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Geology of the Alpi Apuane Metamorphic Complex (Northern Apennines, Italy)

Excursion Guide Book

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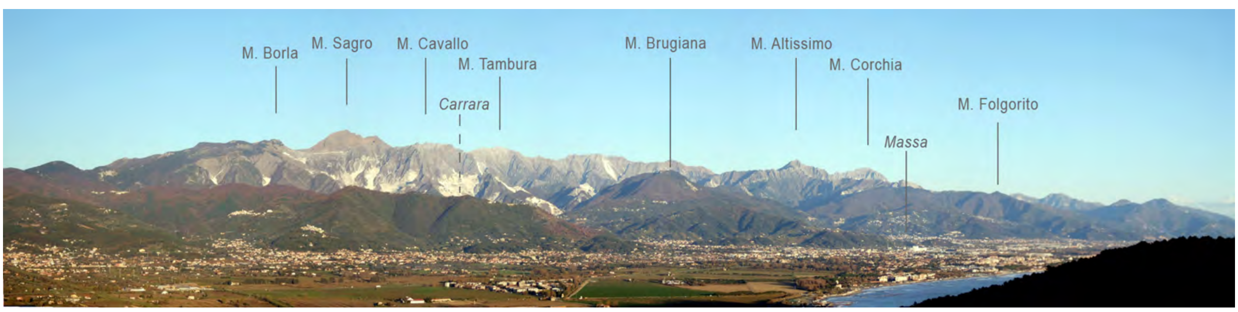

Contents

Foreword

The aim of this excursion is to give a concise but complete picture of the evolution of the Italian Northern Apennines in the Alpi Apuane area (northern Tuscany, Italy). This guide-book includes an outline of the tectonic and sedimentary evolution of the tectonics units outcropping in the Northern Apennines and description of itineraries 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.
- Boccaletti M., Pieri M., Turrini C. & Moratti G. (1991) - *Field Excursion in the Apuane Alps Area, Field Trip Guide Book. 3rd E.A.P.G. Conference.* AGIP - European Association of Petroleum Geoscientists.
- 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.

Topographic maps of the Alpi Apuane are produced by the "Istituto Geografico Militare Italiano", Via Battisti 10 - 50100 Firenze, Italy. The topographic maps that cover the area of interest are:

- 1:50,000 map scale sheets: 249 - Massa Carrara, 250 - Castelnuovo Garfagnana, 260 - Viareggio, 261 - Lucca;
- 1:25,000 map scale sheets: 249I-Piazza al Serchio, 249II-Pania della Croce, 249III-Massa Carrara, 249IV-Fosdinovo, 250III-Barga, 250IV-Castelnuovo Garfagnana, 260I-Pietrasanta, 261IV-Pescaglia.

More detailed (1:10,000) topographic maps can be obtained by the Regione Toscana (Regione Toscana - Dipartimento Politiche Territoriali e Ambientali - Archivio Cartografico Generale, Via di Novoli 26, 50127-Firenze).

Geological maps covering the whole or most of the Alpi Apuane area are:

- Trevisan L., Brandi G.P., Dallan L., Nardi R., Raggi G., Rau A., Squarci P., Taffi L. & Tongiorgi M. (1971a) - *Carta Geologica d'Italia in scala 1:100.000, Foglio 105 - Lucca.* Servizio Geologico d'Italia, Roma.
- Trevisan L., Dallan L., Federici P.R., Giglia G., Nardi R. & Raggi G. (1971b) - *Carta Geologica d'Italia in scala 1:100.000, Foglio 96 - Massa.* Servizio Geologico d'Italia, Roma.
- Zaccagna D. (1890-1902) - *Carta geologica delle Alpi Apuane a scala 1:25.000.* Regio Ufficio Geologico d'Italia, Roma.
- Carmignani L. (1985) - *Carta Geologico-Strutturale del Complesso Metamorfico delle Alpi Apuane, Foglio Nord.* Scala 1:25.000, Litografia Artistica Cartografica, Firenze.
- Carmignani L., Conti P., Disperati L., Fantozzi P.L., Giglia G. & Meccheri M. (2000) - *Carta Geologica del Parco delle Alpi Apuane.* Scala 1:50.000, Parco Regionale delle Alpi Apuane, Massa - SELCA, Firenze.

More detailed geological maps are reported in the Reference list and most of them are available at: *www.e-geo.unisi.it.*

The excursion covers the central and northern sectors of the Alpi Apuane. The excursion is divided in four days:

- the first day is dedicated to the relationships between the Metamorphic Complex and the overlying Tuscan Nappe in the area north of Carrara, and to the stratigraphy and tectonic features in the Tuscan Nappe and in the metamorphic succession; the regional framework of development of regional scale structures will be discussed;
- the second day will focus on the structures developed in the central part of the Alpi Apuane Metamorphic Complex, with examples of superposition of compressional and extensional uplift-related structures;
- the third day is devoted to the geology of the eastern Alpi Apuane;
- the third day focus on geology of the northern Alpi Apuane.

We wish you an interesting and enjoyable excursion in the beautiful Alpi Apuane!

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1

The Northern Apennines

1.1 Introduction

The Northern Apennines are a fold-thrust belt formed during the Tertiary 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 ophiolite covered by deep water sediments, and represent part of the Ligurian-Piemont Ocean (or Alpine Tethys, Fig. 2a). According to most authors this units also suffered the Cretaceous-Paleogene tectonics phases well documented in the Alps (Fig. 2b). The Tuscan-Umbria domain represent the continental margin of the Adria (Apulia) plate (Fig. 2a) and is formed by an Hercynian basement with its Mesozoic-Tertiary cover. A palinspastic reconstruction for the European-Apulia margin in the Late Jurassic is reported in Fig. 2.

Eastward motion (in present day coordinates) of the Briançonnais microcontinent formerly belonging to the European plate (Fig. 2c), led to collision and deformation (Fig. 2d) in the Apulia margin in the Upper 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 (Fig. 21e, f), contemporaneous with eastward migration of subduction, collision zone and deformation.

In the Northern Apennines we find today therefore rocks of the Apulia margin covered by the Ligurian units (Fig. 3, Fig. 4), strongly deformed and metamorphosed during the collisional tectonic phases, and then affected by extensional tectonics, normal faulting, uplift ad exhumation. Before discuss the tectonic features of the area, we first review the stratigraphy of the tectonic units outcropping in the Alpi Apuane area.

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 *et alii*, 1966; Elter & Pertusati, 1973; Elter, 1975; Bortolotti *et alii*, 2001; Marroni *et alii*, 2001), furthermore separated in:

- *Internal Ligurian Domain*, characterized by the presence of Jurassic ophiolites and their late Jurassic- Cretaceous sedimentary cover (cherts, Calpionella limestone and Palombini shales) associated with a Cretaceous-Paleocene silici-clastic turbiditic sequence (Lavagna slates, Gottero sandstones and Bocco/ Colli-Tavarone shaly complex);
- *External Ligurian Domain*, characterized by the presence of Cretaceous-Paleocene calcareous-dominant flysch sequences (Helminthoid flysch) associated with complexes or pre-flysch formations called “basal complexes” in local literature. The pre-Cretaceous substrate is represented in part by ophiolites and in part by continental crust, therefore is a domain that joined the oceanic area to the Apulia continental margin.

Moving toward the continent the *Subligurian Domain* is distinguished, a Paleogenic sequence (Canetolo Unit), intensely deformed and whose original extend and substratum are unknown. This sequence was probably deposited in an area of transition between the oceanic and the continental crust.

In the Apulia continental margin can be recognized, from W to E (in present day coordinates) the following 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):

- The *Internal Tuscan Domain* (Tuscan Nappe), non-metamorphic (to low-grade metamorphic) formations of Upper Triassic to Early Miocene age, completely detached at the level of the Triassic evaporites.
- The *External Tuscan Domain* (“Autochthon” *Auctt.* tectonic unit, or Alpi Apuane tectonic unit), affected by greenschist facies metamorphism, with a Mesozoic-Tertiary succession that cover a Paleozoic basement with Hercynian deformation. This rocks outcrops in the Alpi Apuane area, in the Alpi Apuane Metamorphic Complex. This unit now outcrops below the Tuscan Nappe.

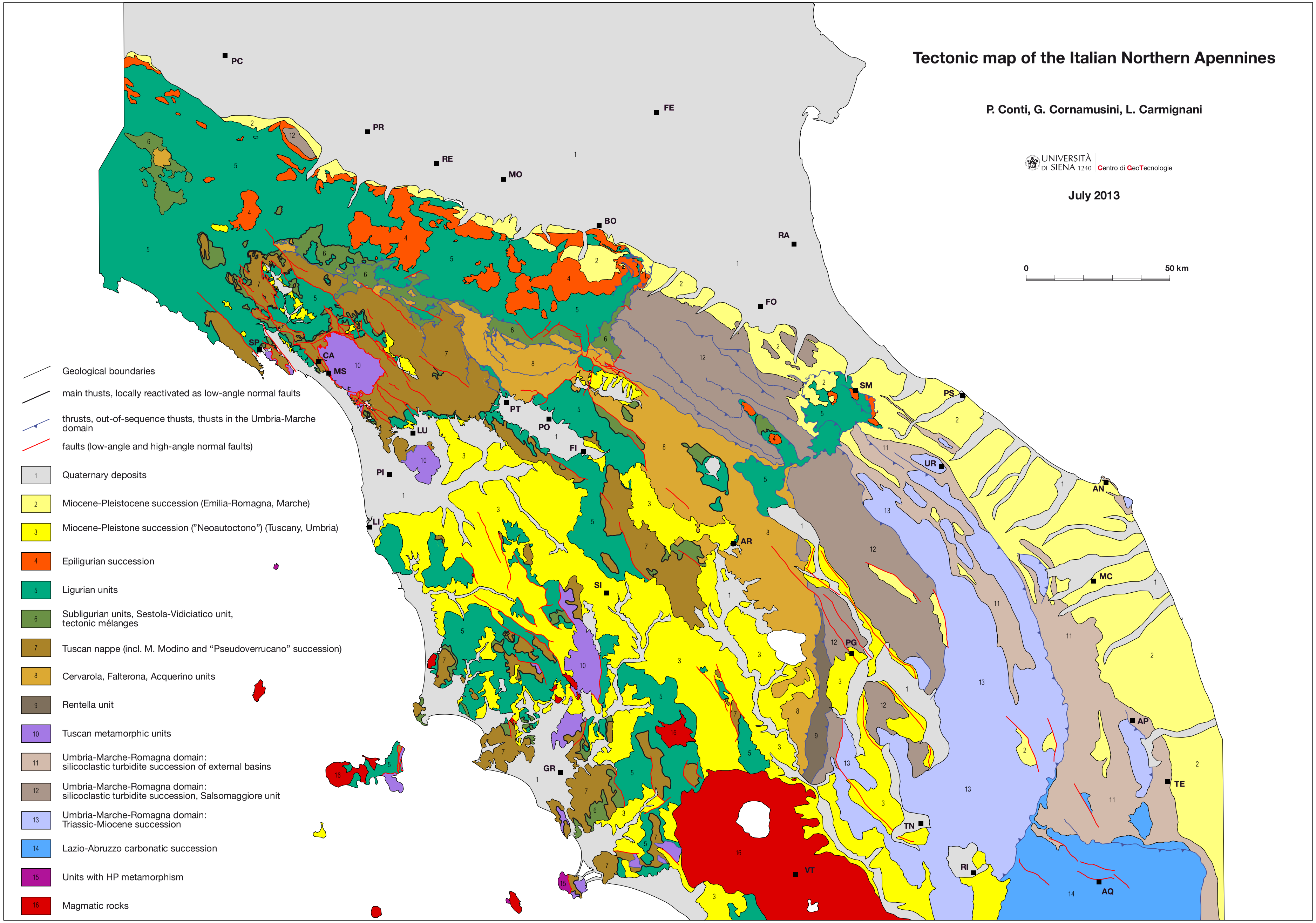
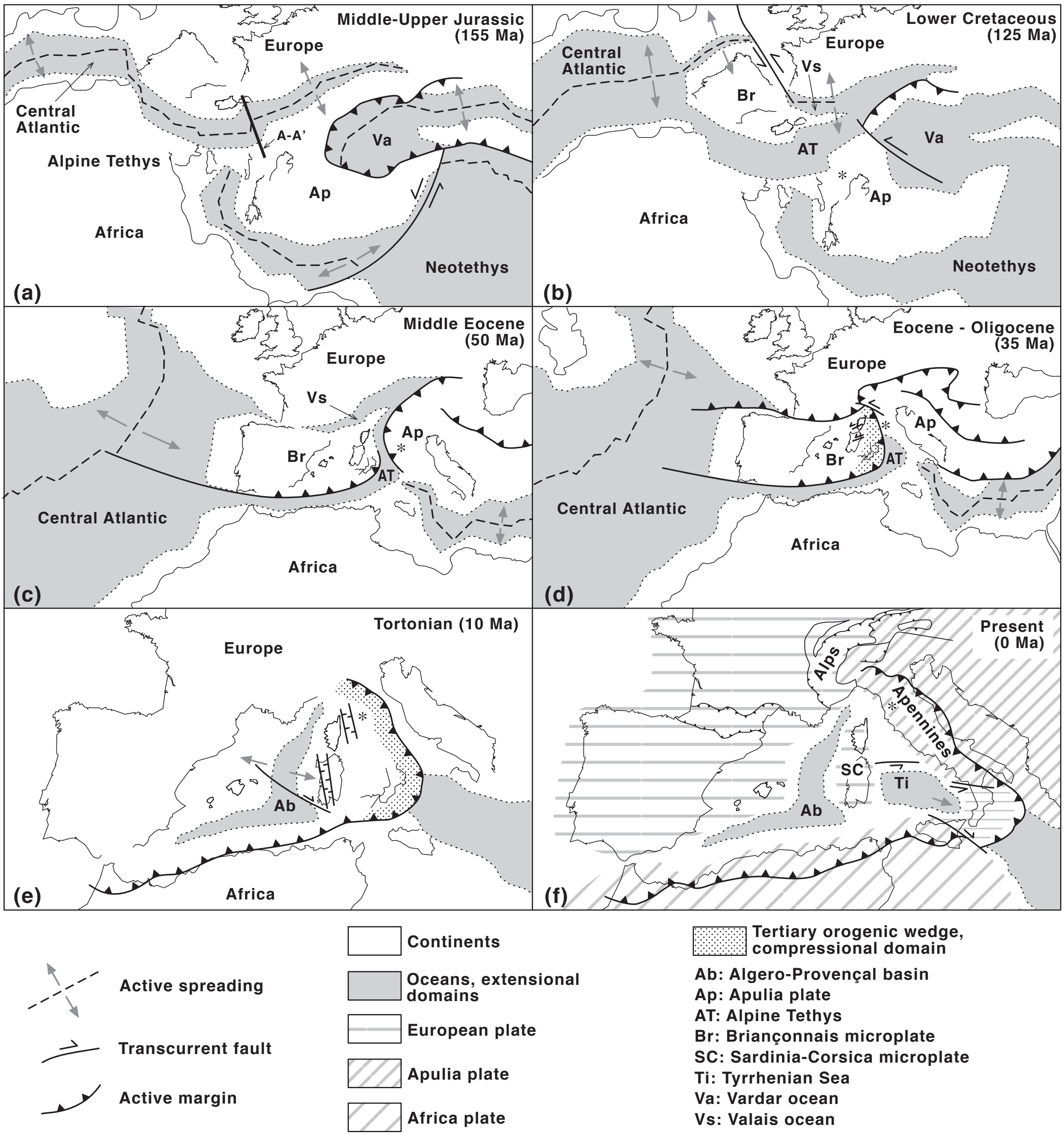


Fig. 1 – Tectonic map of the Northern Apennines, Italy.



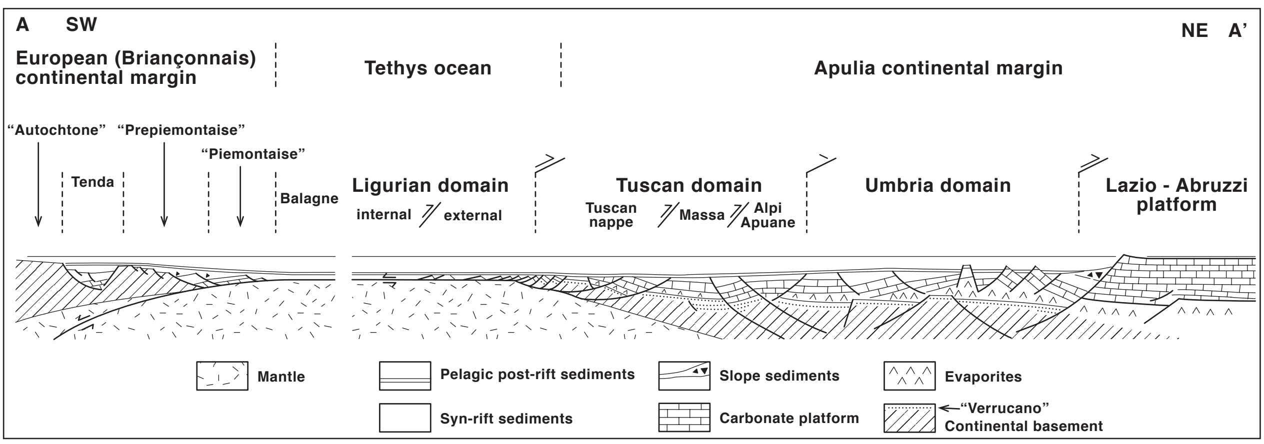


Fig. 2 – Plate reconstruction for the western Mediterranean area , after Stampfli *et alii* (1998, 2001) and Gueguen *et alii* (1998), modified. Asterisk approximately indicate position of Tuscany. Bottom: palinspastic reconstruction of the western continental margin of Apulia, Tethys ocean and adjoining European margin during the late Jurassic; after Hoogerduijn Strating (1990); Marroni *et alii* (1998); Bernoulli (2001); Peybernès *et alii* (2001); Rossi *et alii* (2002), modified. SW and NE are referred to present day coordinates; trace of section A-A' is approximately located in (a).

