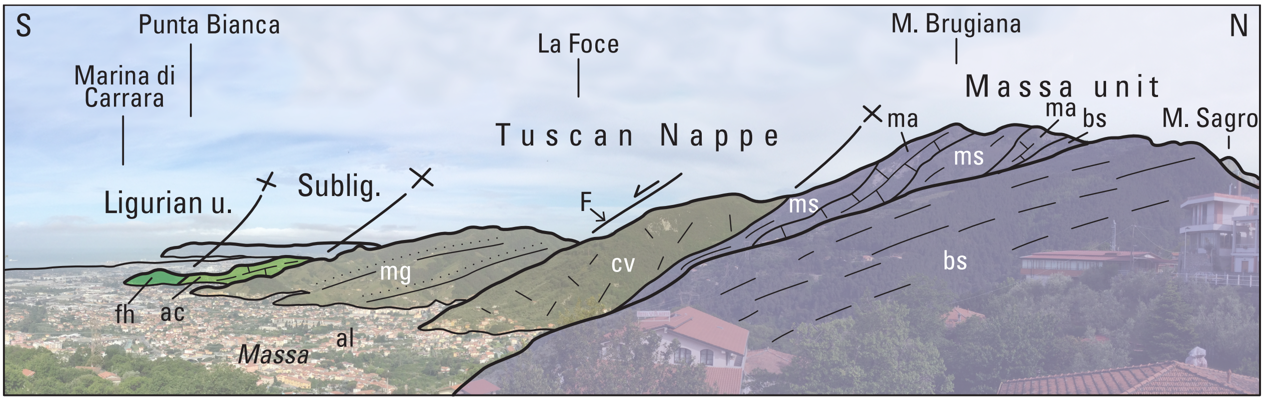

Fig. 21 – Panoramic view from the village of San Carlo, with the superimposition of tectonic units on the western the Alpi Apuane. al-Alluvial deposits; fh–Helminthoides flysch; ac–Canetolo Clays and Limestones; mg–Macigno; cv–Calcare Cavernoso (cataclasite); ms–Phyllite, metaconglomerates, metabasites; ma–marble; bs–Quartzites and phyllites of the Variscan Basement; F–"La Foce" fault.

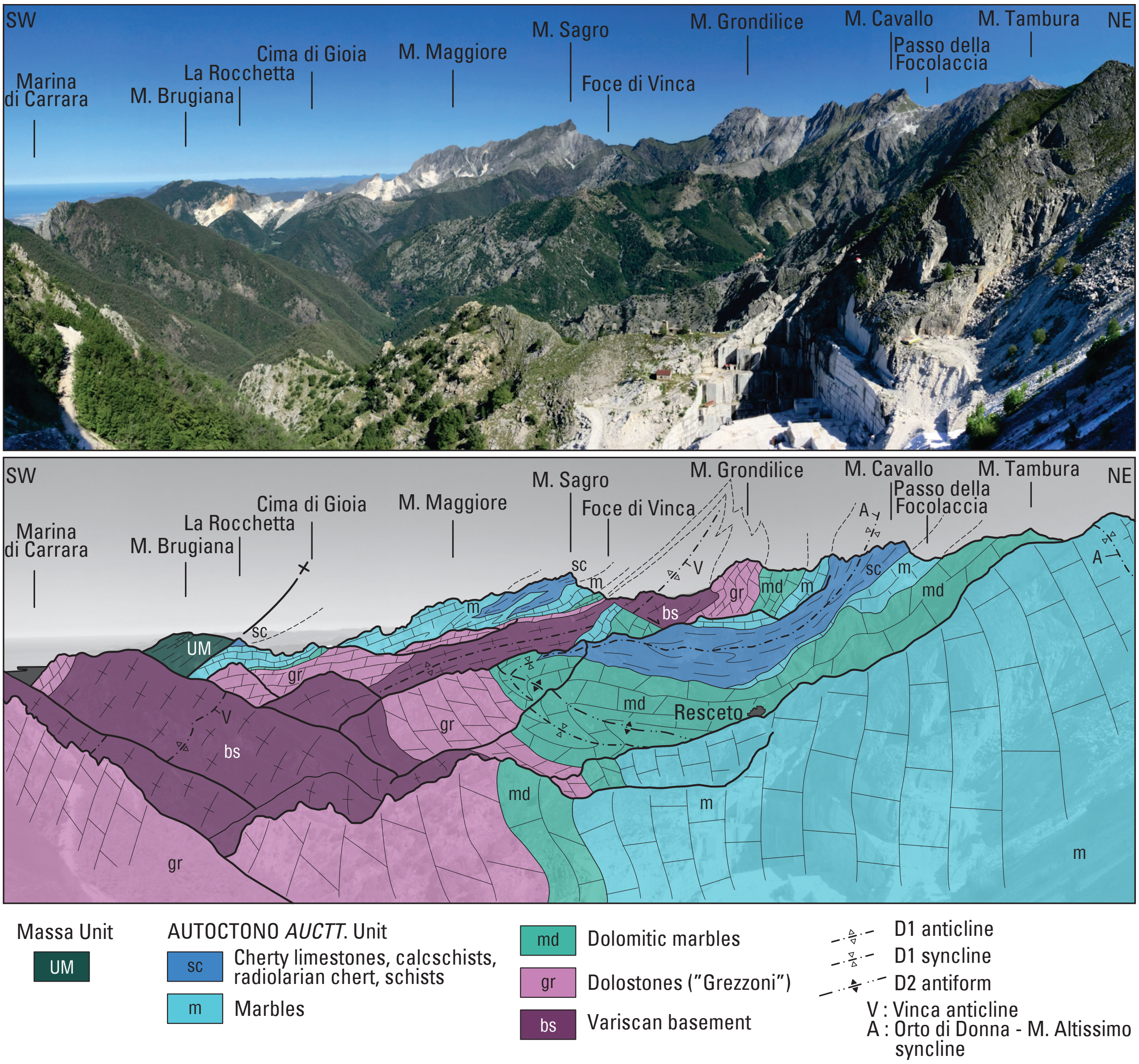

Fig. 22 – Panoramic view of the northern Alpi Apuane, Antona-Arni road, W of the Passo del Vestito tunnel.