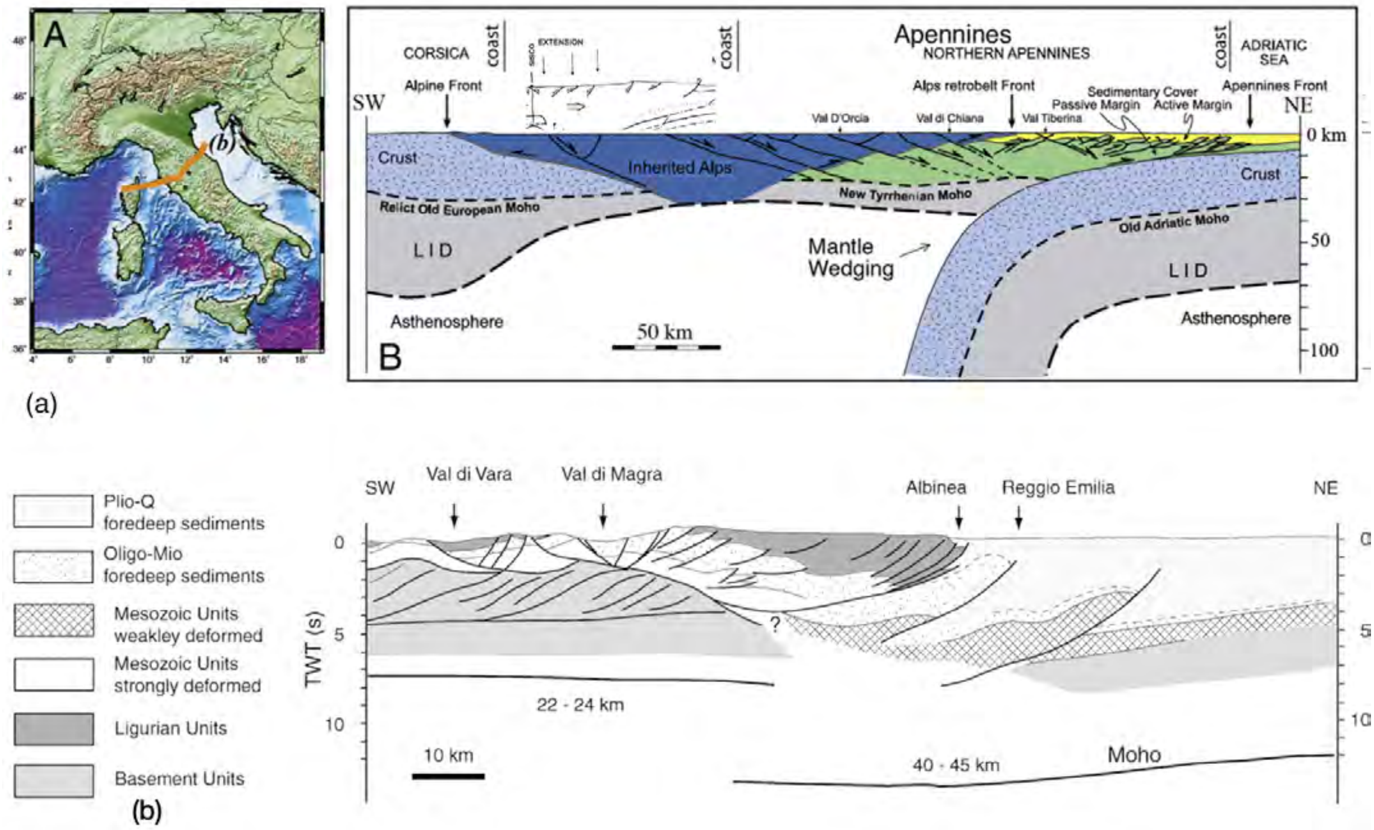


Fig. 3 – (a) Geological cross-section through the Northern Apennines, after Carminati & Doglioni (2012). (b) Cross section from La Spezia to Reggio Emilia, north of the Alpi Apuane, after Argnani *et alii* (2003).

– 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 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). 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 carbonatic deposition occurred all over the continental margin (Calcare Massiccio platform) during the Rhaetian to Early Liassic, locally interrupted by uplift, emersion and development of scree 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 Tertiary pelagic carbonates and shales grading upward to Oligocene- Lower Miocene sandstones and shales (Macigno and PseudoMacigno). As a whole, the Mesozoic to Tertiary stratigraphic evolution of the Tuscan

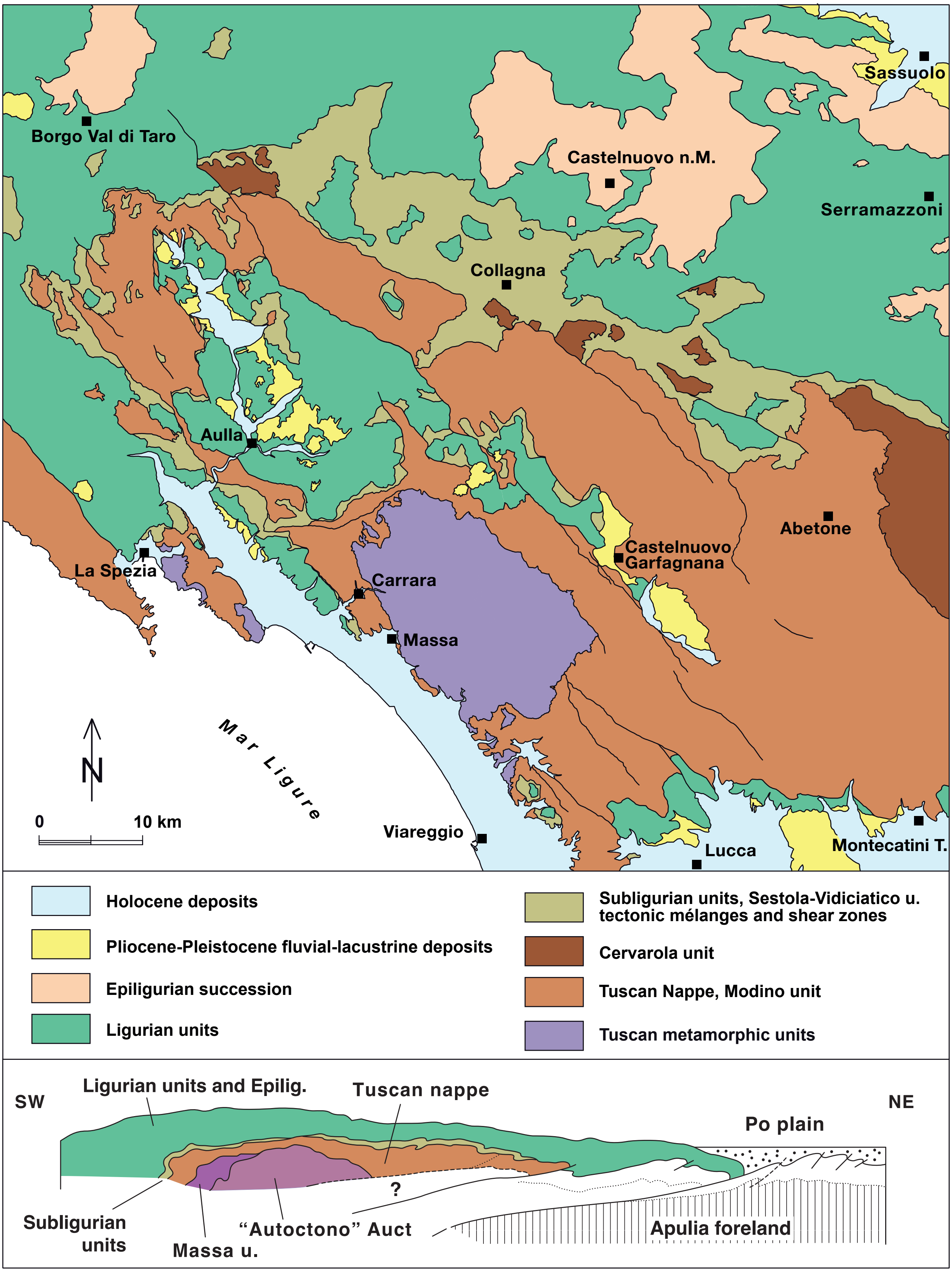


Fig. 4 – Tectonic map of the Norther Apennines and schematic cross section, after Elter (1975).

domain reflects deposition in a rifted continental margin which evolved into a clastic foredeep before being involved in the Late Oligocene/Miocene Apenninic tectonics.

2

Geology of the Alpi Apuane area

The Alpi Apuane is a mountain chain area in the Italian northern Apennines, in northern 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 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" of some authors).

2.1 The Tuscan nappe

The Tuscan nappe (Fig. 6) consists of a Mesozoic cover detached from its original basement along the decollement level of the Norian anidrites and dolostones now transformed almost totally into cataclastic breccias called "Calcare Cavernoso" ("cellular" limestone).

The sequence continues upward with Rhaetian to Hettangian shallow water limestones (Rhaetavicula Contorta, Portoro and Massiccio), 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 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 Up-

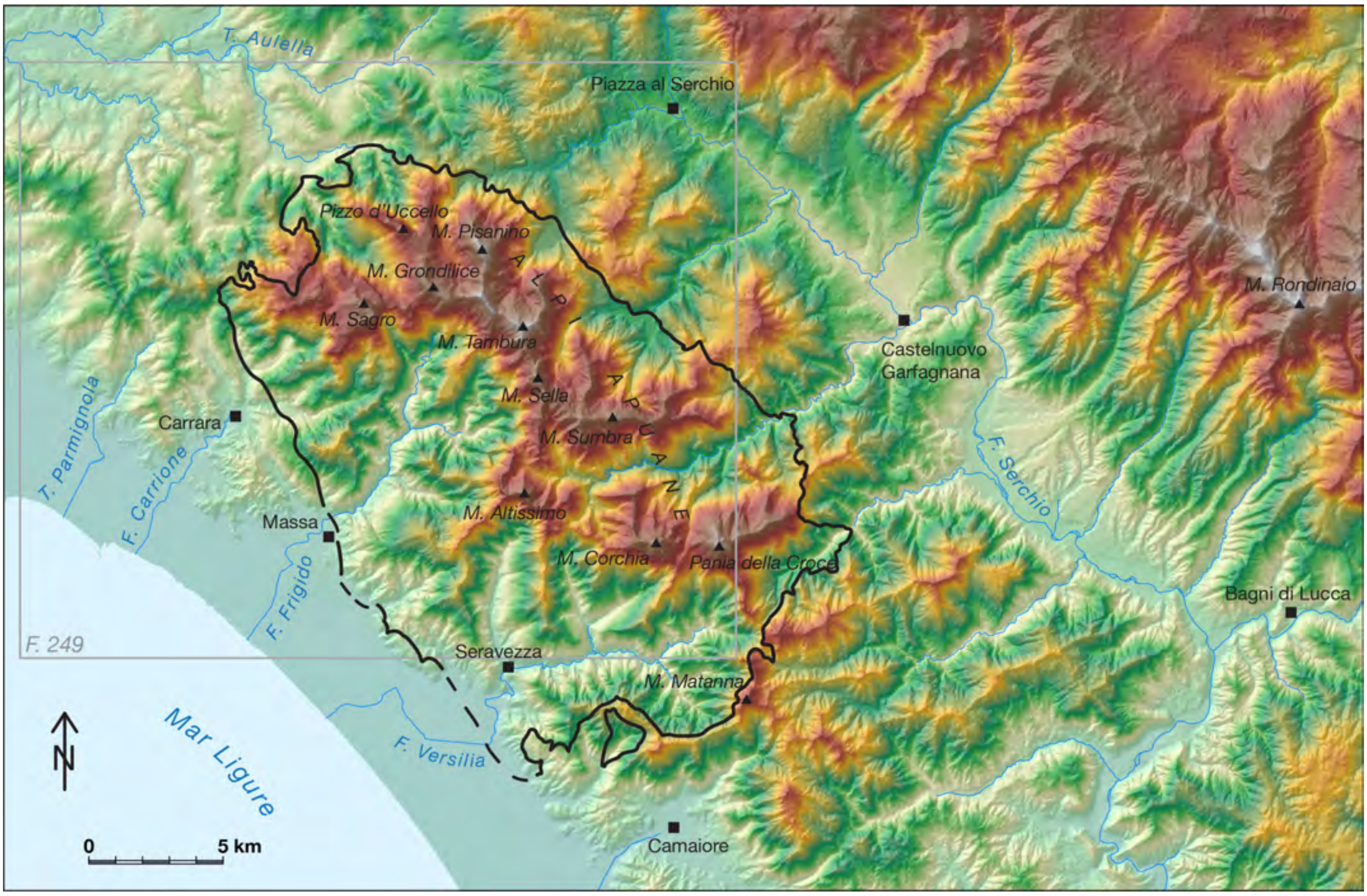


Fig. 5 – The Alpi Apuane region, Italian northern Apennines. Black line is the limit of the Alpi Apuane Metamorphic Complex.

per Triassic-Oligocene meta-sedimentary sequence (Fig. 6).

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 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 the basement rocks in the "Autochthon" Auct. 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) stratigraphycally lying on almost all the Paleozoic formations.

The Mesozoic cover (Fig. 6) 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 Apuane 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). Such data have been recently confirmed and used to interpret some of the microstructural variability in marbles.

The regional tectonic setting of the Alpi Apuane area is well known and generally accepted by re-

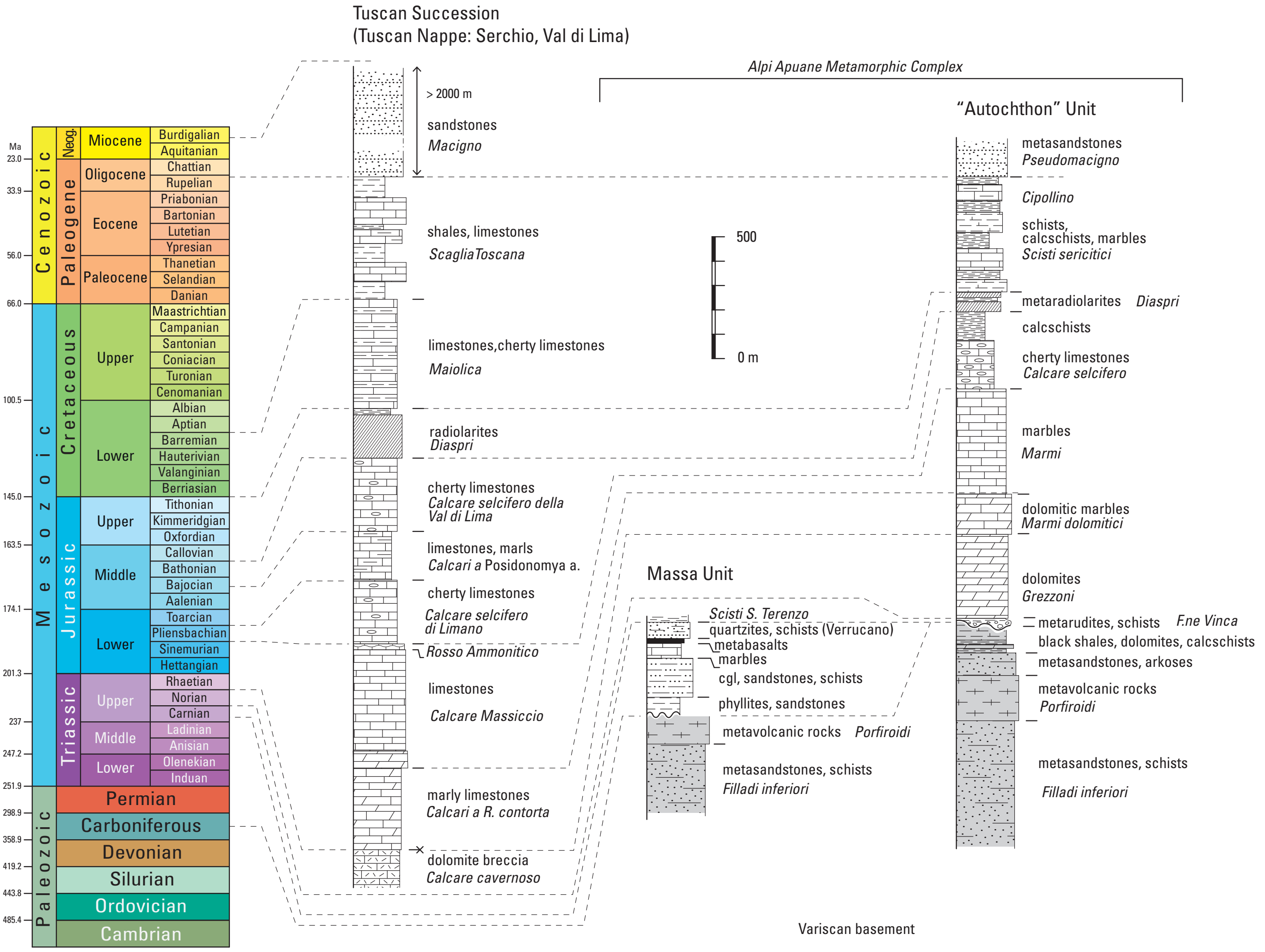


Fig. 6 – Stratigraphic sequence of the Tuscan units (Tuscan nappe and metamorphic units) in the Alpi Apuane area. Grayed are lithostratigraphic units of the Variscan basement.

searchers belonging to different geological schools (Fig. 7). 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.

2.3.1 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 folds, decimeter to kilometer in size (Fig. 8).

Foliation bears a WSW-ENE trending mineral and extension lineation which appears to be parallel to the long axes of the stretched pebble clasts in marble breccias and in quarzitic metaconglomerates. Finite

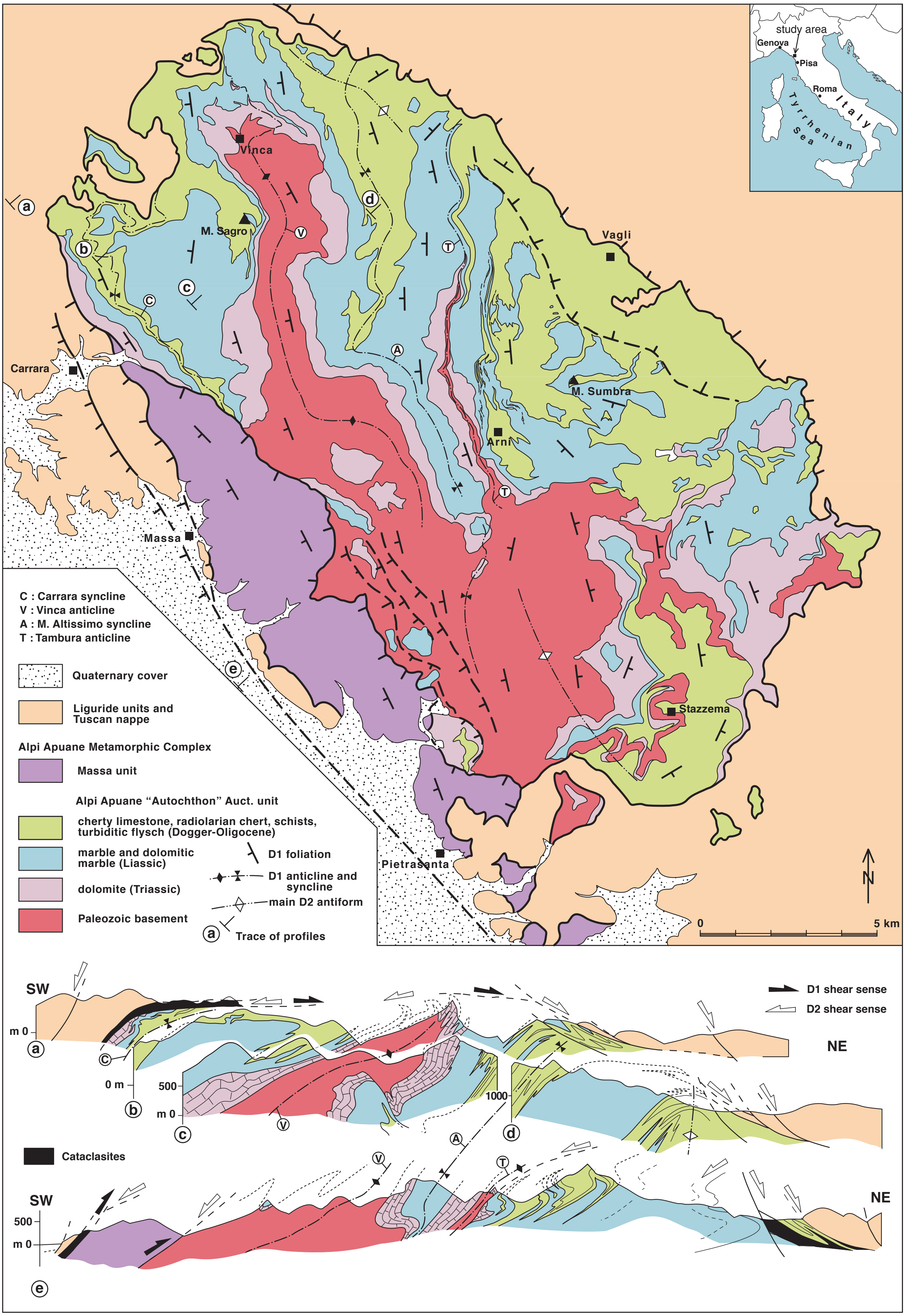


Fig. 7 – Geological sketch map of the Alpi Apuane area.

Fig. 8 – D1 folds in marbles, Carrara, Alpi Apuane.

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" Auct. 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. 7).

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. 9b); (2) "antiformal stack phase" in which further shortening and a crustal scale duplex are realized (Fig. 9b). The development of D1 structures is strongly controlled by the original paleotectonic setting and its lateral heterogeneities.

2.3.2 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. 10).

Late stage 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;

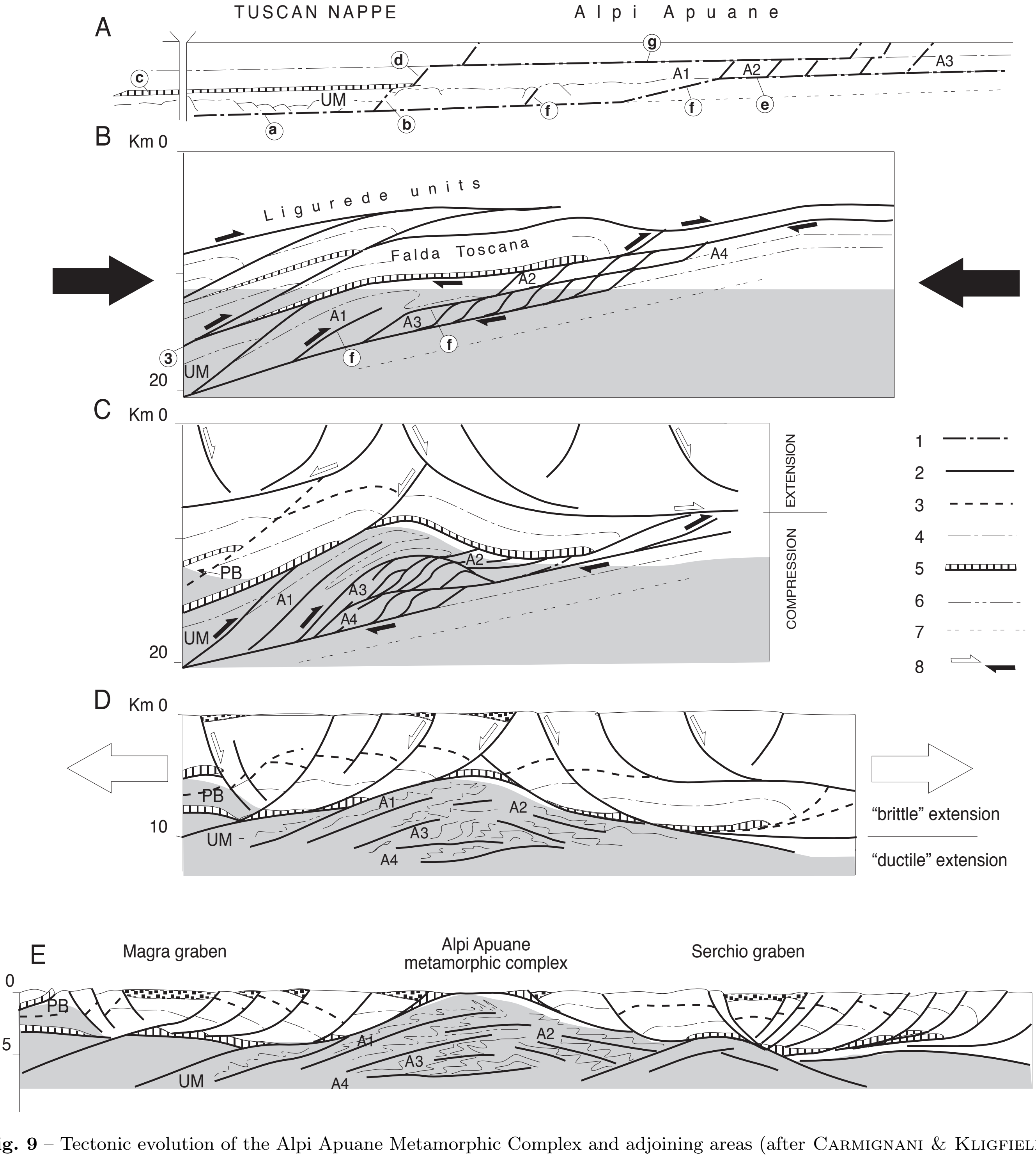


Fig. 9 – Tectonic evolution of the Alpi Apuane Metamorphic Complex and adjoining areas (after Carmignani & Kligfield, 1990, modified). (a) Pre-collisional geometry showing restored state traces of principal thrust faults and ramp-flat geometry. (b) Development of Alpi Apuane duplex structure. Metamorphic 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.

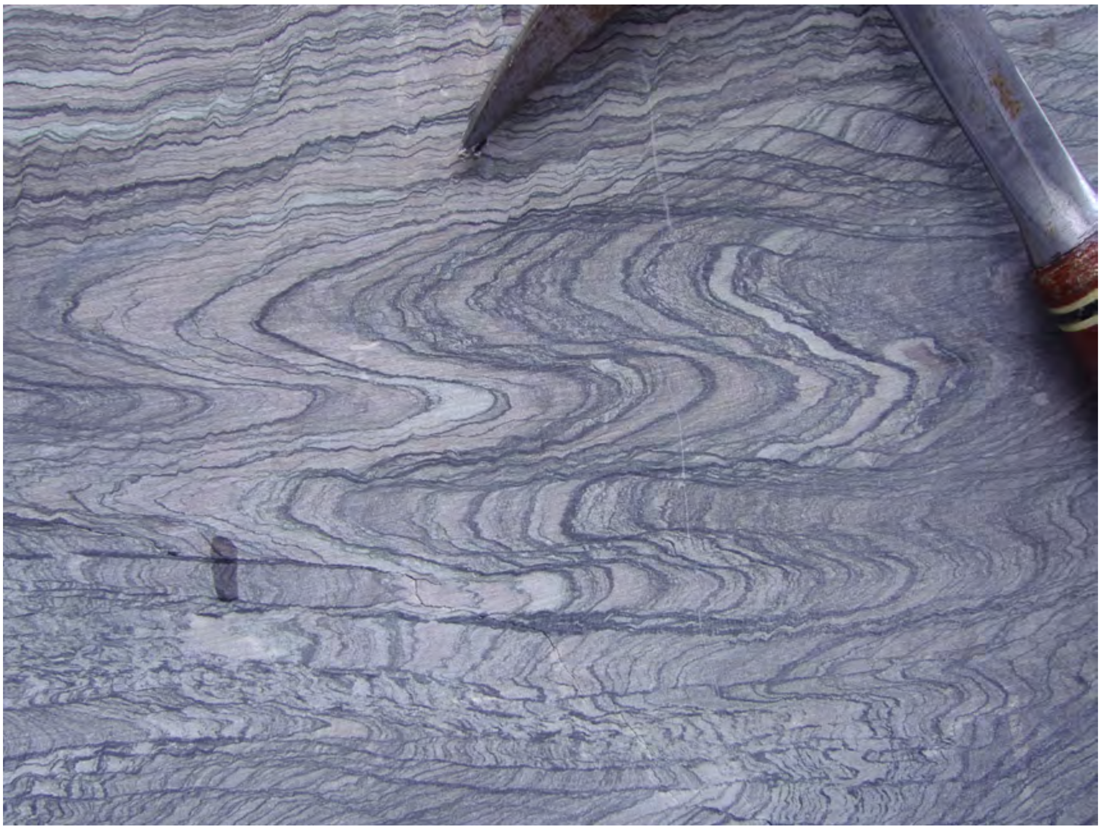


Fig. 10 – D2 folds in Cretaceous calcschists, Valle Turrite, Alpi Apuane)

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 born 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.

2.3.3 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.

2.3.4 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 northeast 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:
- it is an almost pure calcite marble;
- it shows a nearly homogenous fabric, with no or weak grain-shape or crystallographic preferred orientation;
- 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. 11). 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. 12 and Fig. 13):

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. 14):
- static recrystallization (type A microfabric);
- dynamic recrystallization (type B microfabric, further subdivided into two types B1 and B2);
- 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. 15a), 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

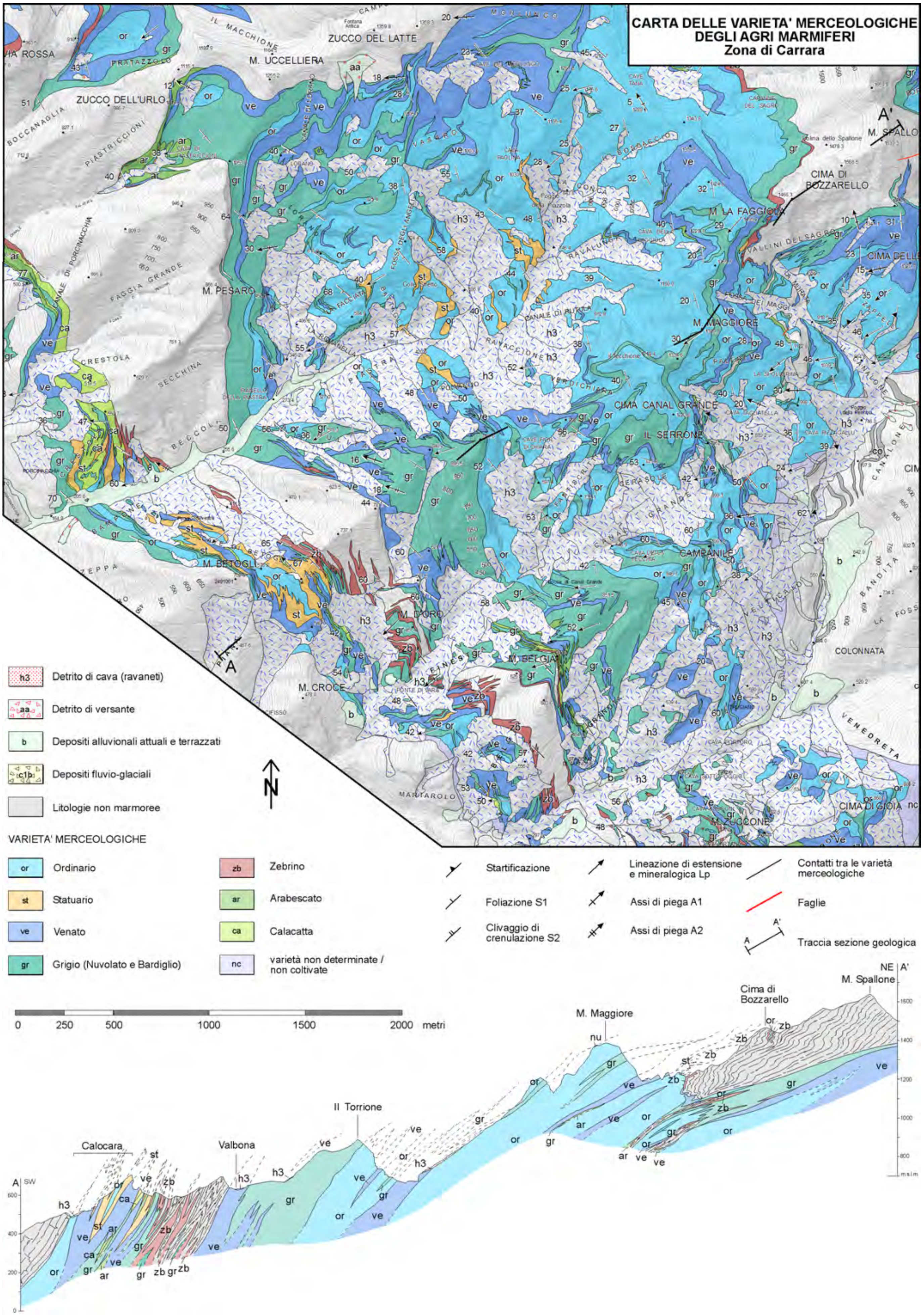


Fig. 11 – Map of marble types in the area north of Carrara.

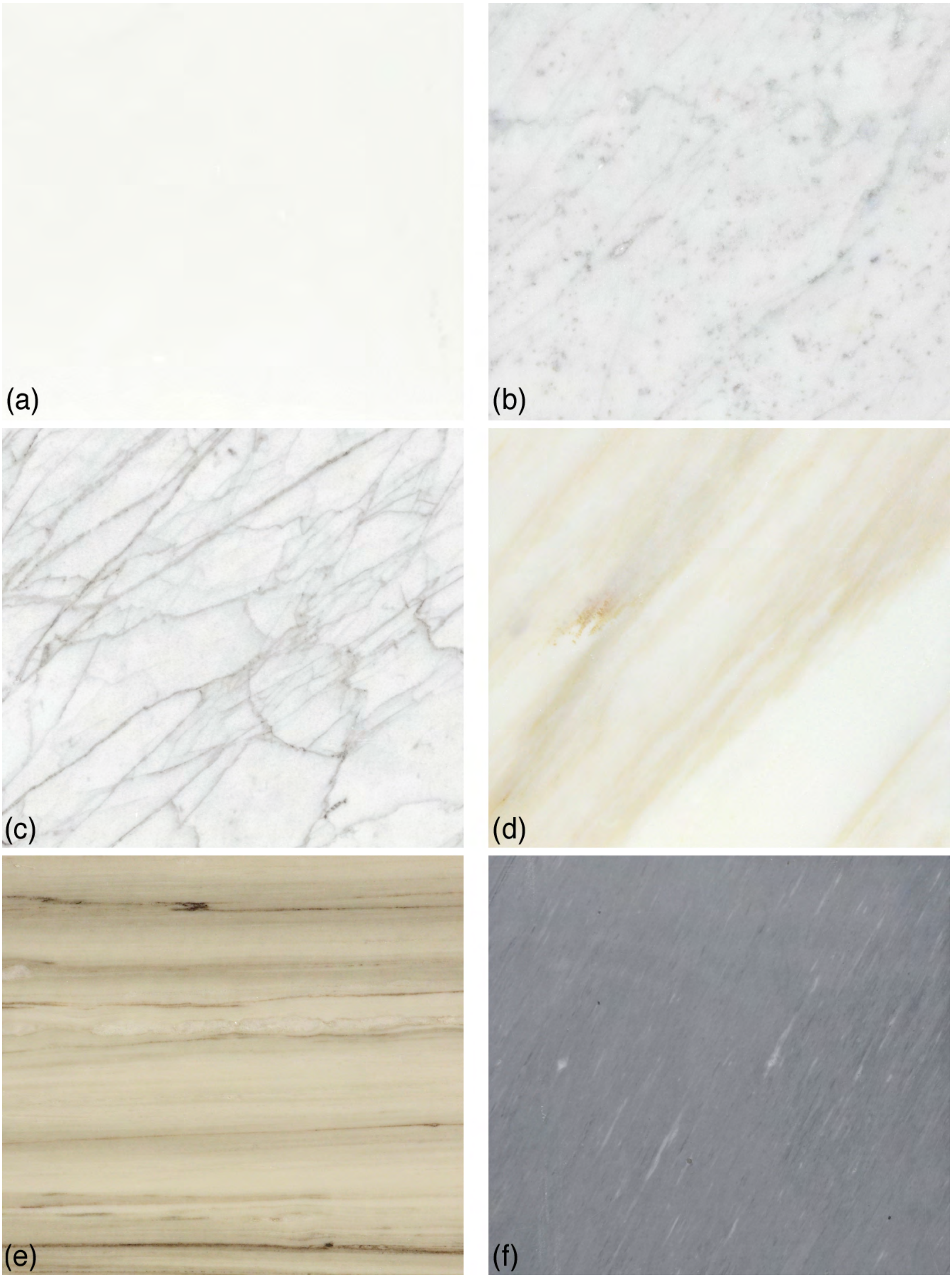


Fig. 12 – Some marble types from the Alpi Apuane: (a) “Statuario”. (b) “Bianco. (c) “Venato”. (d) “Calacatta”. (e) “Zebrino”. (f) “Bardiglio”.

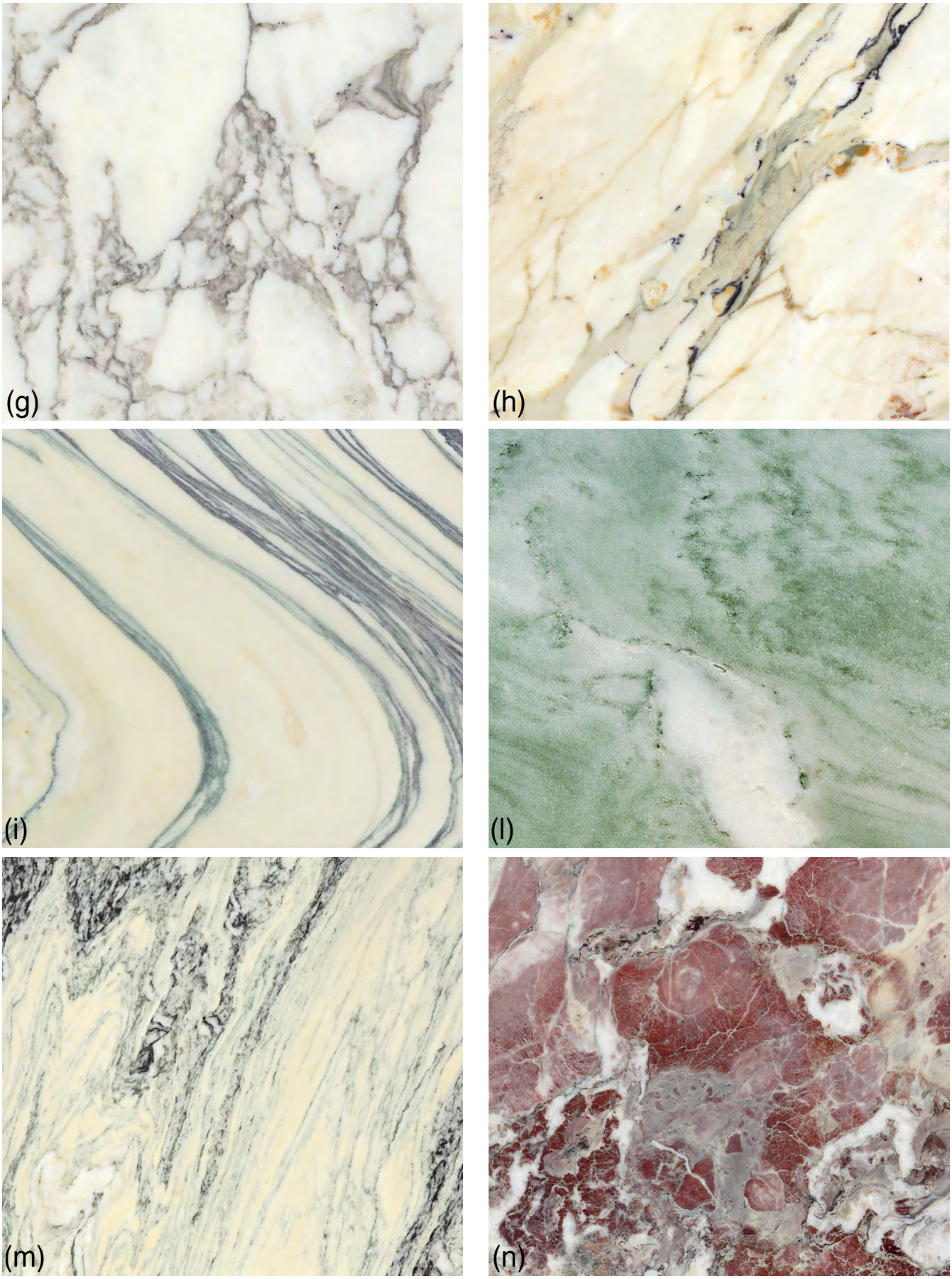


Fig. 13 – Some marble types from the Alpi Apuane: (g) “Arabescato”. (h) “Breccia Capraia”. (i) “Fantastico”. (l) “Cipollino”. (m) “Cremo”. (n) “Fior di Pesco”.