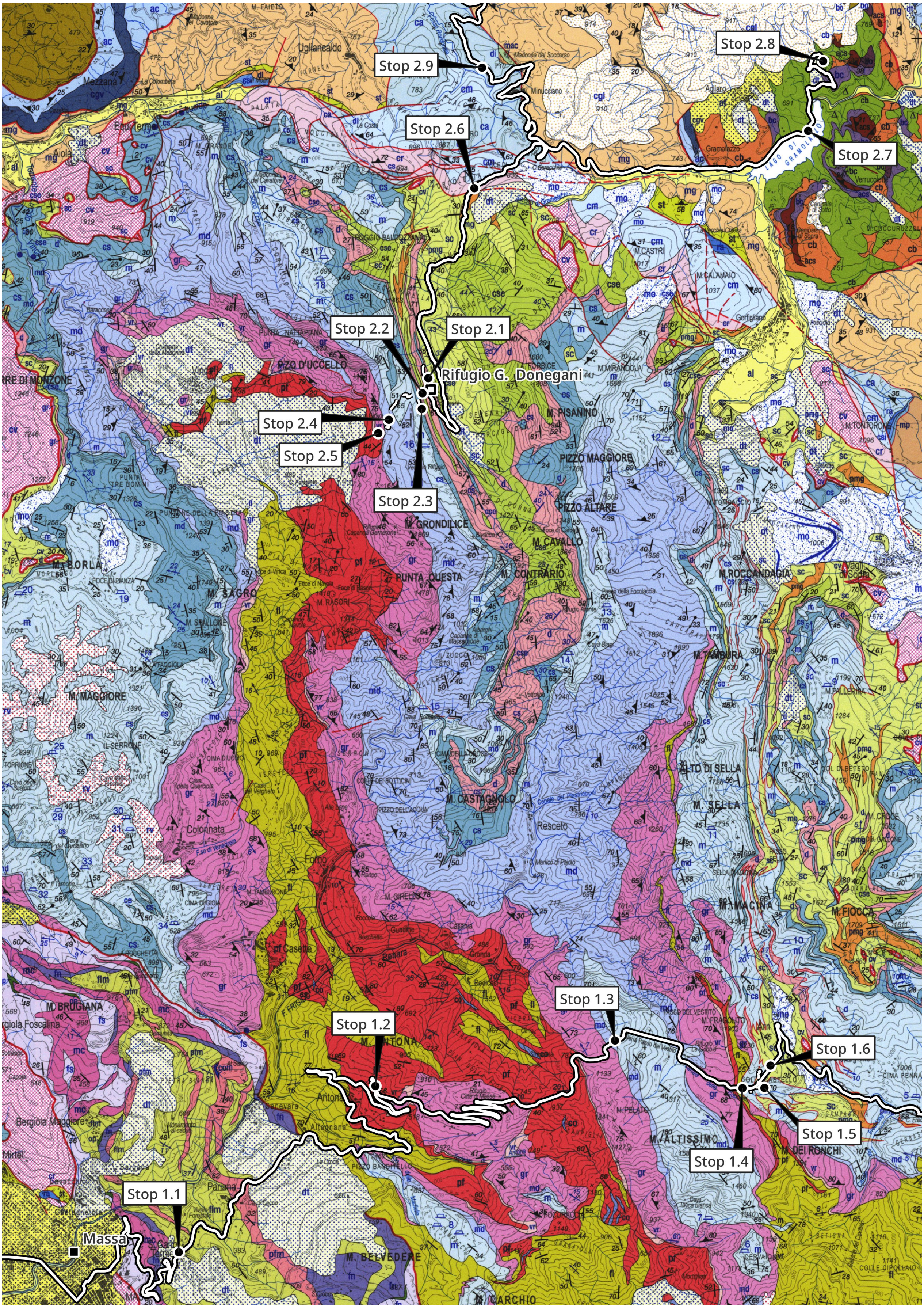

Fig. 23 – Geological map of the northern Alpi Apuane, with stops. fi–Filladi Inferiori Fm. (Cambrian), pf–Porfiroidi (Upper Ordovician), vr–Verrucano (Ladinian-Carnian), gr–dolostones (Norian), md–dolomitic marbles (Rhetian), m–marbles (Lower Liassic), cs–cherty meta-limestones, d–radiolarian chert, sc-phyllites, calcschists, marbles. (Lower Cretaceous - Oligocene), pmg–metasandstones, phyllites (flysch) (Upper Oligocene-Lower Miocene).

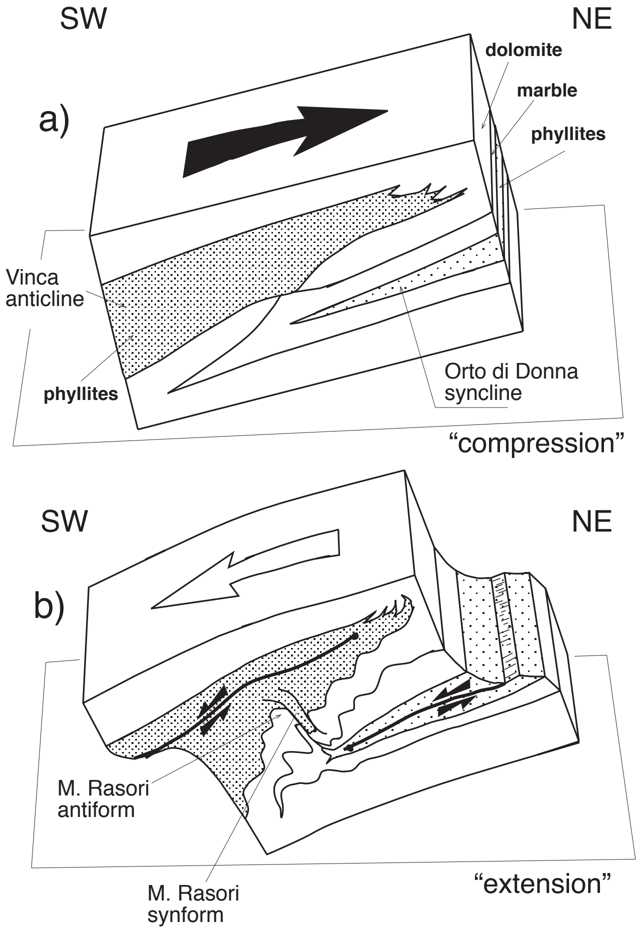

Fig. 24 – D1 and D2 deformation superposition in the Frigido valley (Stop 1.3). Late structures in the inverted limb of the D1 Vinca anticline are interpreted as "transfer folds" between two ductile shear zones.

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 calcschists) and the Vinca anticline (Paleozoic phyllites) that superpose and interference 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. 24.

Stop 1.4

Locality: Castellaccio
44.059105,10.243233

In this stop it is possible to walk across a major Alpi Apuane, structure, the Tambura anticline (see anticline location in Fig. 8). Along the road the core of the D1 isoclinal M. Tambura anticline crops out (Fig. 25) 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 boudinaged, 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 cataclasites.

Stop 1.5

Locality: Landi quarries
44.059086,10.246684

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

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

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

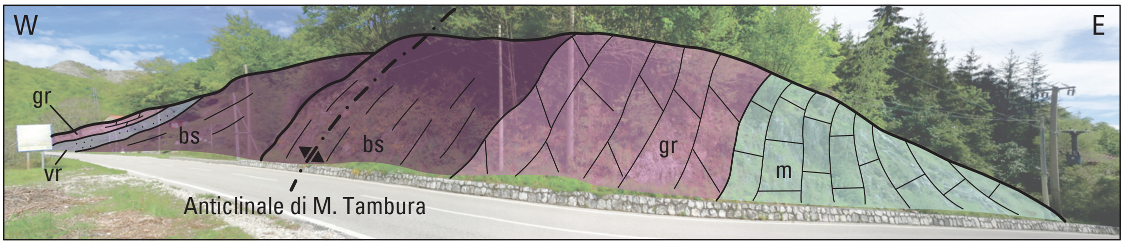

Fig. 25 – Anticline of Monte Tambura, Castellaccio locality. Note how in the overturned limb (towards E) the Grezzoni Formation is reduced to a few metres thickness and is strongly cataclastic, and how the Variscan Basement outcropping at the core of the Anticline is only few metres thick. bs–Variscan Basement (Phyllites, Porphyroids); vr-F.ne di Vinca (Verrucano Auctt.);gr-Grezzoni fm., dolomites; m-marbles.

Stop 1.6

Locality: Colle Castello
44.061680,10.247560

From the previous Stop sign, we follow CAI path no. 31 in a northerly direction to reach the panoramic location of Colle Castello, located above the Monte Castellaccio Tunnel. Along the path, we cross a small abandoned quarry where marble breccias (Arabescato variety) are exposed, associated with white and gray marble. The presence of variably oriented cuts makes it possible to observe the three-dimensional deformational features of these breccias.

When the panoramic point is reached, it is possible to appreciate the polyphasic structure of the Arni valley (Fig. 26).

In the panorama, we can recognize the two kilometric synclines of Arni and Monte Fiocca with, respectively, Cretaceous-Paleogene metasediments (Scisti sericitici fm. observed at Colle Castello) and Pseudomacigno fm. (at Monte Fiocca), and an interposed anticline (Passo Sella anticline) with the Marble fm. at its core. These structures developed during the main deformation phase D1. All of these structures are later folded by kilometer-scale Arni Synform and the Arni Antiform, which developed during phase D2, both with axial planes from sub-horizontal to plunging to the west, producing kilometer-long overturned limbs, further complicating the geological structure of the area (Fig. 27).

Stop 1.7

Locality: W of Capanne di Careggine
44.0692366,10.3141174

In this outcrop, just W of the Capanne di Careggine village (Fig. 28), the Pseudomacigno fm. is strongly deformed and folded. The Pseudomacigno fm. can be considered the metamorphic equivalent of Macigno fm. of the Tuscan Nappe (Chattian-Lower Aquitanian). In less deformed portion 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. 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 1.8

Locality: E of Capanne di Careggine
44.072197,10.325855

About 1 km E of the Capanne di Careggine Village along the road metamorphic cherty limestones ("Calcari selciferi" fm.) outcrops (Fig. 29).

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. 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 1.9

Locality: Vianova
44.095647,10.324210

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. The Calcare Cavernoso (carbonate-cataclasite base of Tuscan Nappe) is not observed here, and the contact is between Liassic carbonates ("Calcari ad Angulata") and the Oligocene metasandstones and slates (Pseudomacigno Fm.).

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

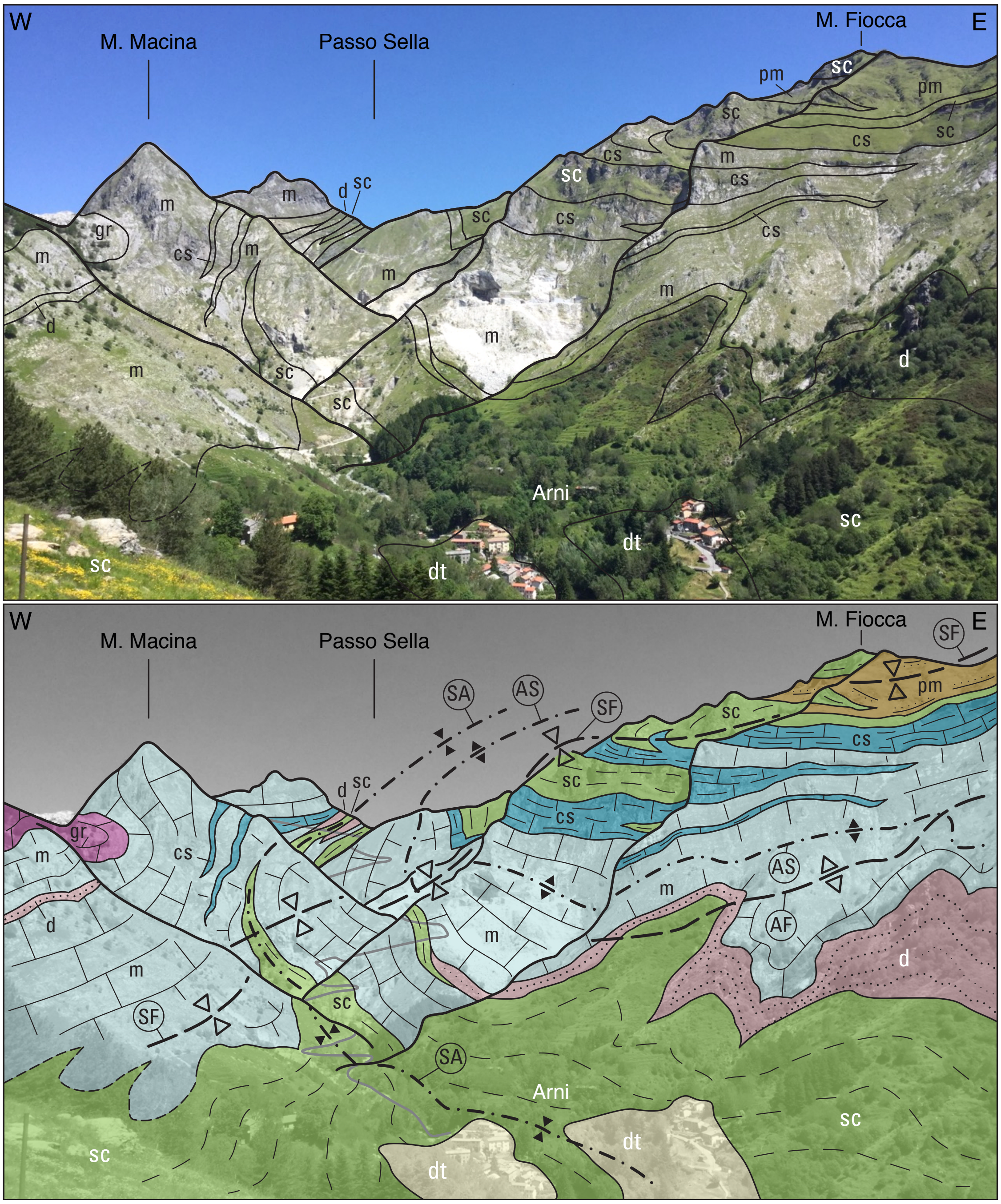

Fig. 26 – Panoramic view of the Arni Valley from Colle Castello, looking north. gr–Grezzoni fm., dolomites,m–marbles, cs–cherty limestones, sc–Scisti sericitici fm (phyllites), pm–Pseudomacigno (metasandstone and phyllites). SA–Arni Syncline, AS–Passo Sella Anticline, SF–Monte Fiocca Syncline, SF–Arni Synform, AF–Arni Antiform.

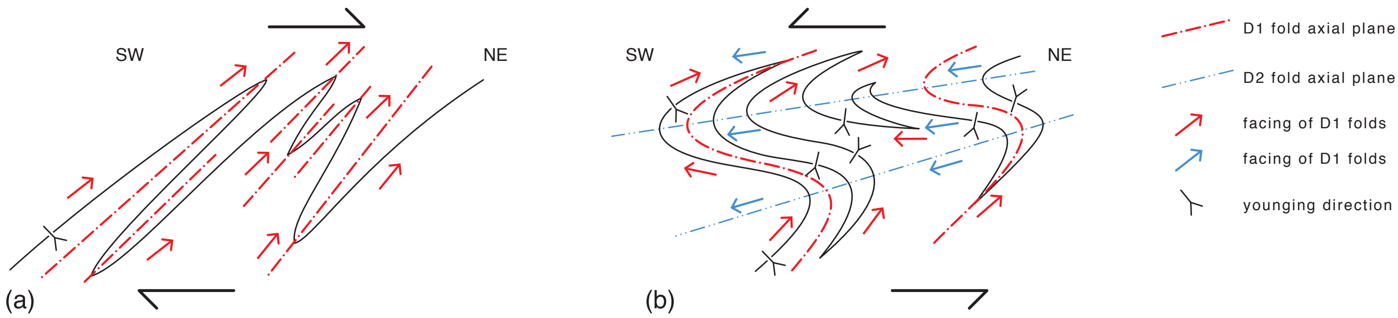

Fig. 27 – Sketch of the folding structure in the Arni area. (a) After D1 folding. (b) After D2 folding.

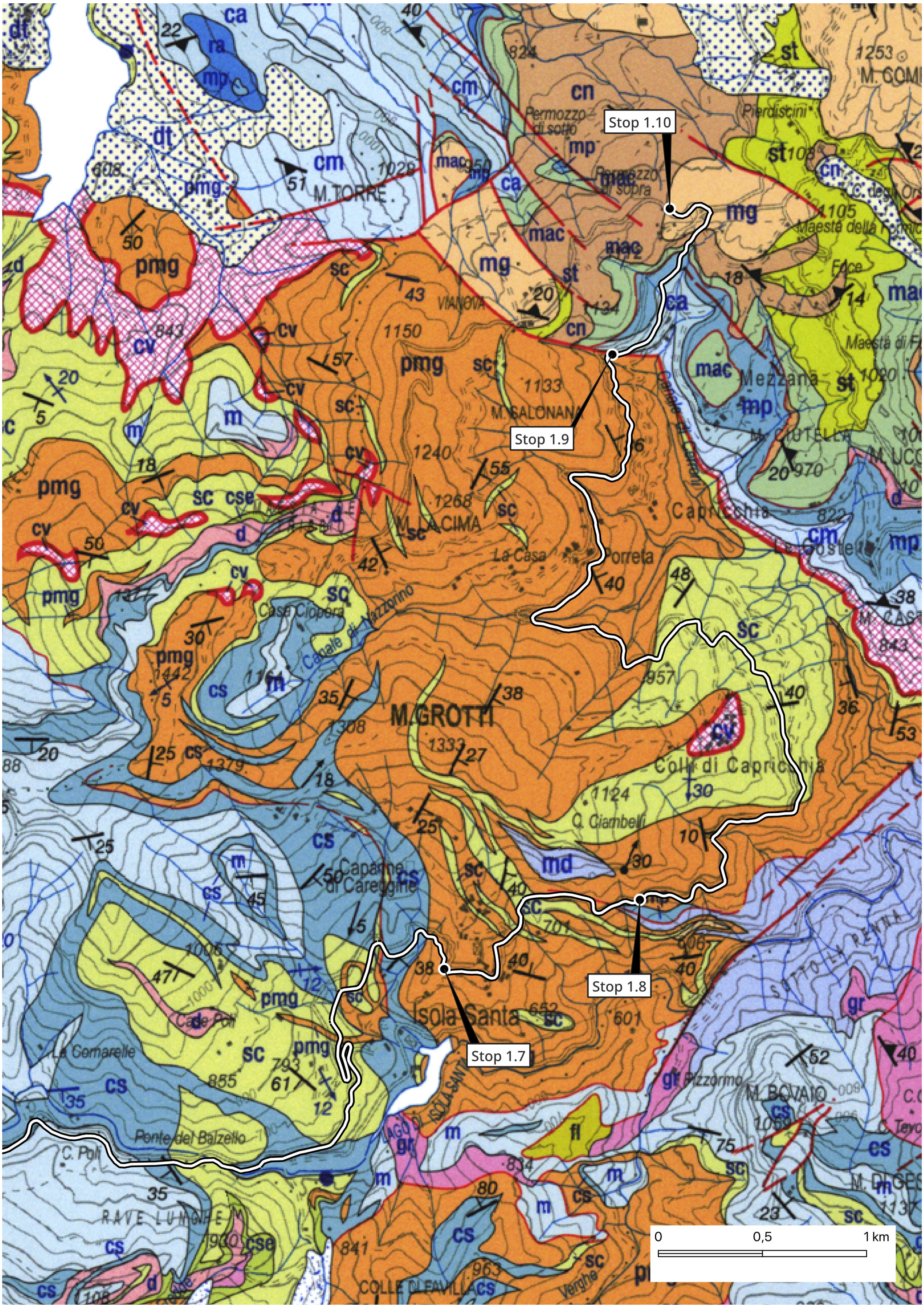

Fig. 28 – Geological map of the north-eastern Alpi Apuane.

Fig. 29 – Mylonitic cherty limestones at Stop 1.8, East of Capanne di Careggine.