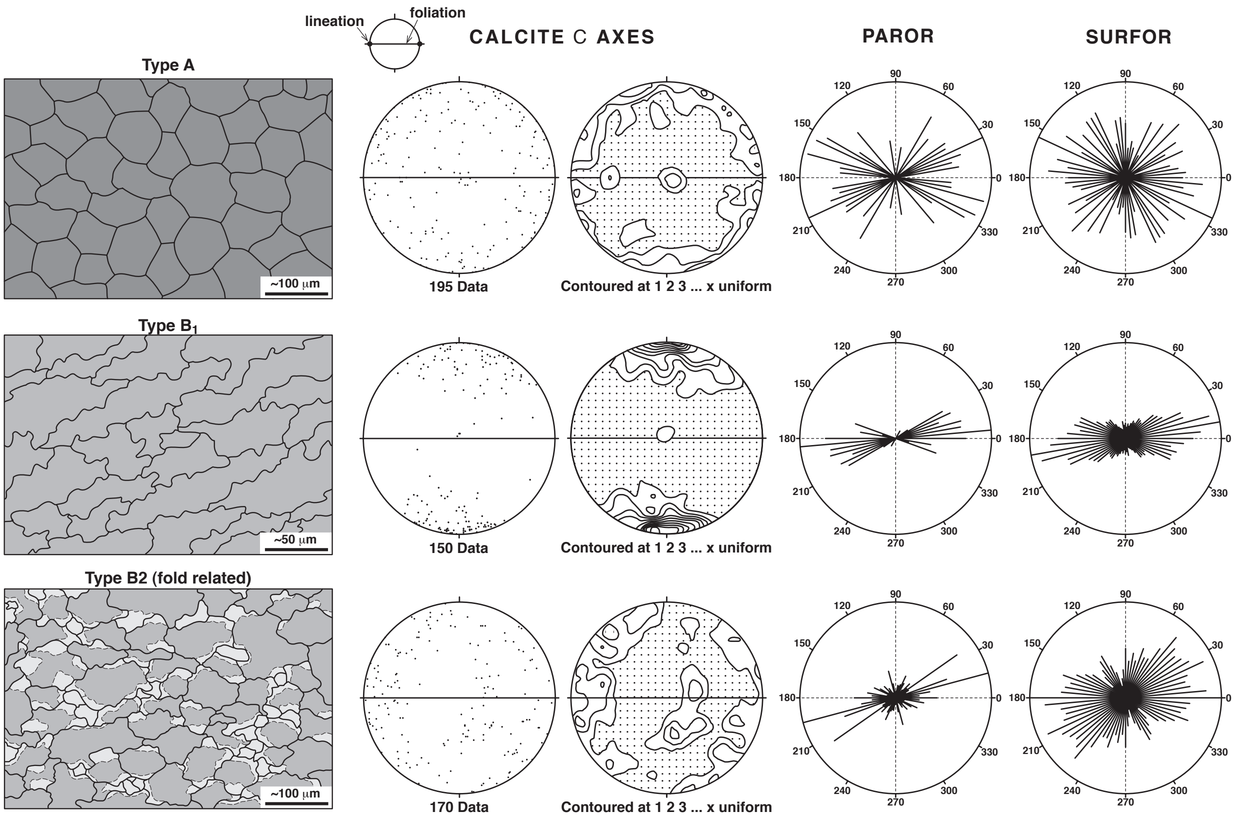


Fig. 14 – Line drawing of microstructures, c-axis orientation (from universal stage measurements) and results of PAROR and SURFOR analysis for calcite microfabric of type-A and type-B. Number of grains analysed with PAROR and SURFOR routines is more than 200 (from Molli *et alii*, 2000a).

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.

3.1.2 Dynamically recrystallized microfabrics (type-B microfabrics)

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

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

Fig. 14 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. 16a), 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,

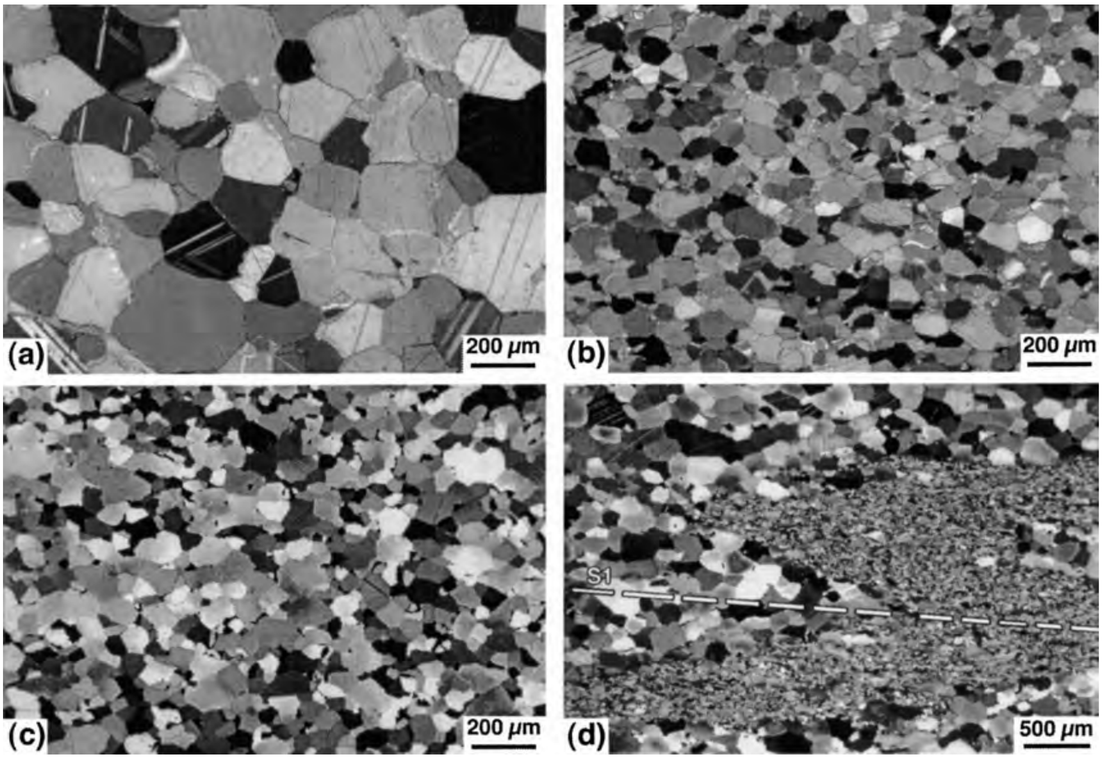


Fig. 15 – Annealed microstructures in Alpi Apuane marbles: (a) Sample 34 (western Alpi Apuane). (b) Sample 39. (c) Sample 180 (eastern Alpi Apuane). (d) D1 fold overgrown by granoblastic microstructure (locality Belgia, western Alpi Apuane). The folded level, made up of fine-grained, calcite dolomite and phyllosilicates, represents a former stratigraphic layer. From Molli *et alii* (2000a).

Fig. 16b). 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. 16c), 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. 16d). 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. 16d). 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.

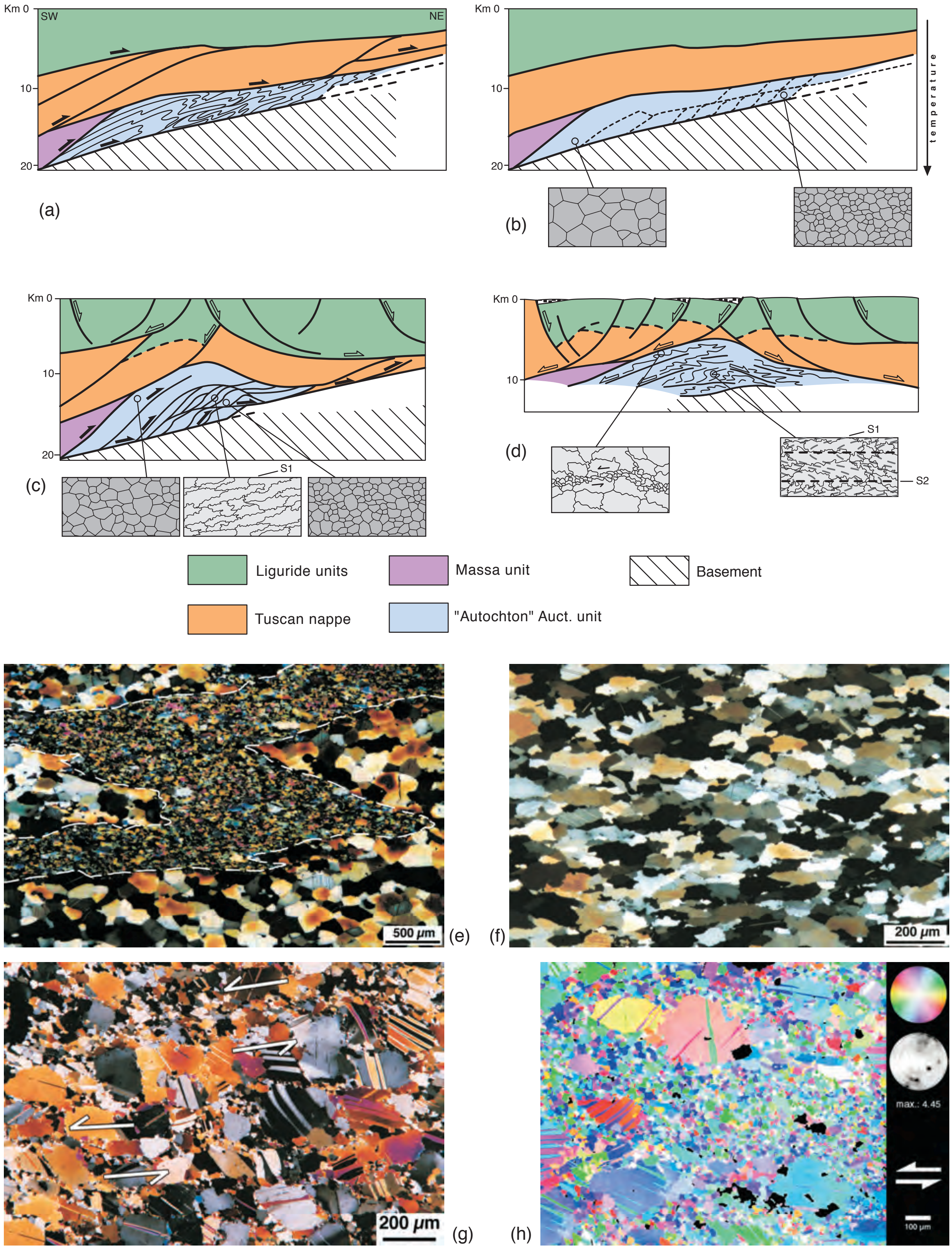


Fig. 16 – Microfabrics in Alpi Apuane marbles (after Molli *et alii*, 2000a). (a) D1 phase, with main foliation and km-scale isoclinal folds developed. (b) After D1 main folding phase annealing occurred, with static recrystalliszation and complete obliteration of earlier microfabrics. (c) During final 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

Day 1 : Carrara - Campocecina - Carrara

Itinerary

Marina di Carrara – S. Lucia – Carrara – Castelpoggio – Campocecina – M. Borla – Carrara.

Themes

The northern Alpi Apuane: relationships between the Metamorphic Complex and the overlying Tuscan Nappe north of Carrara; deformation in the metamorphic units.

Geological overview

From Marina di Carrara we drive toward Carrara, but before to reach the city of Carrara, along the road to the locality S. Lucia we can observe some lithologies of the Ligurian units, the uppermost tectonic unit of the entire Norther Apennines nappe stack. We then cross Carrara we move towards Castelpoggio and arrive at Campocecina. Along the itinerary we first cross the non-metamorphic Tuscan sequence (from the "Macigno" to the oldest formations), and then enter the metamorphic succession.

The area is basically made up of tectonic units with dips towards the Tyrrhenian Sea in this order (from the bottom), from NE to SW: the Apuan Metamorphic Complex, the Tuscan Nappe, the Canetolo Unit and the Ligurian Units.

This transect will give us a chance to correlate and compare the polyphase deformation of the Metamorphic Complex with that of the overlying Tuscan Nappe. The D1 phase is ubiquitous in the metamorphic rocks, evidenced by well developed folds at all scales and in their pervasive axial plane schistosity. In the Tuscan Nappe instead, this phase is only evidenced by the foliation developed in very low grade metamorphic condition, which is well evident in the shaly lithologies. In both units, intersection lineations and the axes of minor folds of the D1 phase strike NW-SE with a slight NW dip; the S0/S1 relationships constantly indicate a NE facing. The late deformations instead are always clearly recognizable in both units: the S0 and S1 fold axial planes are deformed by folds with NW-SE fold axis with a slight NW dip, and with subhorizontal axial planes.

In the area the Castelpoggio Fold is the major late ductile structure (D2) in the Tuscan Nappe: it is a SW facing overturned fold and deforms all the the Upper Triassic - Eocene formations.

Stop 1.1

Locality: S. Lucia, W of Carrara.
Topics: Ligurian units.

Along the road to S. Lucia we can observe the Ottone Flysch (also known in the local literature as "Helmintoid flysch"). Are calcareous and marly turbidites, with alternating limestones, marly limestones, marls and shales. Thickness of this lithostratigraphic units in the area is about 300 m. Age is Upper Cretaceous (Upper Campanian-Maastrichtian). Elter & Marroni (1991); Marroni *et alii* (2001) infer a deposition in an abissal plain nearby an accretionary wedge (Fig. 20).

The Ligurian units represents the uppermost unit of the Northern Apennines nappe stack (Fig. 4), rocks are affected only by very low grade metamorphism or are not metamorphic. These rocks show evidences of Cretaceous deformation (cleavage formation, regional km-scale folds) linked with Alpine Tethys subduction (Fig. 2).

Stop 1.2

Locality: Castelpoggio.
Topics: Calcari ad Angulata formation.

In this Stop the Calcari ad Angulata formation outcrops. This formation belongs to the Tuscan Nappe tectonic unit, of the Tuscan Succession. Are exposed limestones and marly limestones interbedded with yellowish marls. The limestones are slightly folded and a normal fault cuts the bedding in the road cut.

Stop 1.3

Locality: La Maestà.
Topics: Stratigraphy and deformation in the Tuscan Nappe.

In this area, where the more pelitic formations of the Tuscan Nappe sequence crop out, the interference among structural elements of the NE-facing compressional phase and of the SW-facing extensional phase is evident. In particular, in the Scaglia Fm. along the road we see examples of S2-S1-S0 interference, with reciprocal attitude relationships as outlined in Fig. 21.

Taking into account that the stratigraphic sequence is normal, the S0-S1 angular relationships indicates

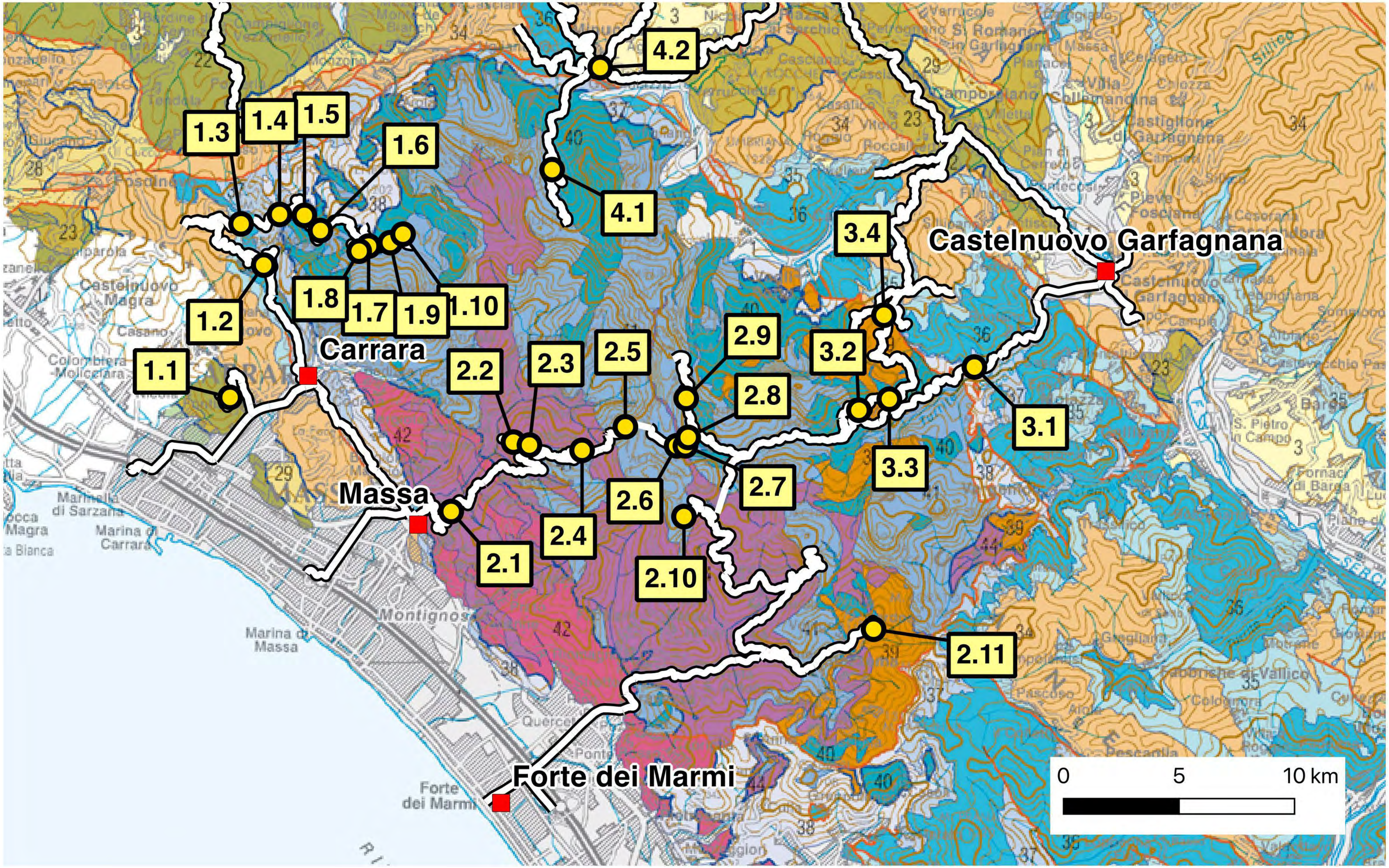


Fig. 17 – Stops during the excursion. Geological map: CARMIGNANI *et alii* (2013).