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

The fault zone is interpreted as part of a low-angle normal fault system related to footwall exhumation of the metamorphic units based on the geometric relationships between: (1) original bedding S0, R-R' fractures and P-foliation in hanging-wall 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) on the metasediments of Pseudomacigno Formation in the footwall and Macigno Formation 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 yielded a ZHe 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 non metamorphic units, already resting at very shallow levels, reached the surface by a combined effect of High angle normal faulting and erosion, as a single coherent body (Fellin *et alii*, 2007).

Stop 1.10

Locality: La Baita.
44.101937,10.327633

We stop in front of the La Baita restaurant. From this point we have a panoramic view toward the North, to the Northern Apennines main chain, the Lunigiana-Garfagnana graben and the Tuscan Nappe succession.

We have the village of Careggine in front of us, which lies on the Scaglia Toscana fm. of the Tuscan Nappe tectonic unit. In the distance the Macigno formation outcrops extensively (usually dipping toward North) and above we can see the Subigurian tectonic unit and the Ligurian unit.

The nappe stack is crosscut by normal faults striking NW-SE that belongs to thew "Garfagnana graben", a fault system that develop a NW-SE oriented valley (Garfagnana Valley), filled with Pliocene-Pleistocene deposits, that separates the Alpi Apuane mountain range from the Northern Apennine main divide.

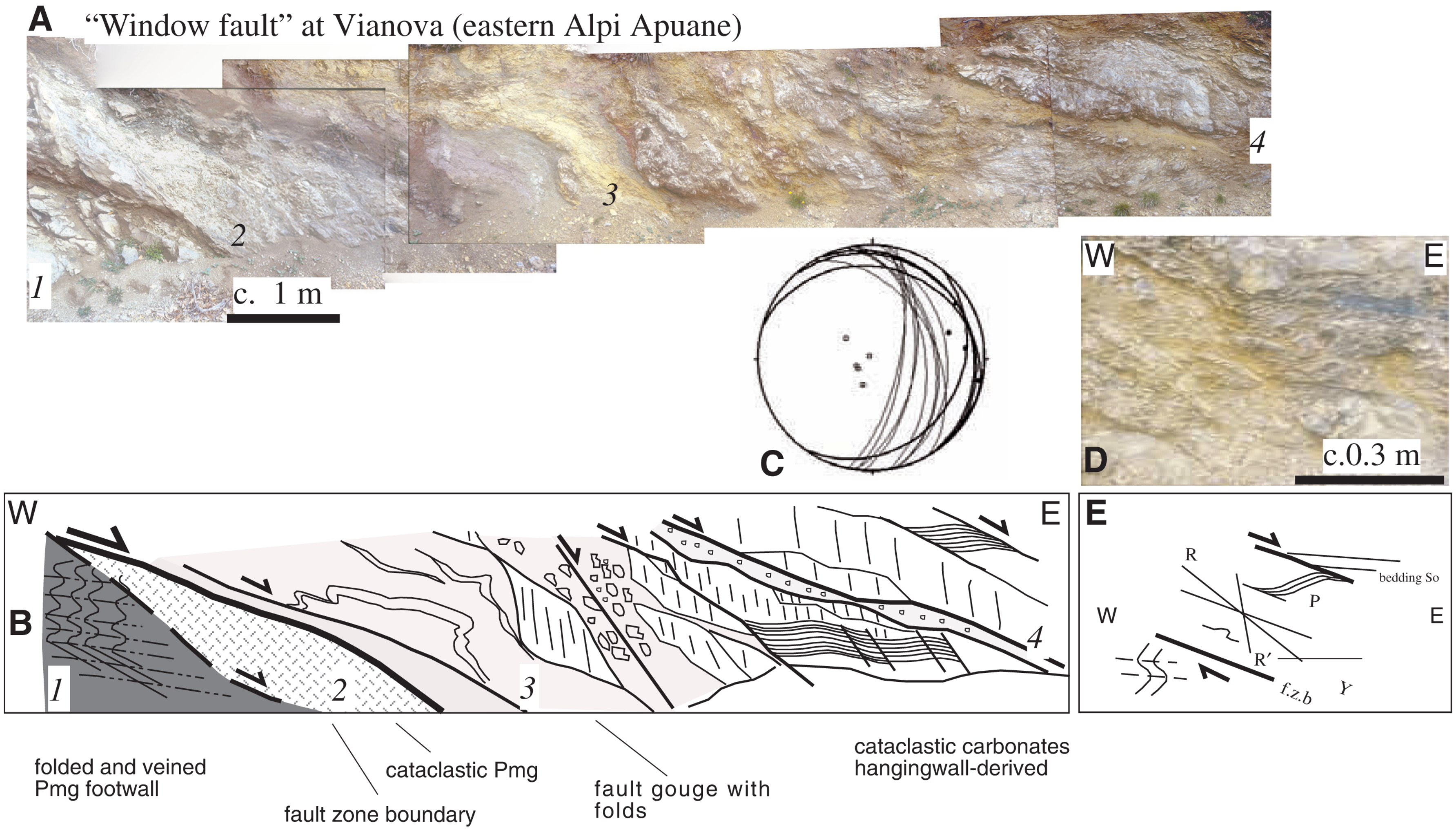

Fig. 30 – Stop 1.9. (A) General view (scale bar 1 m) and schematic representation (B) of the structural elements of the tectonic “window fault” between the unmetamorphic Tuscan Nappe and metamorphic Apuane core, a fault that is observable at Vianova (road toward Capanne di Careggine) eastern Apuane. (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).

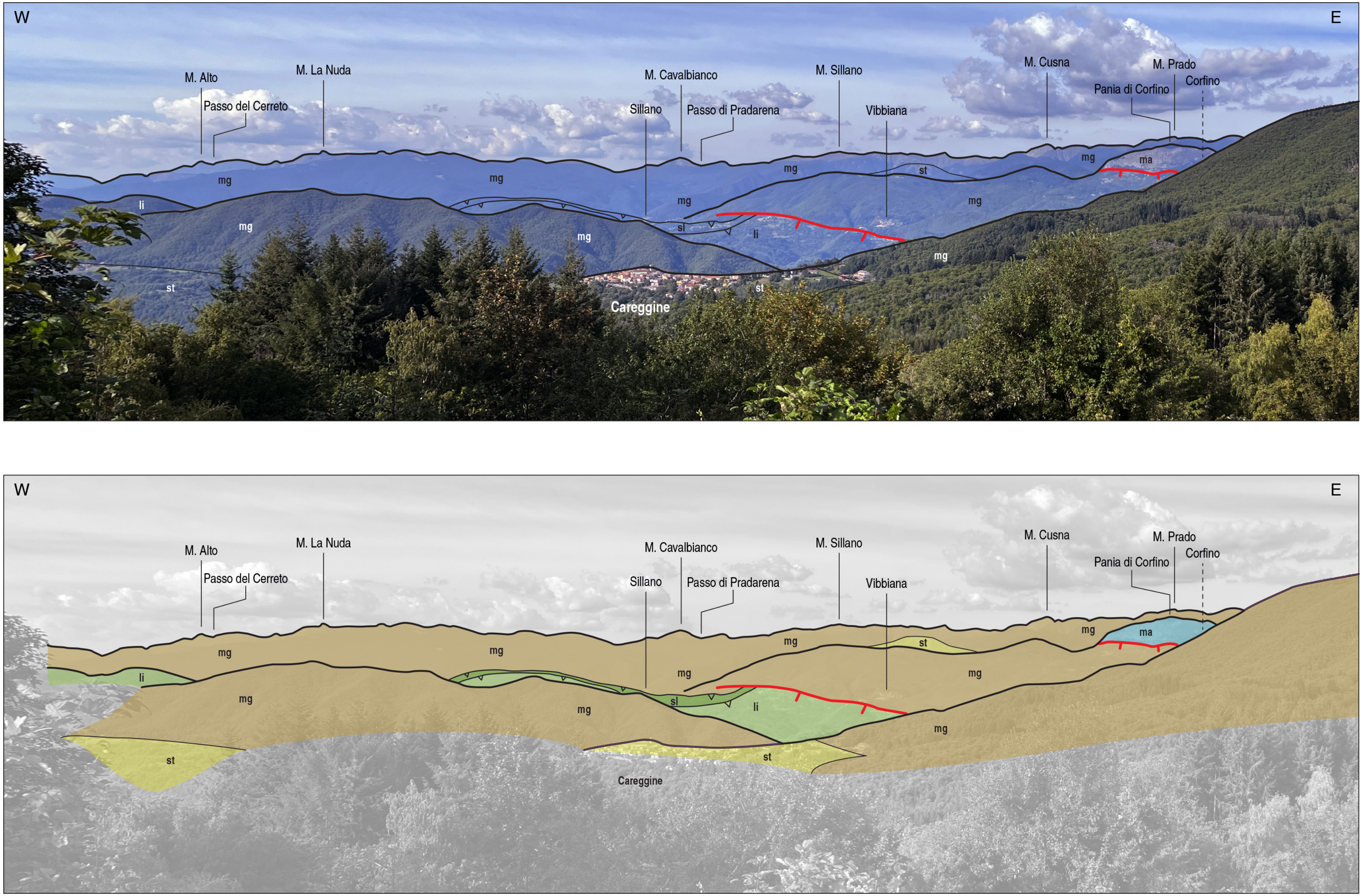

Fig. 31 – Panoramic view from La Baita Restaurant. View toward the North. Tuscan Nappe: ma–limestones, cherty limestones, Calcare Massiccio Fm., Calcari selciferi Fm. (L. Jurassic), st–shales, marls, limestones, Scaglia Toscana Fm. (Cretaceous-Oligocene), mg–sandstone flysch, Macigno Fm. (U. Oligocene-L. Miocene). Subligurian Unit: sl–shales, limestones, Argille e Calcari Fm. (Cretaceous-Eocene). Ligurian Unit: li–basalts, serpentinites, shales, limestones (Jurassic-Cretaceous).

Day 2 : The northern Alpi Apuane

Field Trip Route

Massa - Aulla - Orto di Donna.
Leaving the hotel in Marina di Massa we travel by highway from Massa to Aulla. From Aulla we travel east through the villages of Gassano, Casola Lunigiana, Pieve San Lorenzo and Minucciano. We then enter the Orto di Donna valley, which we travel southwards through, and park in front of the "Guido Donegani" mountain hostel. The whole bus trip takes about 1 hour and 30 minutes.

Topics

Variscan basement and Mesozoic succession in the northern Alpi Apuane, D1 and D2 deformation features. The upper tectonic units (Tuscan Nappe and Ligurian unit).

Stop 2.1

Locality: Orto di Donna
44.138557,10.194239
Topic: D1 deformation in calcschists.

In this first Stop (Fig. 32, Fig. 33) carbonatic phyllites and impure marbles part of Calcschists fm. (metamorphic equivalent of *Posidonomia* marls) may be observed. Structural features as low angle- to bedding-parallel main foliation (D1) and related stretching lineation may be observed altogether with superimposed crenulation cleavage, late folds and related intersection lineations which document late phase D2 structures.

Starting from the road hairpin bend the Calcschists are overlayed by overturned radiolarian cherts (Diaspri Fm.), which may be observed along the road cut. After passing a fold core of "Entrochi" cherty metalimestone (here including levels of quartzite-rich breccias) and Sericitic schists, we will meet another level of Cherts followed by late Jurassic Cherty metalimestone.

Stop 2.2

Locality: Orto di Donna
44.136870,10.193361
Topic: Deformed radiolarian chert.

At this Stop (Fig. 33) meter-scale tight symmetric M-folds track the hinge zone of a hectometer scale main-phase D1 fold (Fig. 34a). The cherts show superimposed meso-structural features: main phase D1 foliation and related stretching lineation, superimposed folds, late phase cleavages and lineations (Fig. 34b).

Stop 2.3

Locality: Orto di Donna
44.136870,10.193347
Topic: stratigraphic contact marble/cherty limestone.

At this Stop (Fig. 33) we will reach the contact of the marbles layer in which an alignment of active quarries may be observed looking South-East. Along the road cut at the starts of the mountain path an overturned highly sheared original stratigraphic sequence from Cherty metalimestone to marbles is exposed (Fig. 35a).

Few meters of white Cherty metalimestones and pinkish-reddish impure marble (equivalent of the original horizon of "Rosso Ammonitico" of the Tuscan Nappe stratigraphy) marks the downdrawing of the Jurassic carbonate platform toward

Fig. 32 – Orto di Donna, Stop 2.1, calcschists (Cretaceous).

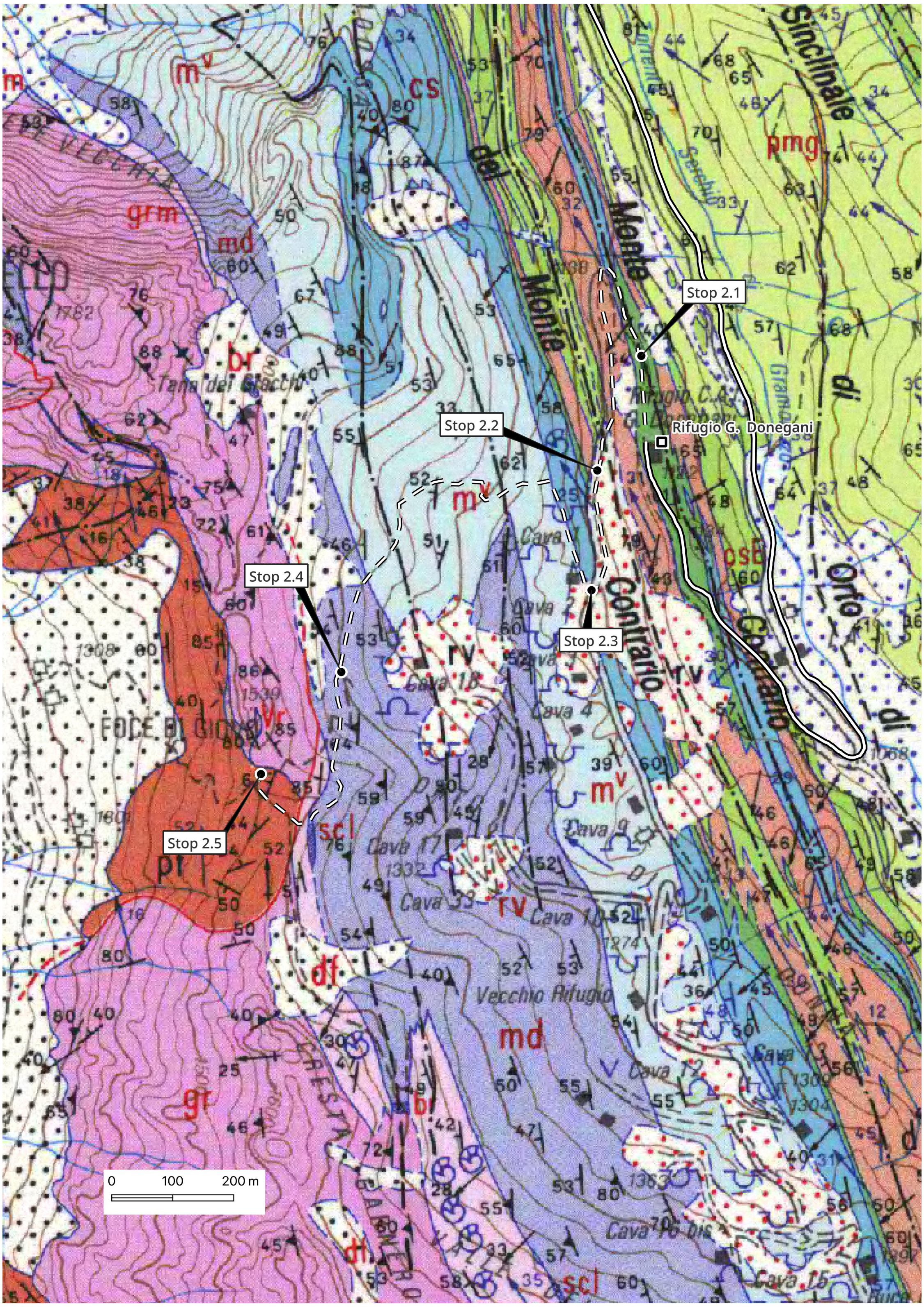

Fig. 33 – Geological map odf the Orto di Donna area, after Carmignani (1985). Locations of stops 2.1-2.5 are indicated.

Fig. 34 – Stop 2.2. (a) D1 folds in the Diaspri Fm. (radiolarian cherts). (b) Detail of the Diaspri Fm., a widespread D1 stretching lineation is evident. Main foliation and lineations are refolded by later D2 folds.

basinal conditions. In the Cherty metalimestone and impure reddish marble small pyritized ammonites have been found and are recognizable altogether with abundant crinoidal stems. Deformation structures (foliation and asymmetric folds) related to main phase of deformation D1 are well observable, fold axes parallel to the stretching lineation (documenting highly non cylindrical folds) are also observable (Fig. 35b).

Stop 2.4

Locality: Orto di Donna
44.133919,10.188125
Topic: marbles, dolomitic marbles.

Along the path in marbles quarries (Fig. 33) we passed different types of marbles, mainly referable to the merceological variety of the *Ordinario*, *Venato* and *Bardiglio*. Differently with eastern Alpi Apuane (what we have seen yesterday) the marbles here basically lack of the marble-breccias in particular those polygenic and with pelitic/green to red matrix (Arabescato, Fantastico, Breccia Rossa). This suggests a lateral and regional scale variability of the former depositional environment inherited in the present-day orogenic structure (Molli & Meccheri, 2012).