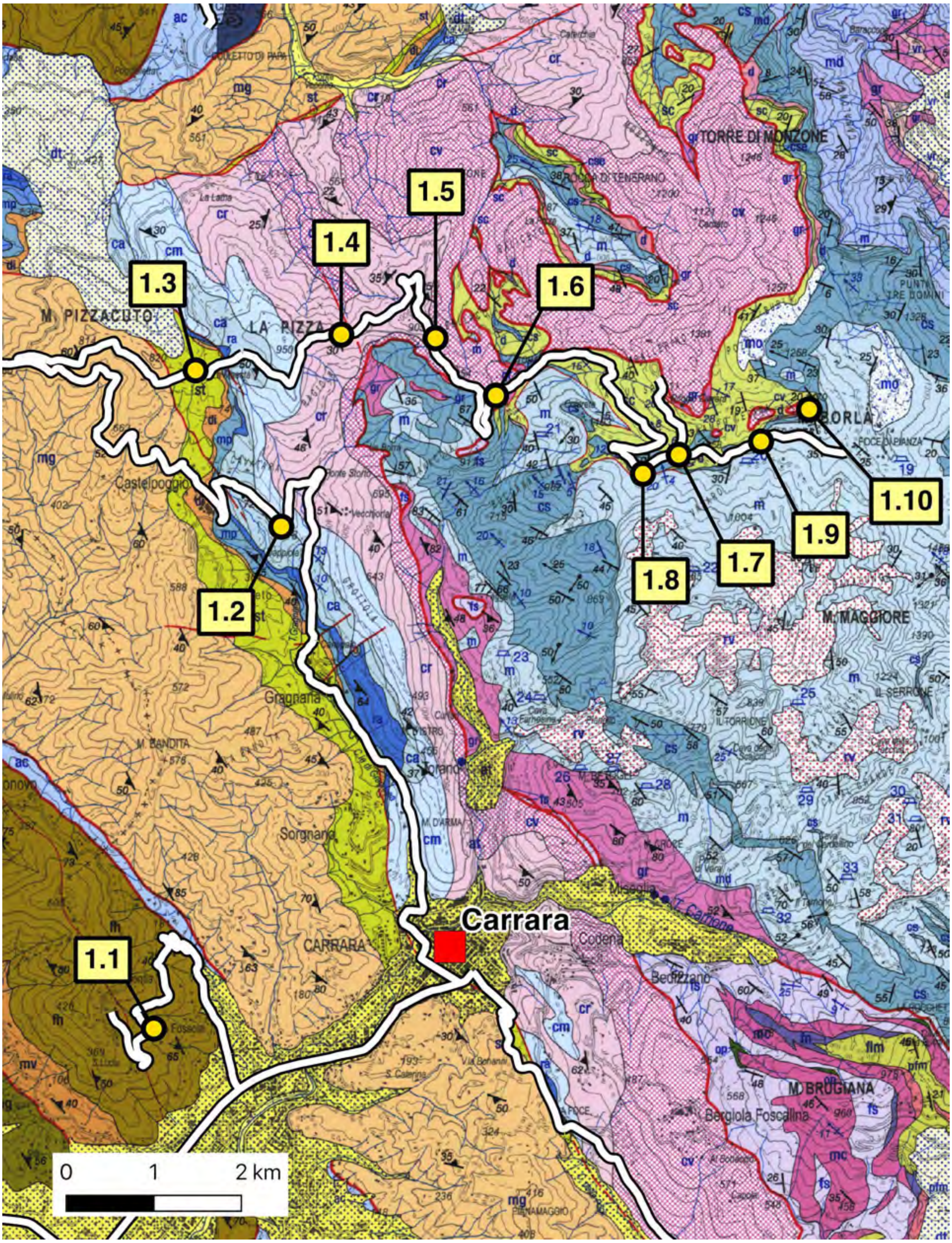


Fig. 18 – Stops during the first day of excursion. Geological map: Carmignani *et alii* (2000).

Fig. 19 – Legend for the geological map of Fig. 18, by Carmignani *et alii* (2000).

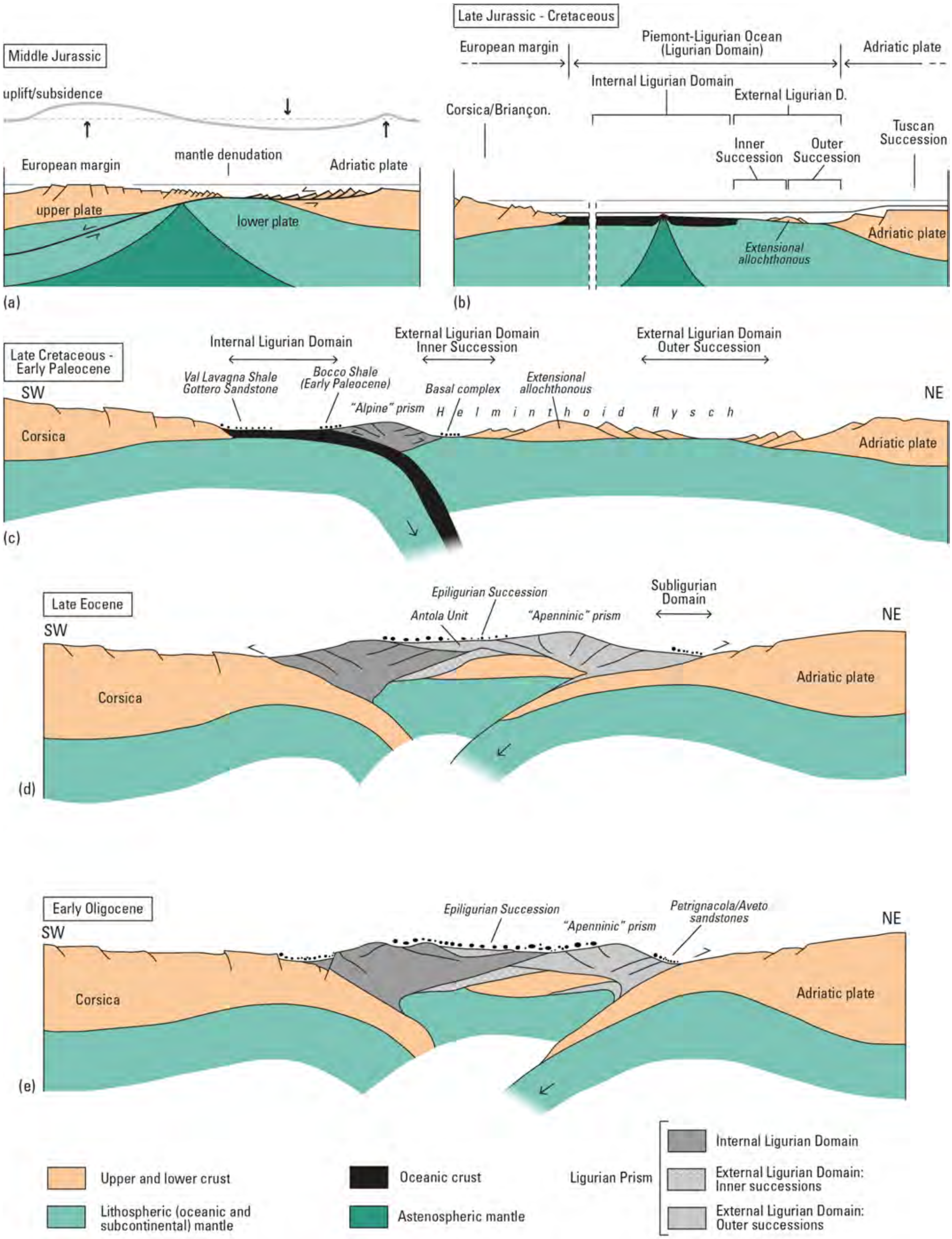


Fig. 20 – (a) Mode of asymmetrical extension of continental crust; based on Wernicke (1985) and Lemoine *et alii* (1987) models. (b) Paleogeography of the Piemont-Ligurian ocean and adjoining areas at the Jurassic-Lower Cretaceous. (c), (d), (e) Reconstruction of the geodynamic setting and evolution for Late Cretaceous (Campanian-Maastrichtian), late Eocene and early Oligocene of the Ligurian Units of the Northern Apennines, after Marroni *et alii* (2010), modified.

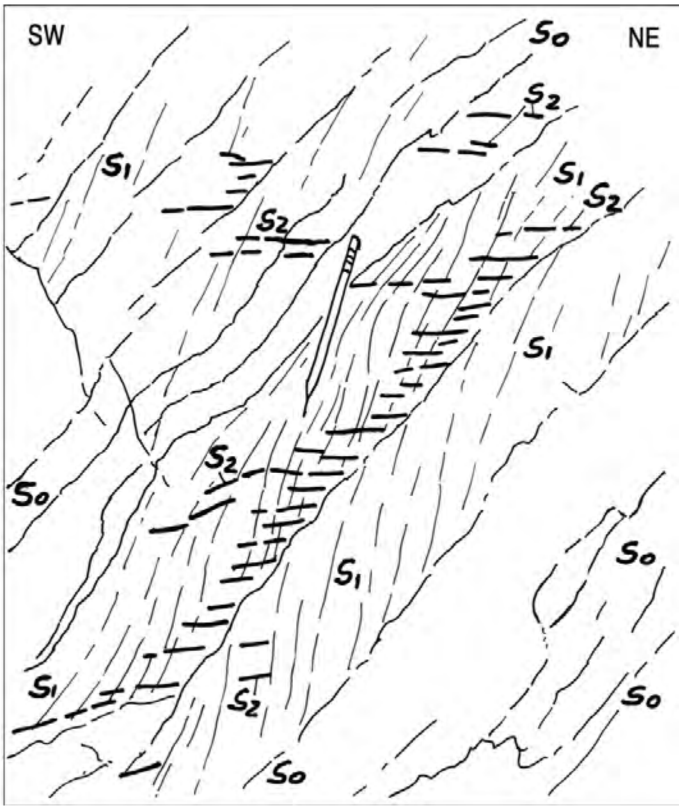


Fig. 21 – Tuscan Nappe (Scaglia Fm.) in locality La Maestà: S0, S1 and S2 interference in the road cut at La Maestà. S0-S1 relationships indicate a top- NE facing for D1 fold, S0-S2 relationships indicate top-SW facing for D2 fold.

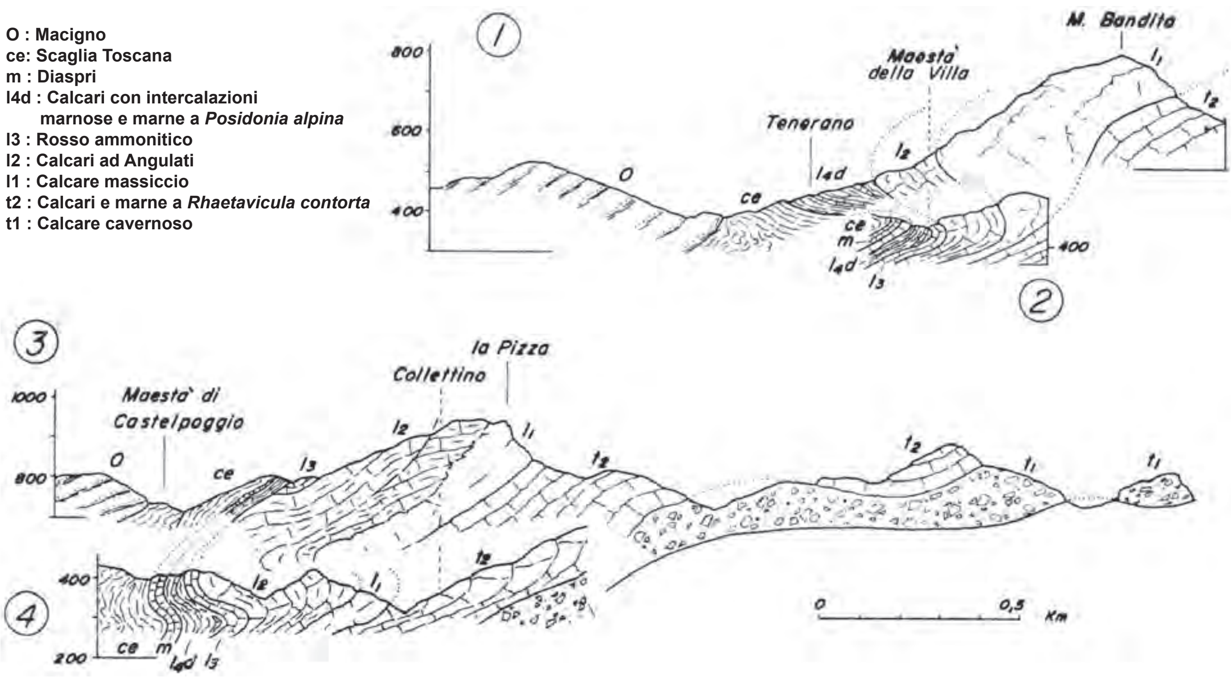


Fig. 22 – Geological cross section in the Castelpoggio area, from Decandia *et alii* (1968).

the NE facing direction. These angular relationships are maintained in all of the Tuscan Nappe formations in the Carrara area, and as further confirmation of the SW-to-NE emplacement of the Tuscan Nappe, the same relationships are recognizable in the eastern flank of the Metamorphic Complex (Vagli, etc.). Usually S1 dips to the W with respect to the S0: it is pervasive in the more pelitic levels where it forms small angles with the bedding, while in the more competent levels it is more widely spaced and the angle with the bedding increases.The D2 phase schistosity is given by spaced cleavage in the axial planes of local open folds which deform S0 bedding and S1 foliation; the cleavage planes are subhorizontal and this attitude is retained in all of the Carrara area.

The S2 cleavage is the axial plane foliation of the large reclined Castelpoggio fold (Fig. 22). In the western part of the Alpi Apuane this is the best example of a ductile structure linked with top-W extensional shear zones.

Stop 1.4

Locality: La Pizza.

Topics: Calcari a Rhaetavicula contorta *formation.*

The formation is composed by well bedded limestones and marly limestones of black and dark gray color. These rocks are deposited in a subtidal carbonate environment, anoxic or poorly oxygenated. Age is Triassic by the distinctive bivalve species *Rhaetavicula contorta*.

Stop 1.5

Locality: La Gabellaccia.

Topics: Tectonic contact between the Metamorphic complex and the Tuscan Nappe.

The Tuscan Nappe is separated from the Metamorphic Complex by polygenic breccia of variable thickness which contain clasts belonging to the formations of both tectonic units. Among these, clasts and blocks of dolomite and dolomitic limestone, strongly fracturacted, are often abundant. We interpret this as a tectonic breccia (cataclasite).

There has been much debate over the years on the geological significance of this breccia, which is everywhere at the basis of the Tuscan Nappe. There are basically two divergent opinions regarding the origin of this breccia:

– the breccia is of sedimentary origin, marine of Tertiary age (Dallan Nardi & Nardi, 1973; Dallan Nardi, 1979; Sani, 1985) and was deposited over a substratum made of the Metamorphic Complex, already metamorphosed and polydeformed. The Tuscan Nappe was later on thrust on on this breccia;
– the breccia has a karst origin, evidenced by data on oxygen isotope ratios obtained from the breccia matrix, which indicates a continental environment (Cerrina Feroni *et alii*, 1976);
– it is a cataclasite tectonically developed at the base of the Tuscan Nappe, mainly at the expense of the Triassic formations, during both the D1 and D2 phases.

The diverging interpretations for the origin of this rock are surely due to its complex history. We interpret this a cataclasite, developed mainly at expenses of the Triassic dolomites and limestones of the Tuscan nappe. The cataclasite acted as a detachment level during top-NE nappe emplacement and during nappe uplift and exhumation. This can explain presence of clasts in the cataclasite with both D1 and D2 folds.

Stop 1.6

Locality: Capanne Ferrari.

Topics: Calcare Cavernoso cataclasite and tectonic contact with the metamorphic unit.

At this stop we can first study the structure of the Calcare Cavernoso formation and then the underlying metamorphic rocks.

The Calcare Cavernoso fm. is here represented by a typical a cataclasite with carbonate clasts mostly from the Calcare a *Rhaetavicula contorta* fm. and subordinately from the Calcare Massiccio fm..

Walking along the road we cross the tectonic contact between the Tuscan Nappe (above) and the "Autochthon" *Auctt.* unit (below).

Stop 1.7

Locality: Piazzale dell'Uccelliera.

Topics: Panoramic view of the Carrara syncline and of the marble quarries in the Carrara area.

We reach the Uccelliera locality (Fig. 23) and we park here.

From here it is possible to have a panoramic view of the marble quarries of the Carrara area, from where the well known Carrara marble is quarried. In this and in the following stops we are now in the metamorphic unit of the Alpi Apuane ("Autochthon" unit).

We walk along the road to the following stop.

Stop 1.8

Locality: M. Uccelliera.

Topics: D1 and D2 folding in metamorphic cherty limestones.

In a road cut metamorphic cherty limestones outcrops, just south of M. Uccelliera (Fig. 23). Here isoclinal D1 folds can be observed, refolded by D2 open

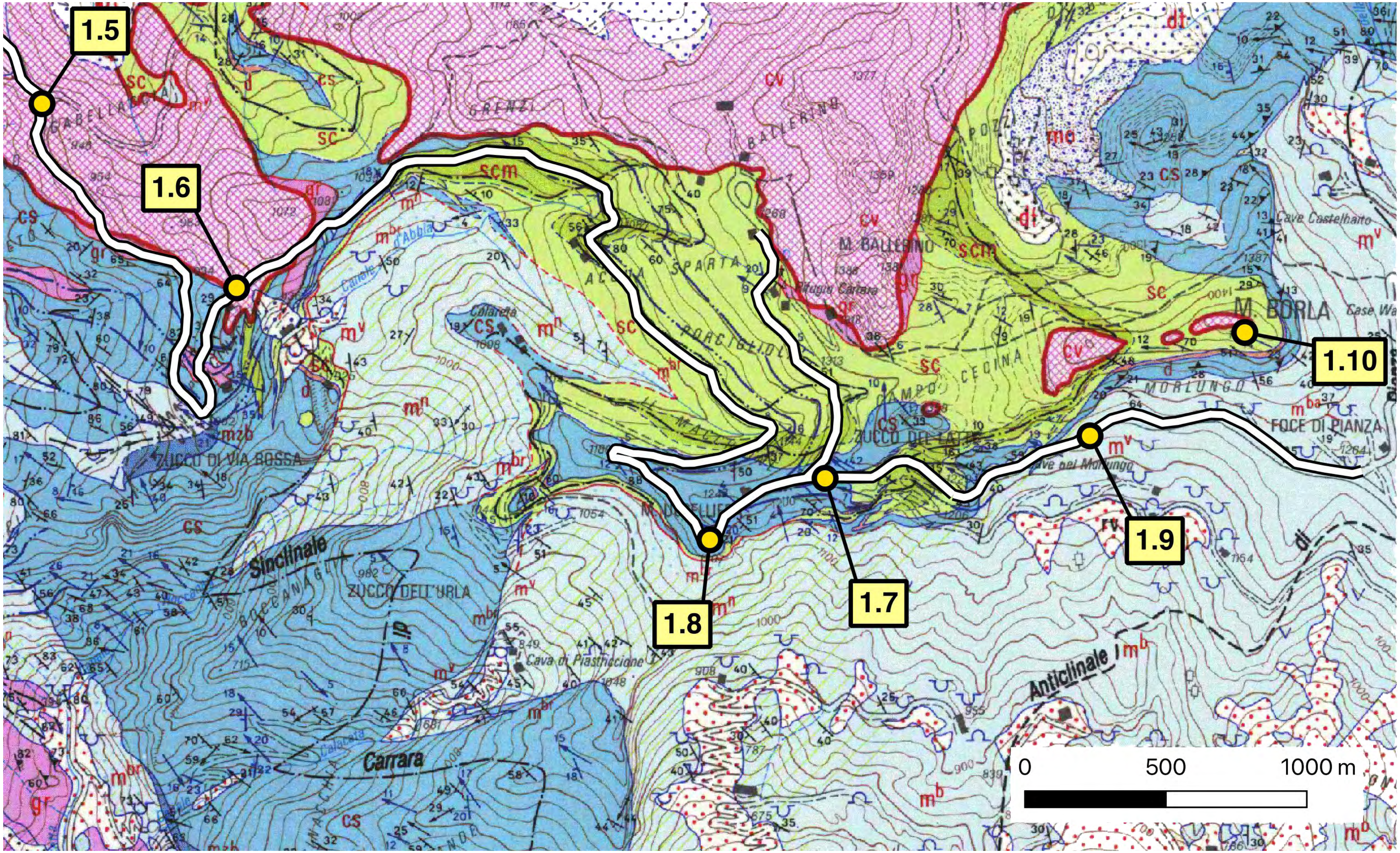


Fig. 23 – Stops in the Campocecina-M.Borla area. Geological Map: CARMIGNANI (1985); see Fig. 19 for geological map legend.

folds. Chert lenses are strongly elongated during D1 deformation and a widespread L1 stretching lineation developed.

We walk back to the previous stop and continue toward Foce di Pianza locality.

Stop 1.9

Locality: M. Uccelliera - Foce di Pianza road.
Topics: Interference between NE-facing structures of the D1 phase and SW-facing D2 folding.

Along the road outcrop formations in the core of the Carrara Syncline (Fig. 7, Fig. 23), as:

- *Marble*: white metalimestones and/or veined with variously-sized breccia clasts; right upstream of the Foce di Pianza quarry, there is a fossiliferous area with ammonoids (rare) and lamellibranch shells, concentrated in some "lumachelle" beds or dispersed in banks containing pisolite and oncolite.
- *Cherty limestone*: metalimestones with layers and nodules of whitish quartzite. The metalimestone generally derives from calcilutite, but some containing a pelitic-siltitic fraction are also found. The lower portion of the formation contains pyritized ammonoids. The very thick level which stands out along the southern flank of the ridge, known as the "Morlungo bank", is a metarudite with predominant quartzite clasts. In this area it represents an example of intraformational resediments of variable grainsize, produced by erosional mechanisms connected to the synsedimentary block-faulting tectonics during the Early Liassic.
- *Chert*: it is represented by a few meters of thin, centimetric layers of greenish and/or whitish quartzite, separated by millimetric levels of silty phyllite rich in chlorite.
- *Schists* ("Scisti sericitici") and Nummulite limestone *Auctt.* : these are green, to violet-grey, silty phyllite; in the upper portion they contain levels of white marble and metasandstone, and polygenic breccia.

The Carrara Syncline is a large-scale NE-facing fold of the D1 phase with an Apennine-trending axis and a SW-dipping axial plane; it has parasitic folds on both limbs. Along the roadcut at Foce di Pianza, we observe two of these parasitic folds (a Marble-cored anticline and, below, a syncline with a Cherty Limestone core) on the normal limb of the main structure. These parasitic folds are refolded by a D2 SW-facing structure of some hundreds of meters in size, the Morlungo antiform and synform, again with axes with an Apennine direction and with horizontal to slightly NE-dipping axial planes. The interference of these two phases creates a type-3 pattern. Along the roadcut we can see different varieties of Marble ("ordinary white", "veined", and to a lesser extent "bardiglio" and "bardiglietto"), including deformed breccia which in the Carrara area usually are located the upper part of the marble formation, providing good commercial marble varieties ("arabescato", "calacatta", etc.).

We walk to the next stop.

Stop 1.10

Locality: M. Borla.
Topics: Cataclasite/metamorphic rock relationships along the path to M. Borla; panorama of the large scale structure of the norther Alpi Apuane.

From the previous stop we walk along a path to the M. Borla. Along the path we will stop at the "Rifugio Carrara".

We cross some metamorphic formations (schists, cherty limestones) strongly folded. Along the M. Borla crest we can see Calcare Cavernoso (cataclasite) klippen, similar what we have seen before at the Gabellaccia locality. Again these klippen represent the base of the Tuscan Nappe, which tectonically cuts the overturned limb of the Carrara syncline.

From M. Borla we will have a panoramic view of the main anticlines and synclines of the northern Alpi Apuane, of the main ridge of the Northern Apennines and of the main recent extensional basins of Tuscany along the Ligurian sea coastline.

We drive back to Carrara and north-east of Carrara we will visit a large underground quarry.

Day 2 : Massa - Arni - Seravezza - Massa

Itinerary

Massa – Pian della Fioba – Arni – Seravezza – Massa.

Themes

Large scale, folded structures in the central Alpi Apuane; superposition of D1 and D2 tectonic features.

Geological overview

During the second day of excursion we will cross the central part of the Alpi Apuane. Along the itinerary we will observe the km-scale antiform and synform developed during D1 deformation (Vinca anticline, Orto di Donna syncline, M. Altissimo syncline, M. Tambura anticline), and D2 folding of earlier structures. This will be evident in the panoramic view of the Arni valley.

Later on we will visit a marble quarry (Cervaiole) and a Pseudomacigno quarry (Cardoso). In both quarries exploitation reveal beautiful D1 folding structure, parasitic minor folds and faulting.

All the observations testify the tectonic evolution of the Alpi Apuane metamprphic Complex, with an earlier stage of shortening, metamorphism and intense internal deformation of rocks, followed by uplift and exhumation accompanied by folding and faulting.

Stop 2.1

Locality: San Carlo Terme.
Topics: Panoramic view of nappe stack.

In this stop a panoramic view of the western side of the Alpi Apuane region can be observed from La Spezia and the Punta Bianca promontories up to the relief of the Alpi Apuane (Fig. 24, Fig. 25). The stack geometry of the nappe pile from the Ligurian units to the metamorphic complex can be appreciated and discussed as well as the main neotectonic features of the region.

Stop 2.2

Locality: Antona.
Topics: Filladi inferiori formation.

In this stop outcrops the Filladi inferiori formation, the oldest formation outcropping in the Alpi Apuane and in the whole Apennines (Fig. 6). The Filladi inferiori formation belongs to the Variscan basement, in the Alpi Apuane this formation is not dated but a Lower-Middle Cambrian age is inferred based on correlation with similar succession, not metamorphic, outcropping in southern Sardinia.

The formation consists of alternating, phyllites, metasandstones and quartzites. Different generation of folding events are recognizable.

Stop 2.3

Locality: Antona.
Topics: Porfiroidi e Scisti porfirici formation.

In this stop outcrops the *Porfiroidi e Scisti porfirici* formation of the Variscan basement (Fig. 6). The formation consists of massive metamorphic volcanic rocks, likely pyroclastic rocks with acidic-intermediate composition. Quartz clasts of volcanic origin are recognizable, as altered feldspar and plagioclase. Fine grained levels (*Scisti porfirici*) are present. Inferred age is Middle Cambrian, based on correlation with similar successions in Sardinia.

Stop 2.4

Locality: Pian della Fioba.
Topics: Stratigraphic contact between Variscan basement/Mesozoic succession.

We stop in locality Pian della Fioba. The stop it is along the contact between the Paleozoic basement and the Mesozoic cover. The Paleozoic basement is here represented by Ordovician metavolcanic rocks ("Porfiroidi"), folded during D2 deformation. The overlying Mesozoic cover is represented by Triassic dolomites ("Grezzoni" Fm.), locally few dm of a transgressive conglomerate ("Formazione di Vinca") can be found (Fig. 6).

Above the Verrucano the Triassic dolomitic "Grezzoni" formation is exposed, affected by widespread jointing.

Stop 2.5

Locality: Passo del Vestito
Topics: Panoramic view toward the northern Alpi Apuane.

At this stop (Fig. 26), 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. 27, Fig. 28).

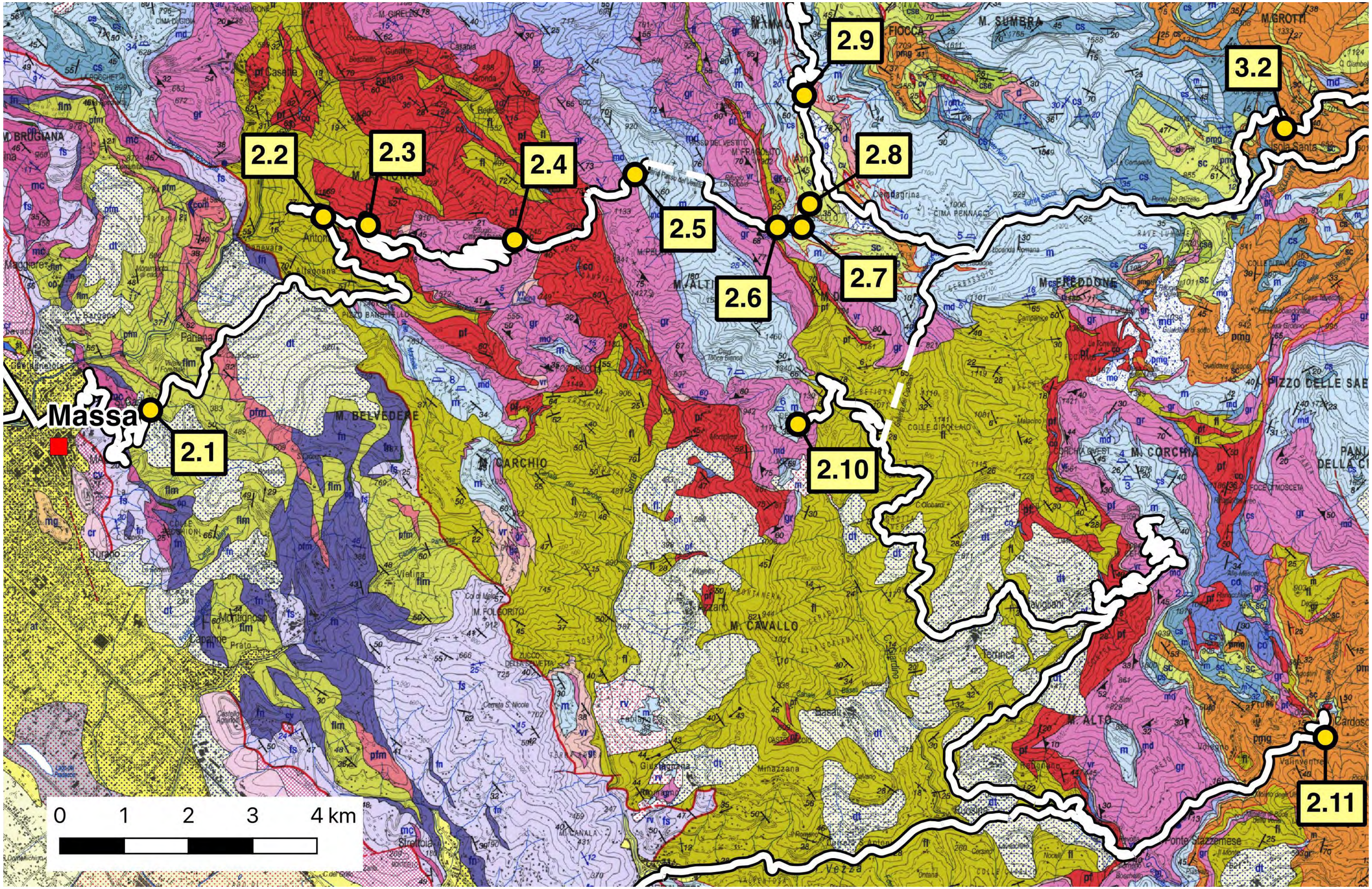


Fig. 24 – Stops during the second day of excursion. Geological map: CARMIGNANI *et alii* (2000). See Fig. 19 for geological map legend.

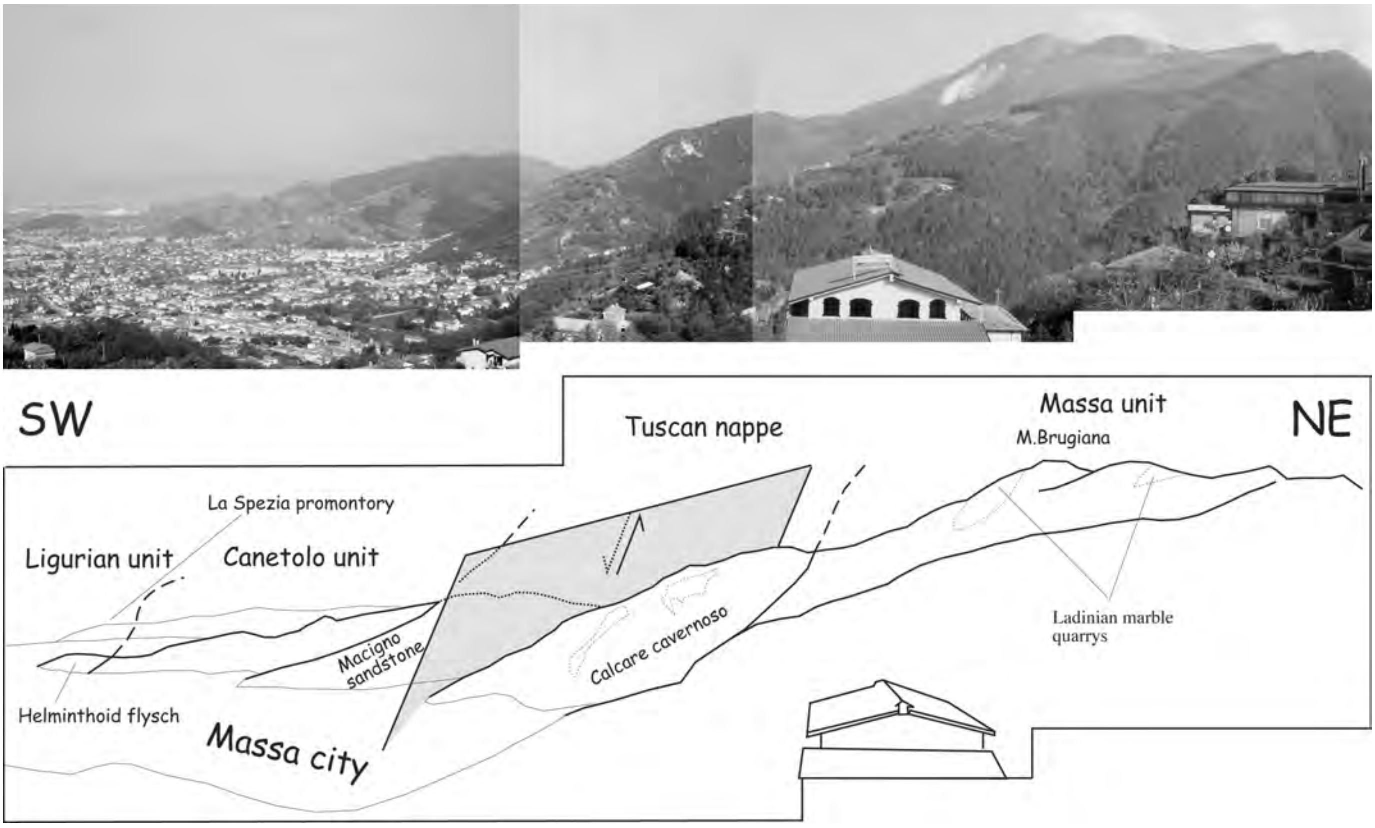


Fig. 25 – Panoramic view from San Carlo near Massa (after CARMIGNANI *et alii*, 2004).

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 calc-schist) 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. 29.

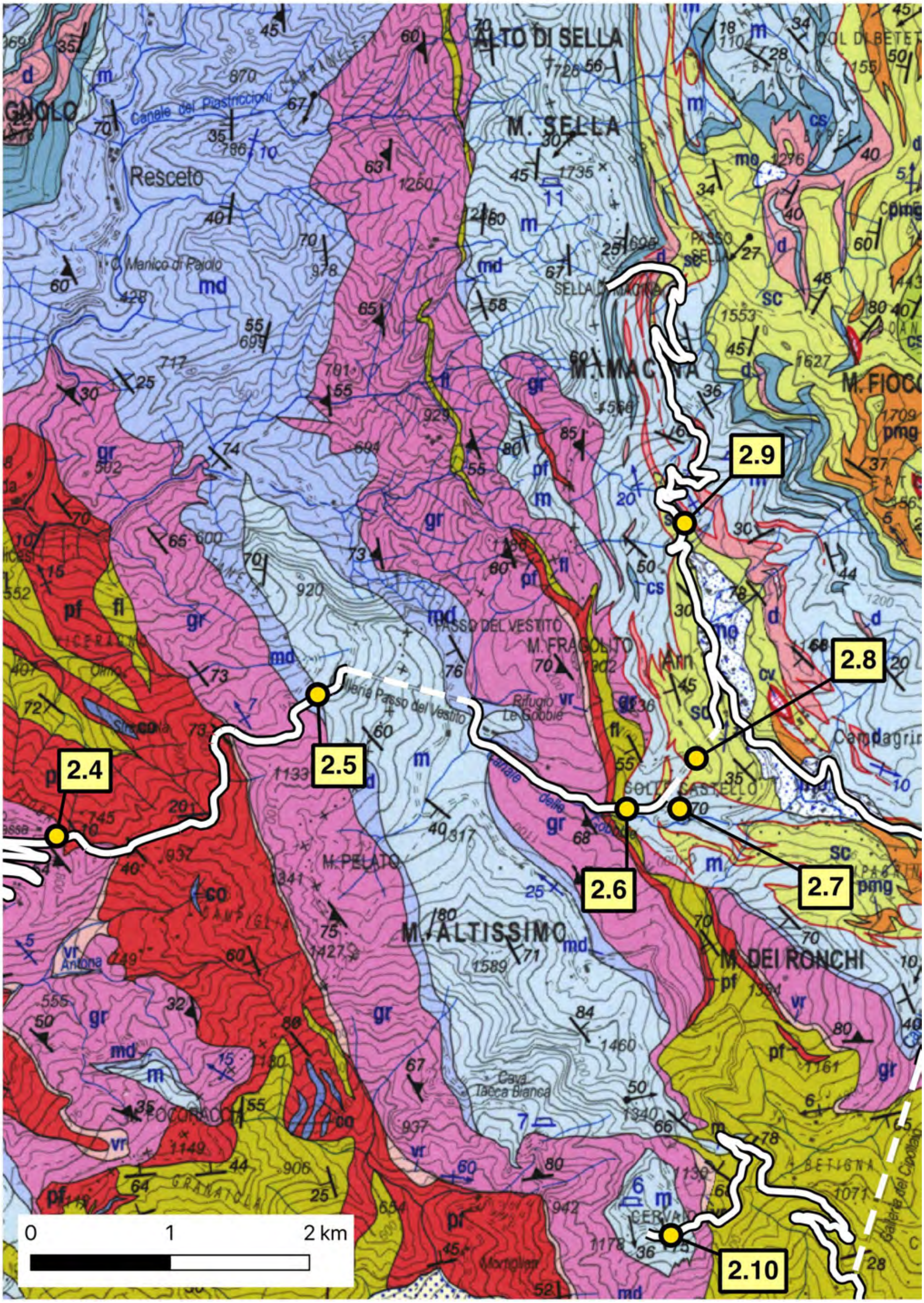


Fig. 26 – Geological map of the central Alpi Apuane, after Carmignani *et alii* (2000), see Fig. 19 for geological map legend. Stops 2.5 – 2.10.