At Stop 2.3 Dolomitic marble characterized by millimetric trails to decimeter to meter-thick dolomite layers can be observed. The high strain localized in the marble layers is here well evident by symmetric to asymmetric dolomite-rich nodules and lens defining porphyroclast systems and winged inclusions.

The Dolomitic marble commonly marks the basal portion of Jurassic Marble, where they are directly above the Triassic Dolomites (common setting at regional scale). Elsewhere, as here in the Orto di Donna, they lay above a Late Triassic carbonate platform (Marmi a Megalodonti fm.) and breccias (Brecce di Seravezza). These terms are observable in a small, abandoned quarry along path before to enter in the final part of mountain path characterized by Triassic Dolomites and basement rock-types.

Stop 2.5

Locality: Foce di Giovo
44.132397,10.186474
Topic: panoramic view, regional setting of the northern Alpi Apuane.

At this Stop (Fig. 33) spectacular 360° panoramic views can be seen which allow to discuss the general setting of the northern Alpi Apuane and surroundings.

Two major regional scale folds form the northern Alpi Apuane, that is the Orto di Donna syncline and the paired Vinca-Forno anticline. Both structures which can be followed for more than 20 kilometers with a North-Northwest/South-Southeast map-scale trends are east-facing main phase (D1) regional scale folds.

The Orto di Donna valley, which give the name to the geological structure, is carved within the hinge zone of the syncline that double an original basin-related stratigraphic sequence from Triassic dolomites to Tertiary Pseudomacigno fm. Whereas the basal Mesozoic terms from Triassic dolomites up to the Jurassic marbles are only exposed in the overturned and normal limbs (i.e along the route of the mountain path we passed and at the opposite side of M.Pisanino peak east of Foce Giovo), the Cherty metalimestones, Calcschists, Cherts, Encrinites-bearing (Calcari a Entrochi *Auctt.*) cherty metalimestone, Sericitic schists and Pseudomacigno Fm., may be found doubled different times in hectometer-scale parasitic folds in the valley.

The Vinca-Forno anticline has in the Pizzo d'Uccello peak (Fig. 36) one of the parasitic folds of the hinge zone. With its kilometer long inverted west-dipping limb the structure may be properly define as a fold-nappe.

From structural point of view in the valley ubiquitarian main phase D1 foliation and related isoclinal folds are observable from meso- to hundreds-meters up to kilometer-scale.

D1 fabrics and structures are in a medium to high angle west-dipping attitude due to the position of the Orto di Donna syncline and the Vinca-Forno anticline in the western limb of a regional scale late to post main phase dome shape antiform whose origin has been and still is the object of debate.

All previous structures are deformed by D2 crenulation folds with a characteristic subhorizontal to low-angle axial plane

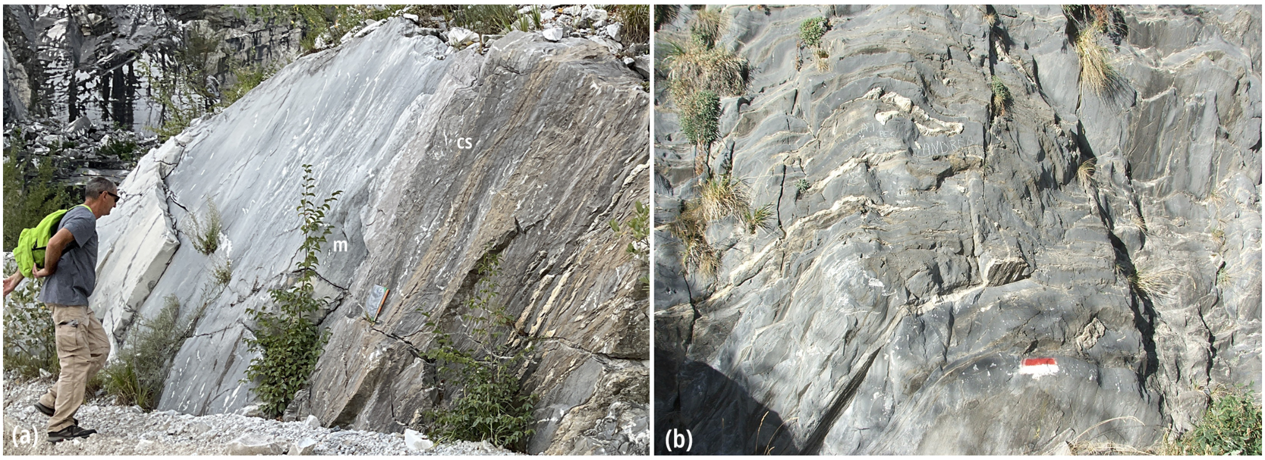

Fig. 35 – Stop 2.3. (a) Contact between marbles (m) and cherty metalimestones (cs, "Calcare selcifero" Fm. (b) The "Calcare selcifero", with with chert layers strongly elongated during D1 deformation and with well developed non-cylindrical (sheath) folds.

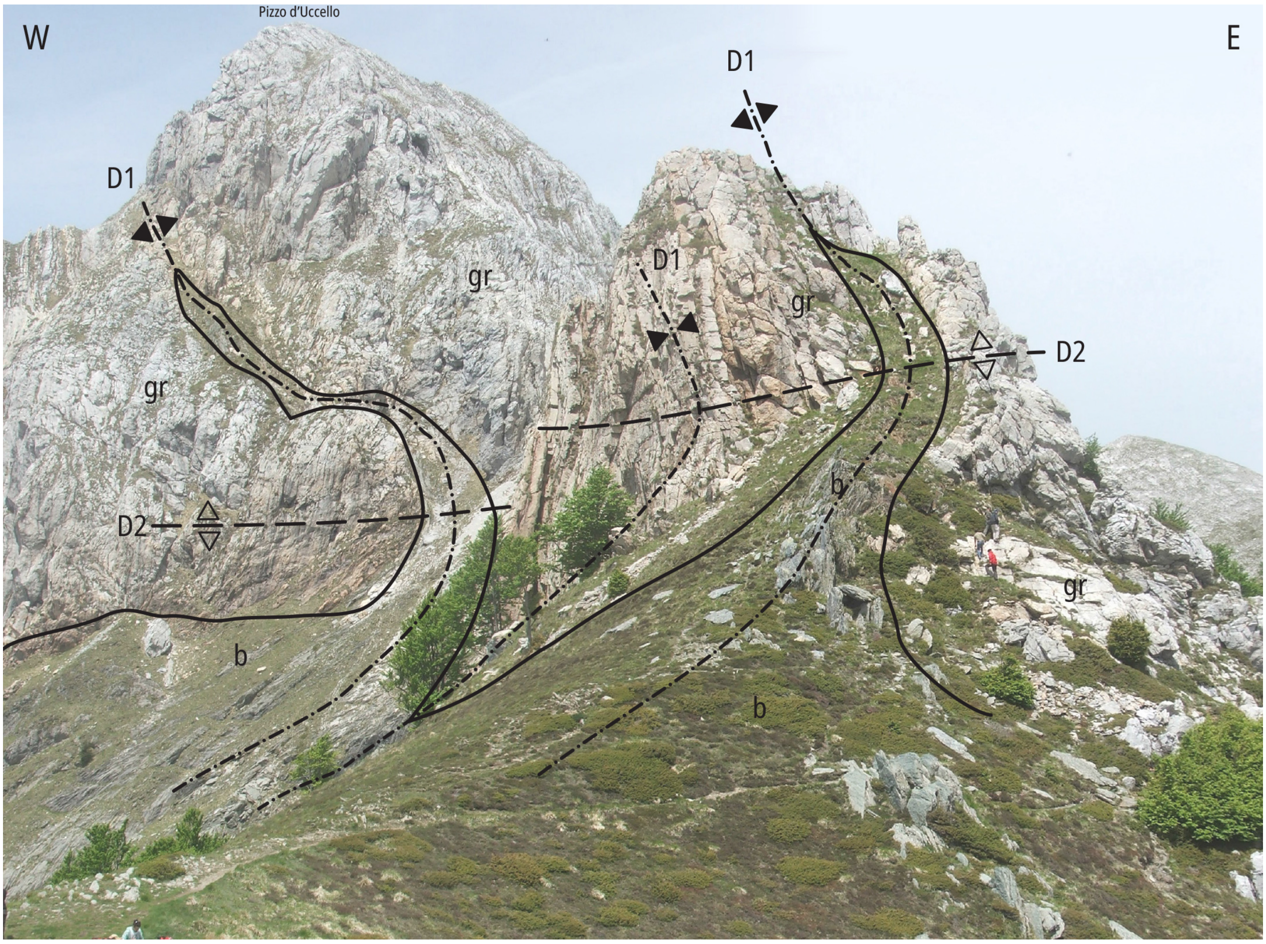

Fig. 36 – Panoramic view looking north from Foce di Giovo, Stop 2.5. Two small folds of the km-scale D1 Vinca Anticline are visible, refolded by D2 folds with a horizontal fold axial plane.

which produces a common type-3 (Ramsay, 1967) interference pattern observable from meso-to mountain-scale as witness looking to the Pizzo d'Uccello panorama in front of us (Fig. 36).

Following the path along the divide from Foce Giovo northward, different kind of Variscan basement rocks and overlying Verrucano (Triassic) deposits may be observed. After a track within the Triassic dolomites will have the opportunity to reach the Carnian terms of Vinca Fm. which directly cover the Paleozoic basements units. The Vinca Fm. is made up of pinkish dolomites locally including Verrucano-like deposits (Fig. 37a), alluvial floods fed by nearby landmass where peneplaned Variscan rocks were exposed. The Vinca Fm. mark the beginning of Alpine sedimentary cycle record of Pangea fragmentation ending with the opening of Jurassic Ligurian Tethys ocean which remnants will be observed in the second half of day.

Stop 2.6

Locality: South of Foce di Rifoglia
44.159829,10.201465
Topic: cataclasite along the Alpi Apuane Metamorphic Complex and the Tuscan Nappe.

At this Stop (Fig. 23), along the way back to Gramolazzo, we can observe the contact between the Apuane metamorphic core and the overlaying Tuscan Nappe. The contact is characterized by a fault zone 10s of meters thick where it is possible to distinguish different fault-rock types. Between them and differently to what we have seen at Stop 1.9 yesterday they also include the Calcare Cavernoso Fm. (Fig. 37a).

This is a carbonate-cataclasite derived from original evaporite-dolomite protoliths, which localized the early basement-cover detachment during the contraction and nappe piling, later it was reworked during extensional-exhumation of the Apuane metamorphic core. Systems of brittle asymmetric domino-like bands defined by Ridel shear indicate a clear top-to-NE extensional kinematics as well as the foliated cataclasites locally present.

Above this Calcare Cavernoso layer, Triassic limestones of the *Calcare a Rhaetavicula contorta* Fm. may be observed along the road.

Stop 2.7

Locality: lakeside path Gramolazzo
44.166181,10.253560
Topic: Jurassic pillow basalts of the Ligurian unit.

Along the lakeside path of Gramolazzo we will reach this Stop (Fig. 23), where Jurassic pillow basalts may be observed (Fig. 38).

These basalts are part of "basal complex" typical of the External Ligurian Unit. These units are characterized by the presence of Late Cretaceous calcareous dominant sequences (the Helminthoid Flysch) associated with complexes or pre-flysch formations called "basal complexes" (Elter *et alii*, 1991). The "basal complexes" are formed by mono- and polymict pebbly sandstones and mudstones, with intercalations of coarse- to fine grained lithoarenites. They also include huge (up to pluri-hectometer-scale), slide-blocks ("olistoliths") of mantle ultramafics, gabbros and basalts with geochemical T-MORB affinities as well as fragments of supraophiolitic pelagic sedimentary sequences (Palombini shales, Calpionella limestones and Cherts). The basal complex locally includes mafic and felsic granulite as well as Late Variscan granitoids (here around outcropping close to the village of Agliano). For all these characters the original paleotectonic setting from which the basal complex was tectonically derived, is interpreted as the former Ocean Continent Transition (OCT) originally located close to the thinned Adria continental margin (Molli, 1996; Marroni *et alii*, 1998; Malavieille *et alii*, 2016).

Stop 2.8

Locality: Castagnola
44.173929,10.255883
Topic: Panoramic view of the Northern Alpi Apuane, Tuscan Nappe and Ligurian unit.

At this Stop (Fig. 23) a panoramic view of the northeastern termination of the Alpi Apuane metamorphic core can be observed. The complete Northern Apennines nappe stack and the post-orogenic Villafranchian (Late Pliocene-Pleistocene) local deposits can be outlined (Fig. 40).

The present morpho-structural setting is the result of the last 5 Ma of tectonic evolution related with the activity of the high angle normal to oblique slip faults which controlled the final exhumation of the Alpi Apuane core and whose activity is still ongoing as the recent Mw 5.3 2013 Lunigiana earthquake testifies (Molli *et alii*, 2021, and references therein).

Stop 2.9

Locality: Minucciano
44.173209,10.202659
Topic: Calcari ad Angulata *Fm. of the Tuscan Nappe.*

This last Stop (Fig. 23) allows to compare carbonate deformation styles of the Alpi Apuane core with that of the overlying very low grade Tuscan Nappe. The outcrop expose the Calcari ad Angulata Fm. of the Tuscan Nappe (named for the presence of *Schlotemia Angulata* ammonite) which is made up by a regular alternation of calcilutites of dark grey and grey calcareous marls, yellowish on alteration (Fig. 39a). Locally bioturbation trace may be recognized gives the rock a massive appearance. The unit is interpreted as related to a sedimentary environment of a distal carbonate ramp/emipelagic basin lateral to that of the Hettangian-Sinemurian Calcare Massicio platform (protolith of the Carrara Marble). From deformation point of view, veins and a pressure solution cleavage at a low angle with the bedding may be observed (Fig. 39b).

The drive back to Marina di Massa will close the Field Trip.

Fig. 37 – (a) Outcrop of the Vinca Fm. at Foce di Giovo, near Stop 2.5. (b) Cataclasite in limestone rocks along the contact between the Alpi Apuane Metamorphic Complex and the Tuscan Nappe, Stop 2.6.

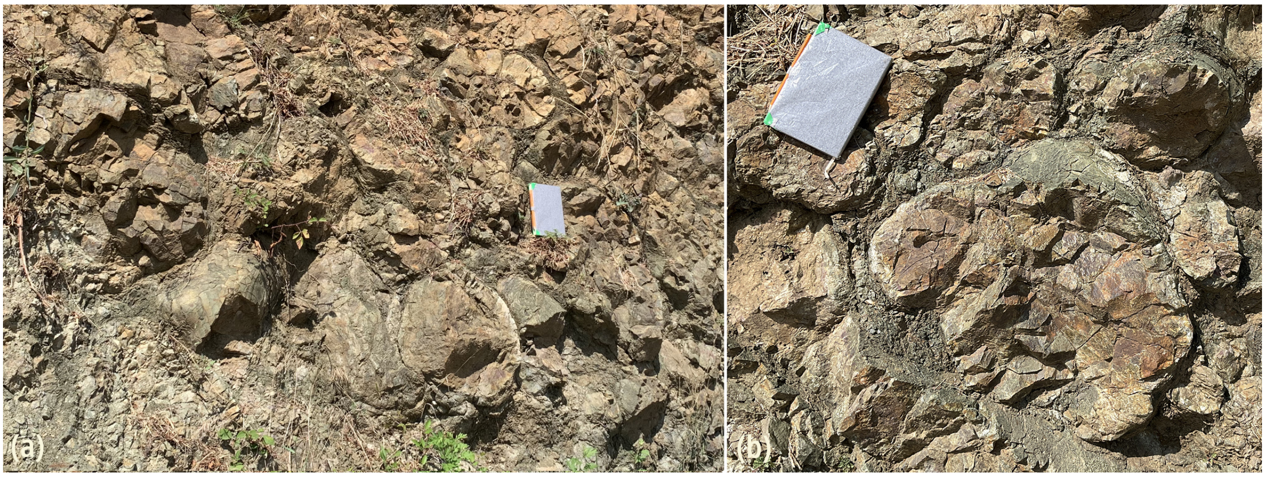

Fig. 38 – Stop 2.7, Jurassic pillow basalts along the shore of Lake Gramolazzo.

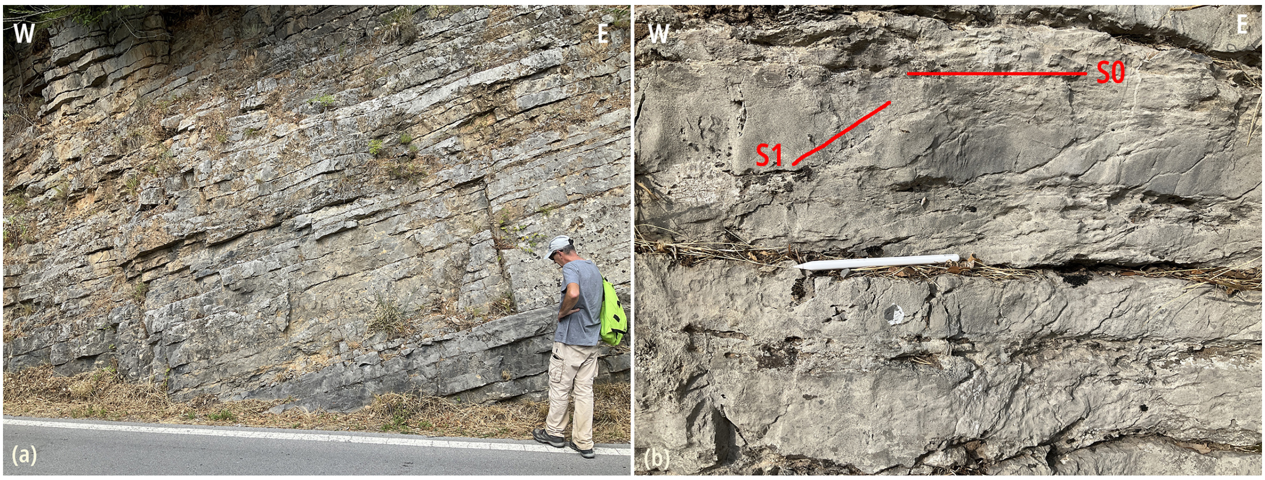

Fig. 39 – (a) Stop 2.9, Calcari ad Angulata Fm. of the Tuscan Nappe tectonic unit, which lies above the Alpi Apuane Metamorphic Complex. No outcrop-scale evidences of folding occur. (b) Detail of outcrop. Bedding (S0) is very evident, cut by pressure-solution foliation (S1). Younging direction is upwards in this outcrop, bedding/foliation relationships indicating therefore a top-NE facing transport direction for this deformation.