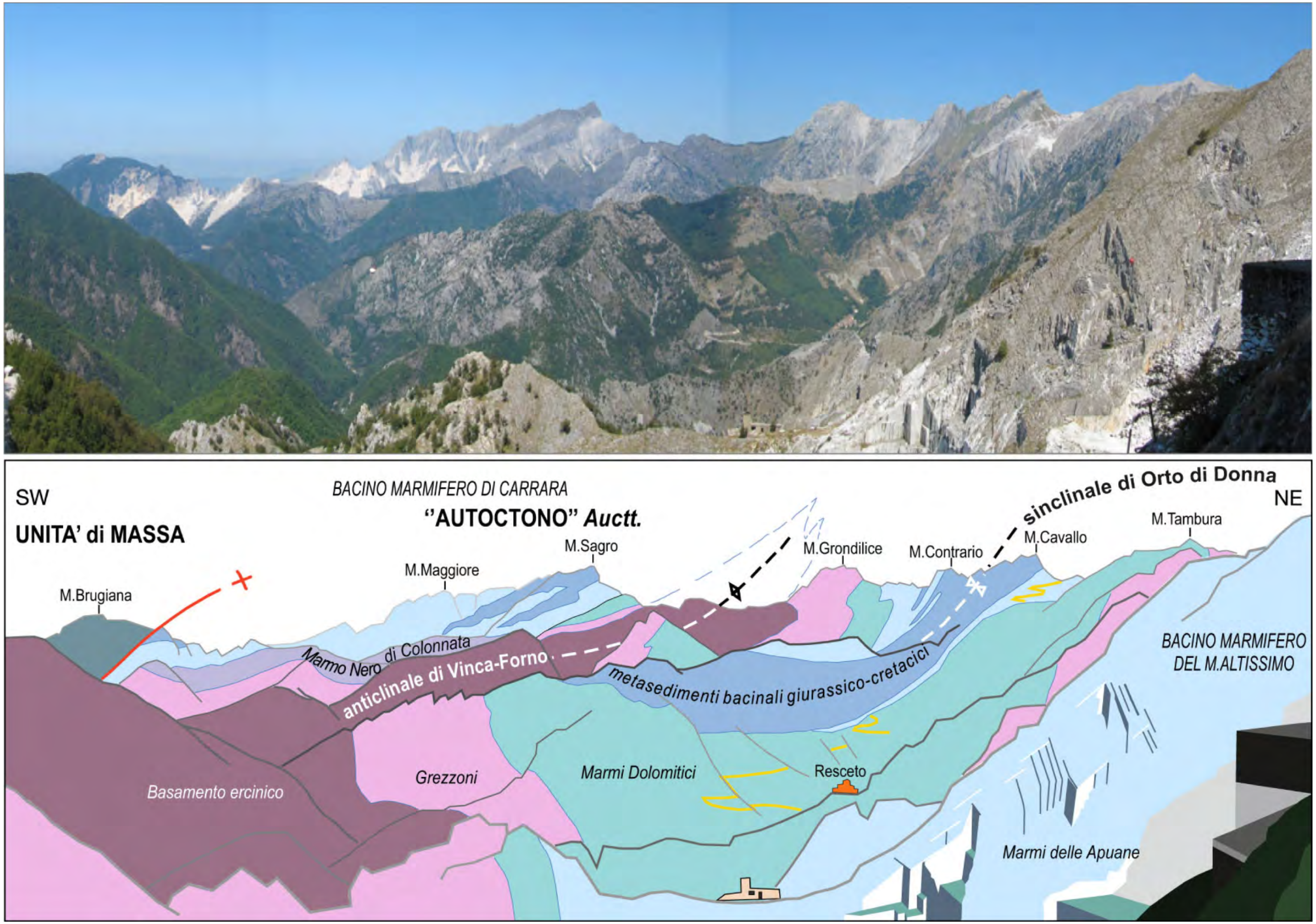


Fig. 27 – Panoramic view of the northern Alpi Apuane, from Stop 2.5, Antona-Arni road, W of the Passo del Vestito tunnel. Line Drawing by E. Patacca and P. Scandone, in Conti *et alii* (2019).

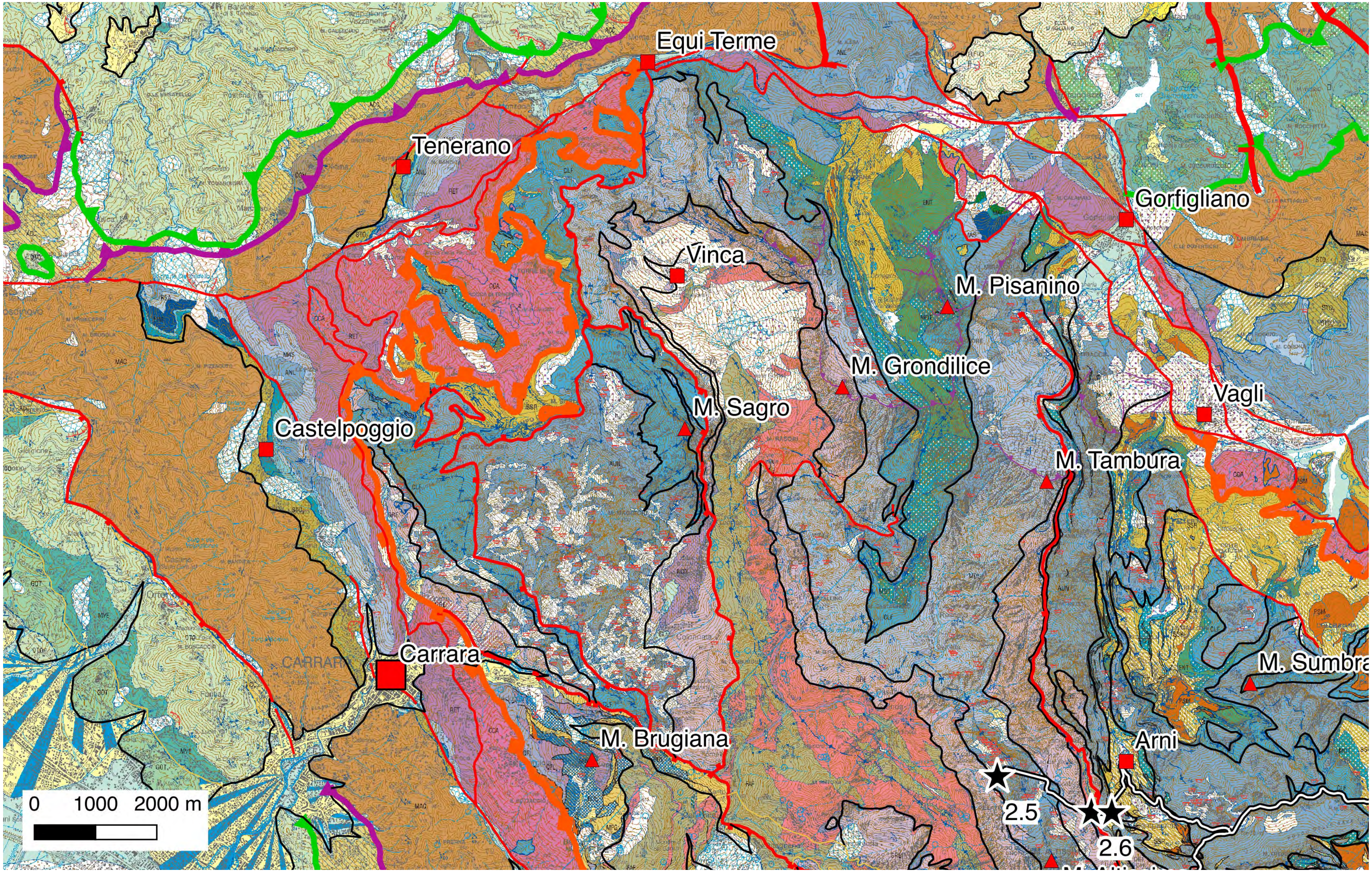


Fig. 28 – Geological map of the northern Alpi Apuane, from Conti *et alii* (2019).

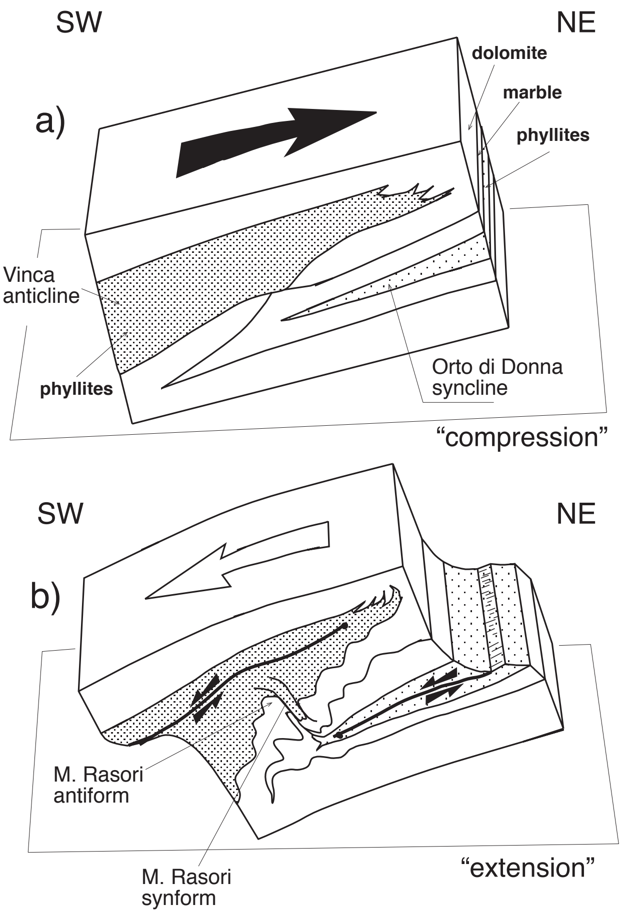


Fig. 29 – D1 and D2 deformation superposition in the Frigido valley (Stop 2.5). Late structures in the inverted limb of the D1 Vinca anticline are interpreted as "transfer folds" between two ductile shear zones.

Stop 2.6

Locality: Capanna del Pastore (Castellaccio).
Topics: Core of the D1 M. Tambura anticline.

Along the road near the Capanna del Pastore locality, the core of the D1 M. Tambura anticline crops out and the "Filladi inferiori" formation (phyllites) is here exposed (Fig. 26).

The Grezzoni formation (dolomites) of the overturned limb is reduced to a few meters of cataclastic dolomite and usually in the area the basement rocks are tectonically in contact with the marble formation. This is produced by 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 is a high angle D2 normal fault marked by non-metamorphic cataclasites.

Stop 2.7

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

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

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

Distributed and localized strain features (folds and shear zones) occurred at different stages of the tectonic evolution and may be recognized on the basis of crosscutting relationships and calcite microstructures.

Stop 2.8

Locality: Colle Castello.
Topics: Panoramic view of the natural section of the Arni valley..

From this stop we have a panoramic view of the Arni structure, discussed in more detail in Stop 2.9.

Stop 2.9

Locality: Arni.
Topics: Panoramic view of the natural section of the Arni valley.

The structure of the Arni Valley has always been important in the tectonic interpretation of the Alpi Apuane. Since the first works on Apuane tectonics (Lotti, 1881; Lotti & Zaccagna, 1881; Zaccagna, 1898) the structure of this valley has been taken as an example of the so-called "double vergence of the Apuane Alps". The Arni zone was interpreted as an overturned syncline between two isoclinal anticlines of opposite "vergence" (Fig. 30).

The attitude of the contacts in the Metamorphic Complex, dipping toward the SW on the western flank of the valley and toward NE on the eastern flank, and the repetition of the formations in both flanks, were the origins of this interpretation. In absence of the fundamental elements that emerged from the structural analyses of the last years, it was obvious to close the anticline toward the top and the syncline toward the bottom. The model was inspired by the interpretation given at that time by Sacher & Heim to the structure at the basis of the Glarus thrust (Swiss Helvetic Alps), which Lotti (1881) makes reference in the last paragraph of his first work.

A very rare case, that of the Apuane, while in Europe the recognition of the nappe structures of the Alps has swept up the autochthonist interpretations since the beginning of the last century, the "double

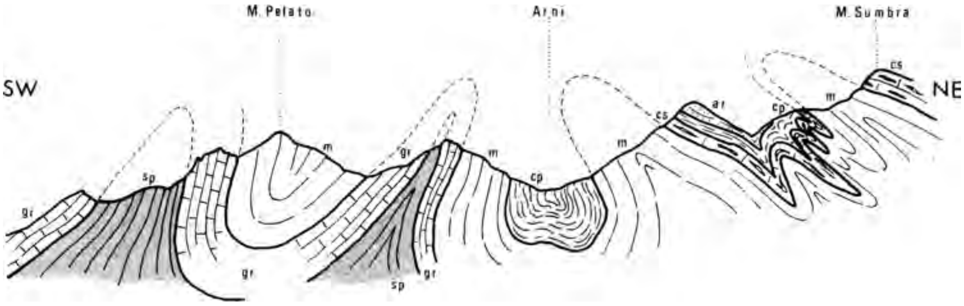


Fig. 30 – The structure of the Arni valley after Lotti LOTTI (1881). sp: Paleozoic phyllites, gr: Triassic dolomites, m: marbles, cs: certy limestones, cp: calcschists, ar: metasandstones flysch .

vergence of the Alpi Apuane" has resisted until a few years ago. Only in 1983 (CARMIGNANI & GIGLIA, 1983) the structure of the Arni valley was interpreted as interference between large late folds and isoclinal structures of a collisional phase. Restoration of this structure demonstrates the possibility that it developed within a west-dipping shear zone connected with the post-collisional extension.

The D1 structure of this area comprises two main isoclinal synclines: the Arni syncline and the M. Fiocca syncline, separated by the Passo Sella anticline. These are refolded by km-scale D2 synform and antiform (Arni synform and Arni antiform) with gently SW dipping fold axis (170/18).

The geological structure of the area is reported in Fig. 31 and Fig. 32.

As shown in cross sections of Fig. 32, the Liassic Marble in the overturned limb of the Arni syncline rest in tectonic contact directly on the Paleozoic basement (the Triassic dolomite are reduced to a few discontinuous cataclastic levels).

In detail, the D1 structure is complicated by:

- D1 folds and ductile thrusting that caused repetitions of stratigraphy;
- sheath-like geometries of the D1 folds testify by the closed form of the cores of anticlines (marble) and synclines (Pseudomacigno) and of the parallelism of the axes of minor folds and of the intersection lineations with the extension lineations.

D1 structures are deformed by two large folds that are overturned to the west (Arni Synform and Arni Antiform), which can be followed continuously from the Arnetola (Vagli) valley to the of the Arni valley and along the high valley of Turrite Secca. Between Arnetola and Arni, the axes of these D1 folds is N-S oriented and gently dipping toward the N; in the Turrite Secca valley, D1 fold axes abruptly assume an E-W orientation and dip toward the east.

These structures develop along a length of about ten km and involve a belt that reaches a maximum width of 2.5 km at M. Fiocca. Seen from the south, the structure forms a large "S" (Fig. 32), whose overturned limb crops out on the eastern side of the Arni valley and has a width measured normal to the axes of about 1 km. The kinematics of this structure is consistent with a km-scale W-dipping normal shear zone, delimited by Grezzoni of M. Tambura and whose lower limit does not crop out.

In Fig. 33 restored sections show the interference in the Arni valley, assuming that the late folds are related to a homogeneous D2 W-directed shear deformation. Removing a shear strain of $\gamma = 3$, we obtain a structure in which the S1 axial plane has a sigmoidal form consistent with a D1 top-E-directed shear. This geometry is the result from an transport inhomogeneity and from internal strain variation along a large top-E verging D1 shear zone. Inhomogeneous deformation during D1 shear seems to be confirmed also by the structural style; approaching the M. Tambura stack, the strain increases, the extension lineation on the S1 schistosity are more pronounced and associated isoclinal structures are more flattened (isoclinal structures of Passo Sella and isoclinal synclines on the eastern flank of M. Tambura: "Cintole del M. Roccandagia").

Shortly, the complex interference patter of the Arni valley can be understood in terms of:

- an inhomogeneous top-E shear deformation during D1 Fig. 33a);
- a top-W shear deformation during D2 (Fig. 33b, c, d).

We leave the Arni valley and we drive across the Cipollaio tunnel to Seravezza.

Stop 2.10

Locality: Cervaiole quarry.
Topics: Marble types and exploitation technologies.

Just after the Cipollaio tunnel we take the road to the Cervaiole quarry. If the weather conditions permit, we will have a magnificent panoramic view of the coastal plain and southeasternmost Apuane where the geology of M.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

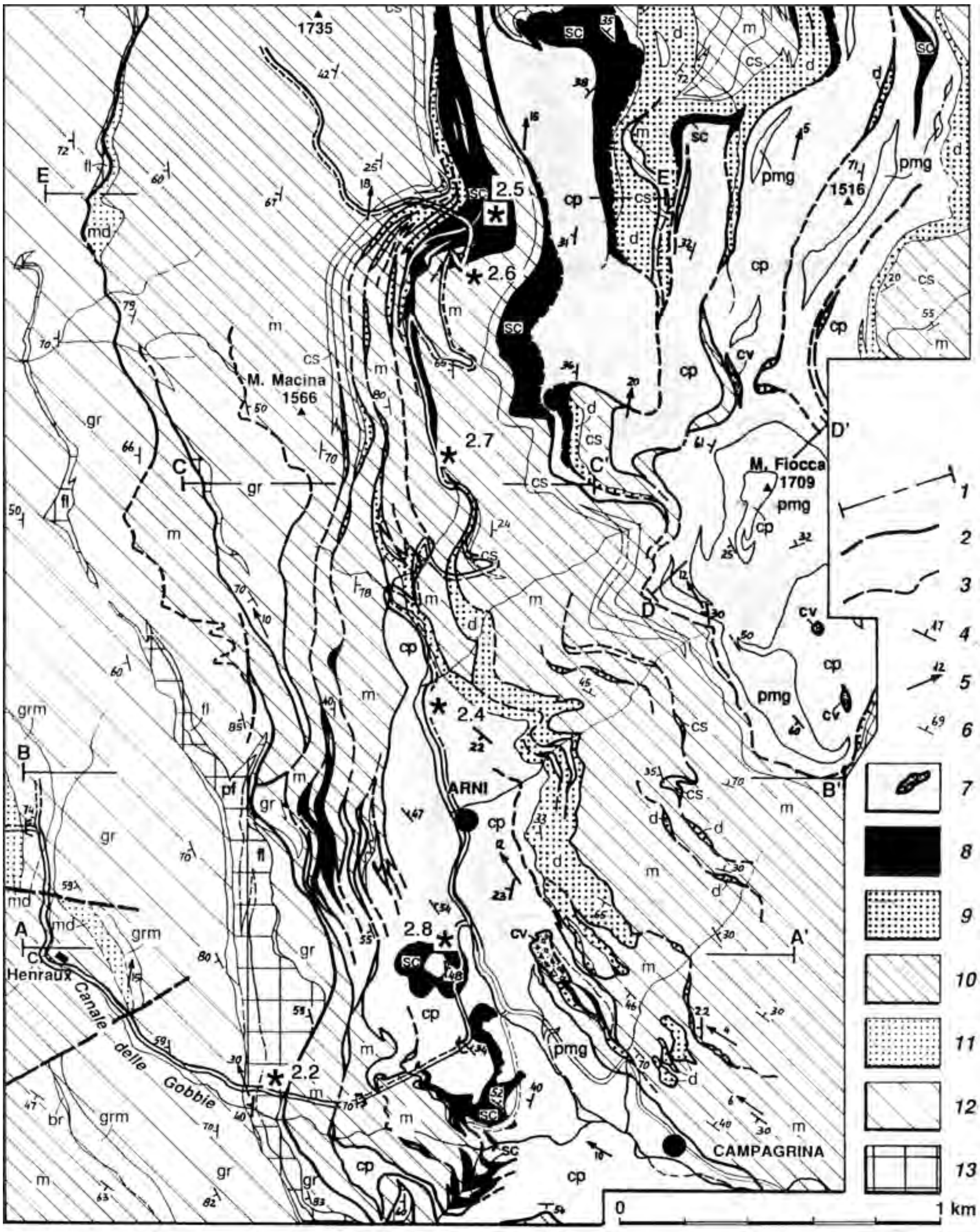


Fig. 31 – Geological map in the Arni valley. 1: traces of sections of Fig. 32; 2: faults; 3: tectonic contacts; 4: D2 foliation; 4: D2 fold axis; 6: D1 foliation; 7: "Pseudomacigno" metasandstones (pmg), calcschists (cp), "Calcare cavernoso" (cv); 8: "Scisti sericitici" phyllites (sc); 9: Cherts (d); 10: Calcschists (csc), cherty limestone (cs), marble (m); 11: Dolomitic marble (md); 12: Seravezza Breccia (br), "Grezzoni" dolomite (gr), "Verrucano (fV+Vr); Paleozoic phyllites (pf+fl).