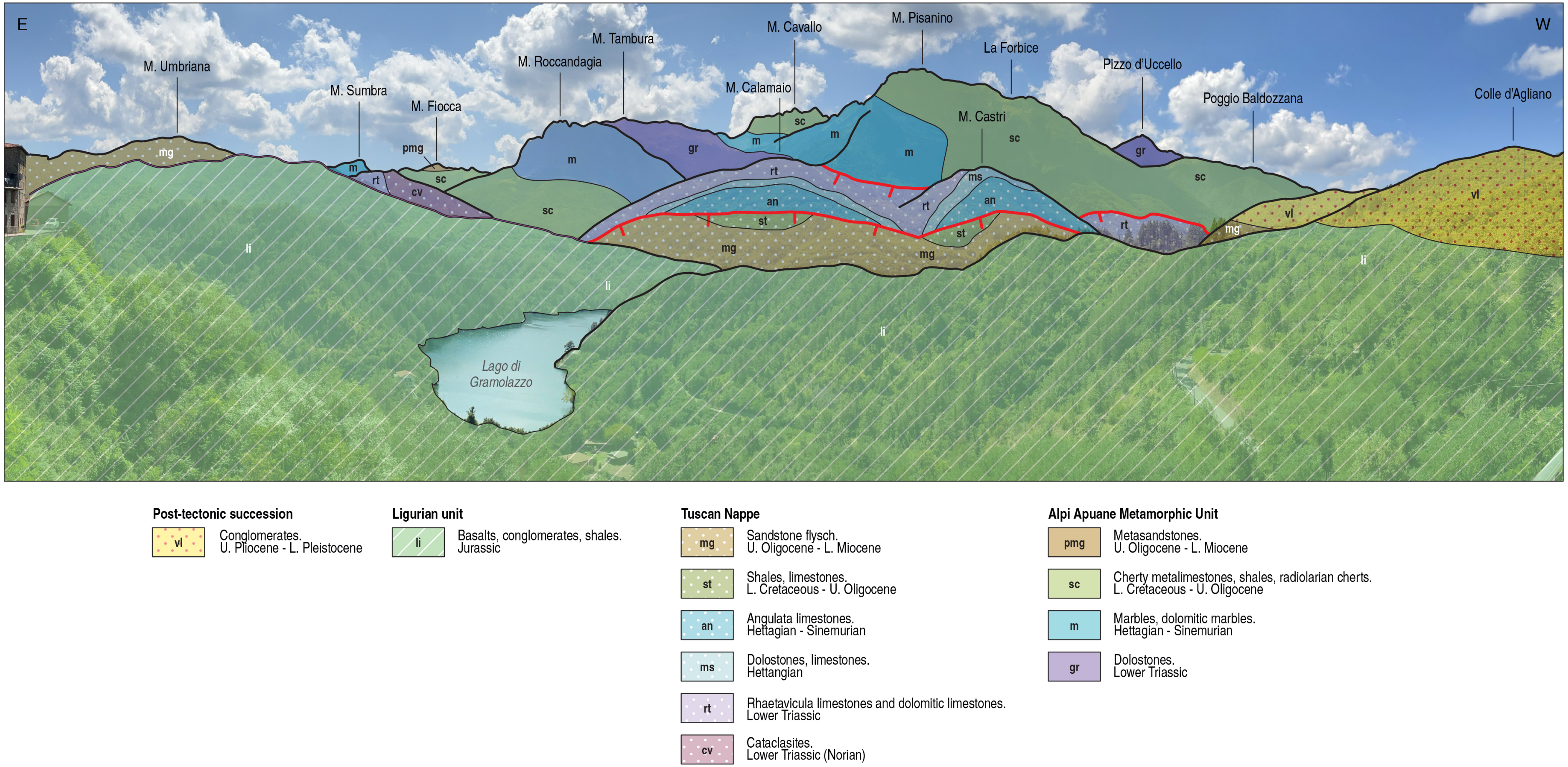

Fig. 40 – Panorama view from the village of Castagnola. View is towards south-west.

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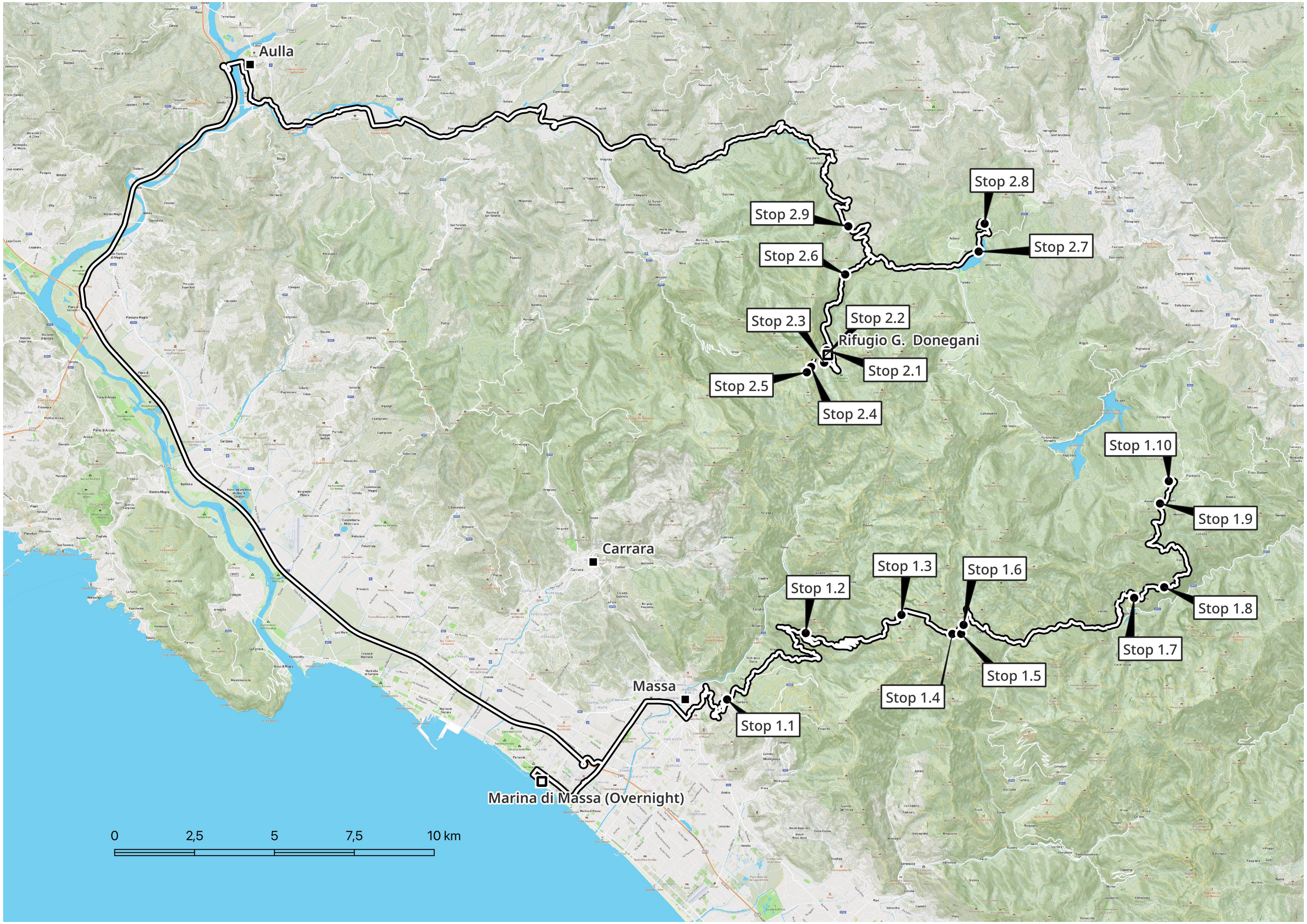
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