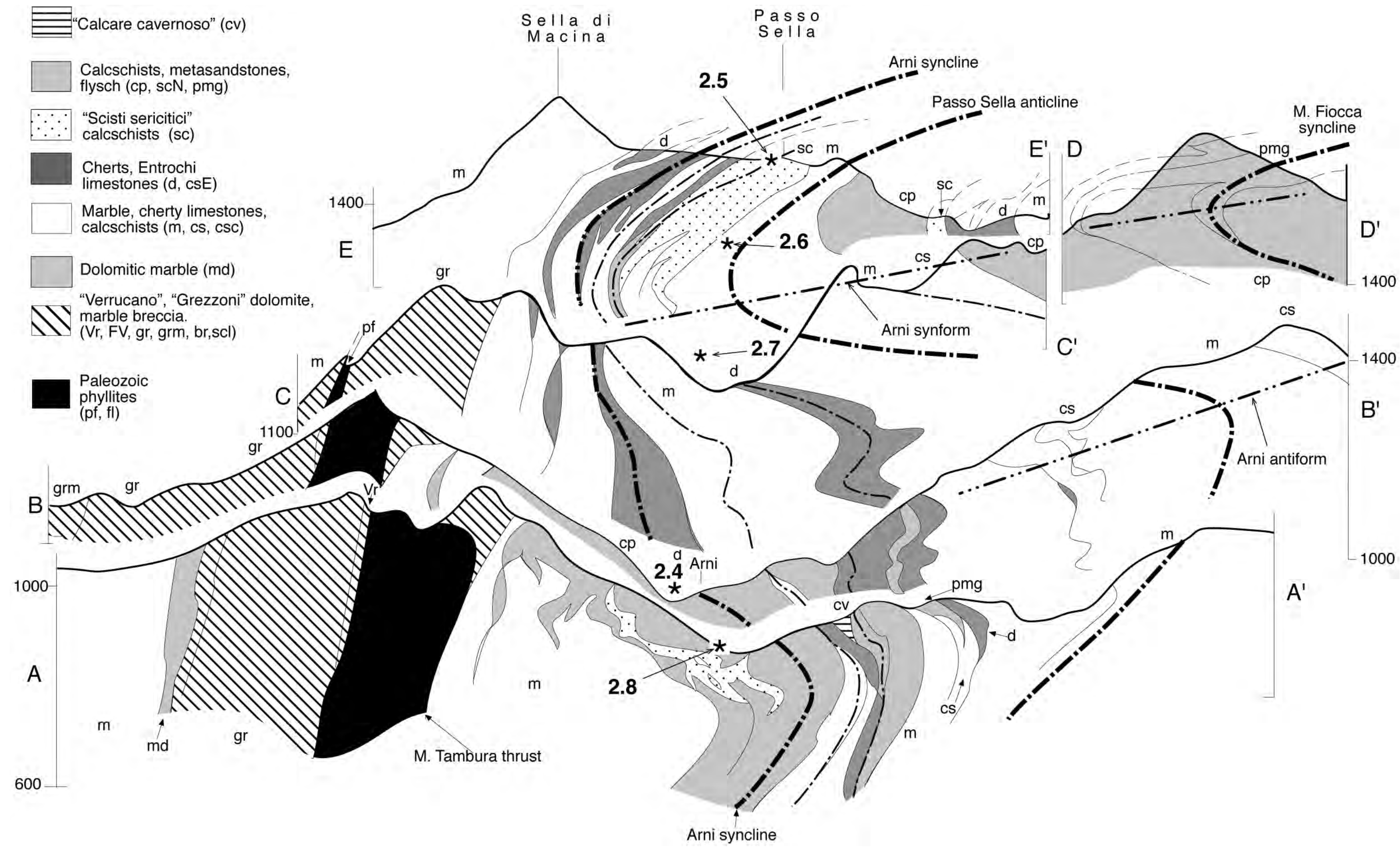


Fig. 32 – Geological cross section in the Arni valley. See Fig. 31 for locations.

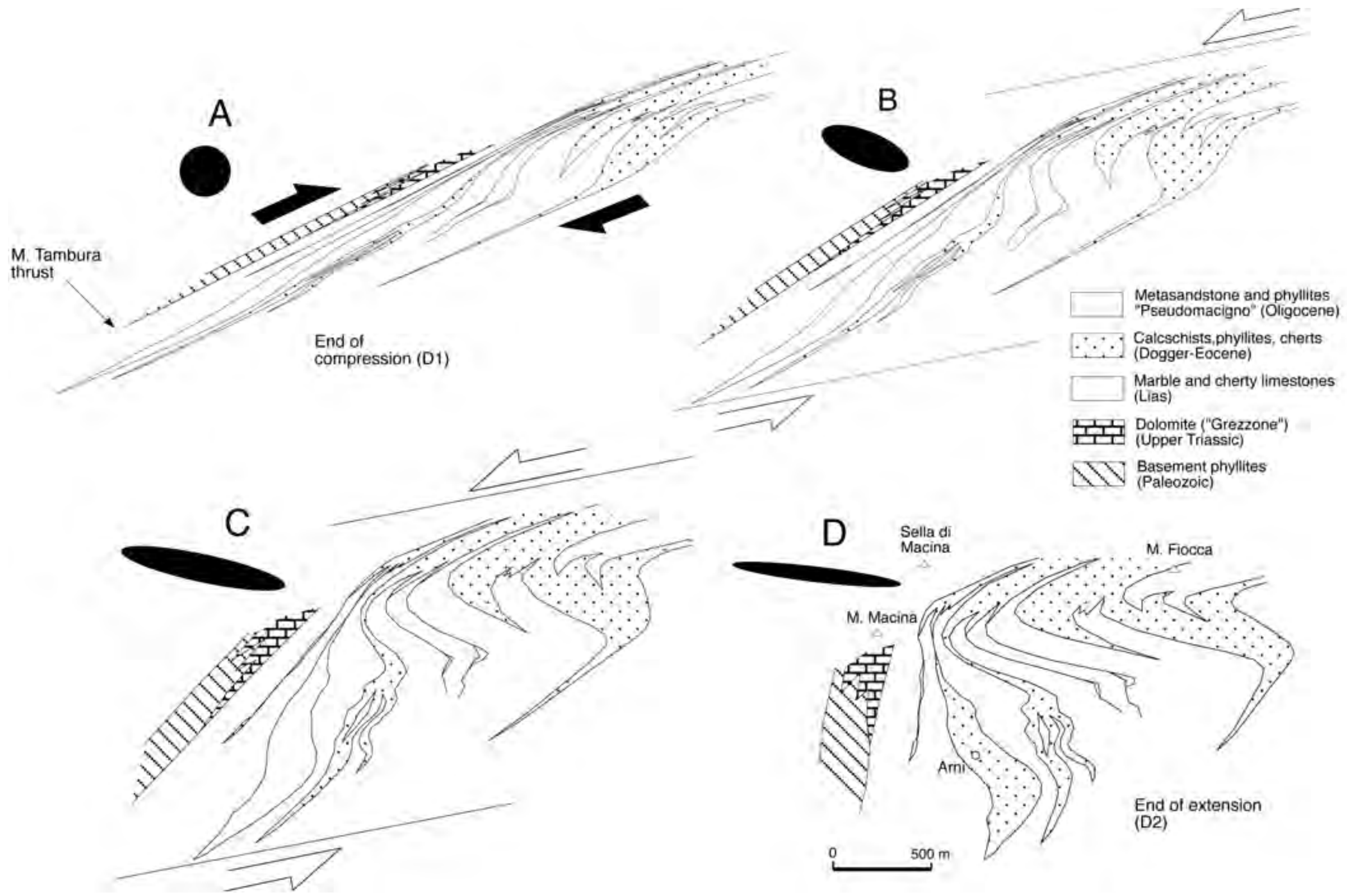


Fig. 33 – Reconstruction of the kinematic evolution of tectonic structures in the Arni valley.

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 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 modified 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).

Stop 2.11

Locality: Cardoso.
Topics: Structures in the Pseudomacigno formation.

In this stop we will visit a quarry of slates and sandstones used for roofing and outside floors. These lithologies belongs to the "Pseudomacigno" Fm. a Tertiary siliciclastic turbitide deposit (flysch), that can be correlated with the non metamorphic "Macigno" formation of the Tuscan Nappe. In the quarry we can observe details of D1 deformation and associated minor structures.

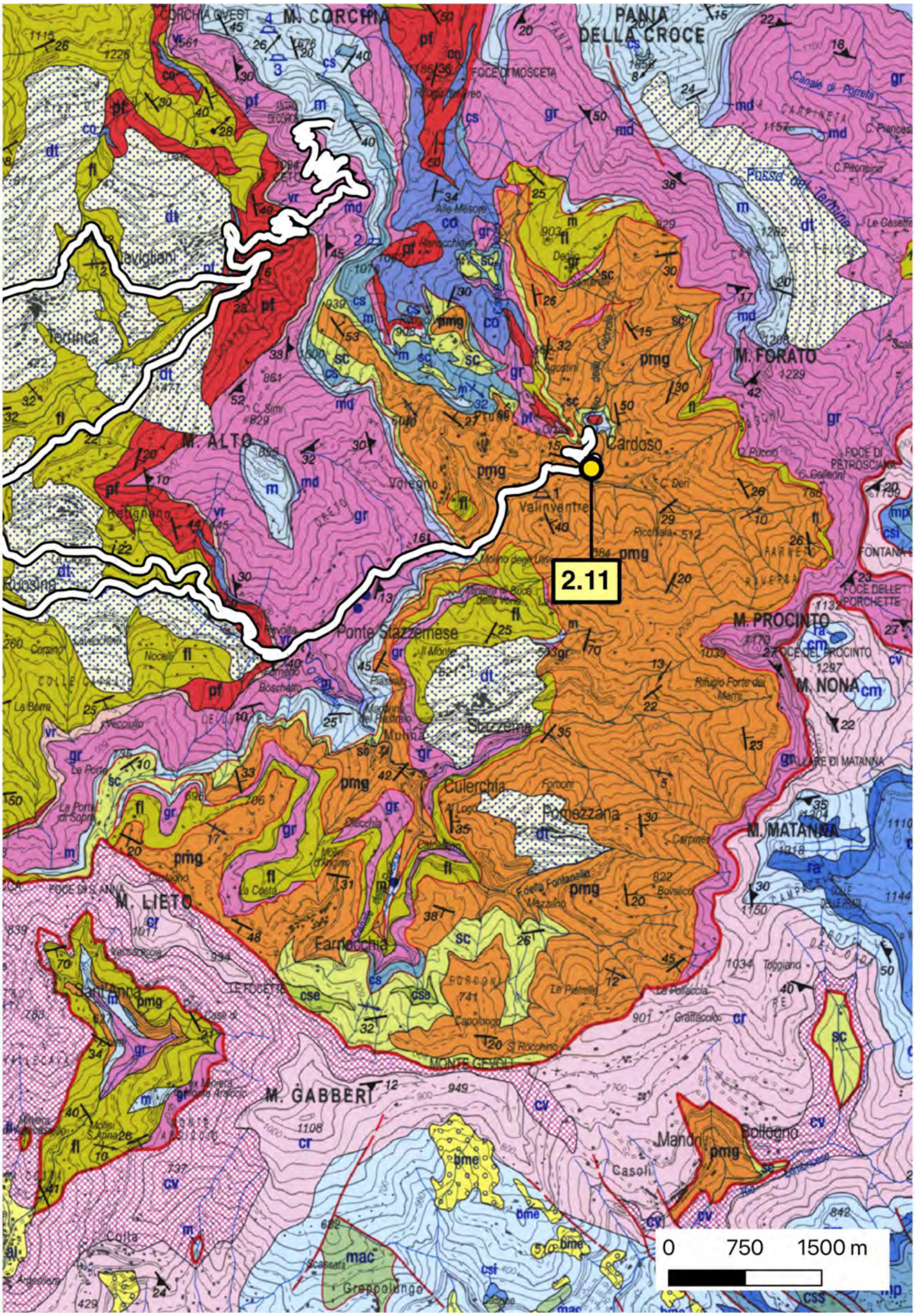


Fig. 34 – Geological map of the Cardoso area (southern Alpi Apuane) , after Carmignani *et alii* (2000), see Fig. 19 for geological map legend.

Day 3 : Castelnuovo Garfagnana - Minucciano

Itinerary

Castelnuovo Garfagnana – Vagli – Orto di Donna – Minucciano.

Themes

Tectonics of the eastern Alpi Apuane, contact between the Metamorphic unit and the Tuscan nappe, Quaternary deposits.

Geological overview

During the third day of excursion we will cross the central and eastern part of the Alpi Apuane. Along the itinerary we will study the tectonic contact with the overlying Tuscan Nappe and the internal deformation of this portion of the metamorphic unit.

Stop 3.1

Locality: Turrite Secca
Topics: The Calcare Cavernoso fm.: cataclastic rocks at the top of the metamorphic unit.

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. 35).

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. 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 3.2

Locality: Capanne di Careggine
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 3.3

Locality: E of Capanne di Careggine
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. 35). 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. 37). The main foliation recognizable at outcrop scale (S1) is the axial plane foliation of some isoclinal folds showing NE-facing. Some of these folds refolds an earlier foliation, we interpret this features as related to progressive deformation during D1 deformation (subduction-related), but some shearing and deformation during exhumation processes cannot be ruled out.

The intense shearing and strain the rocks suffered is testified by strong boudinaged of cherty lenses, now completely transposed along S1. Most of dynamic recrystallization occurred in carbonate-rich layer, now

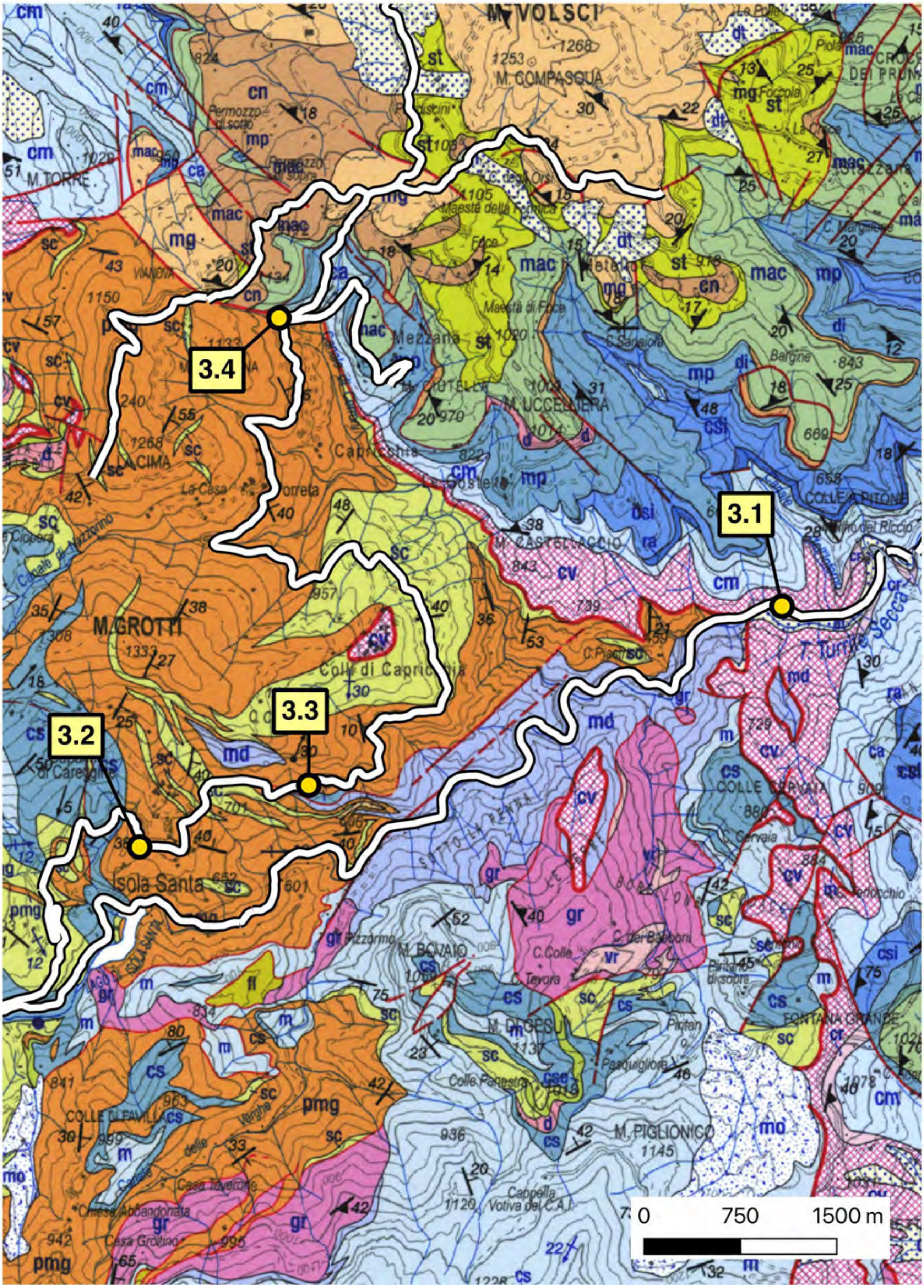


Fig. 35 – Stops during the third day of excursion.

Fig. 36 – D2 folds in the Pseudomacigno fm., Stop 3.2.

Fig. 37 – Mylonitic cherty limestones during D1 deformation, Capanne di Careggine. Stop 3.3.

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 3.4

Locality: Vianova

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 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 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 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 not metamorphic units, already resting at very shallow levels, reached the surface, probably via erosion, as a single coherent body (Fellin *et alii*, 2007).

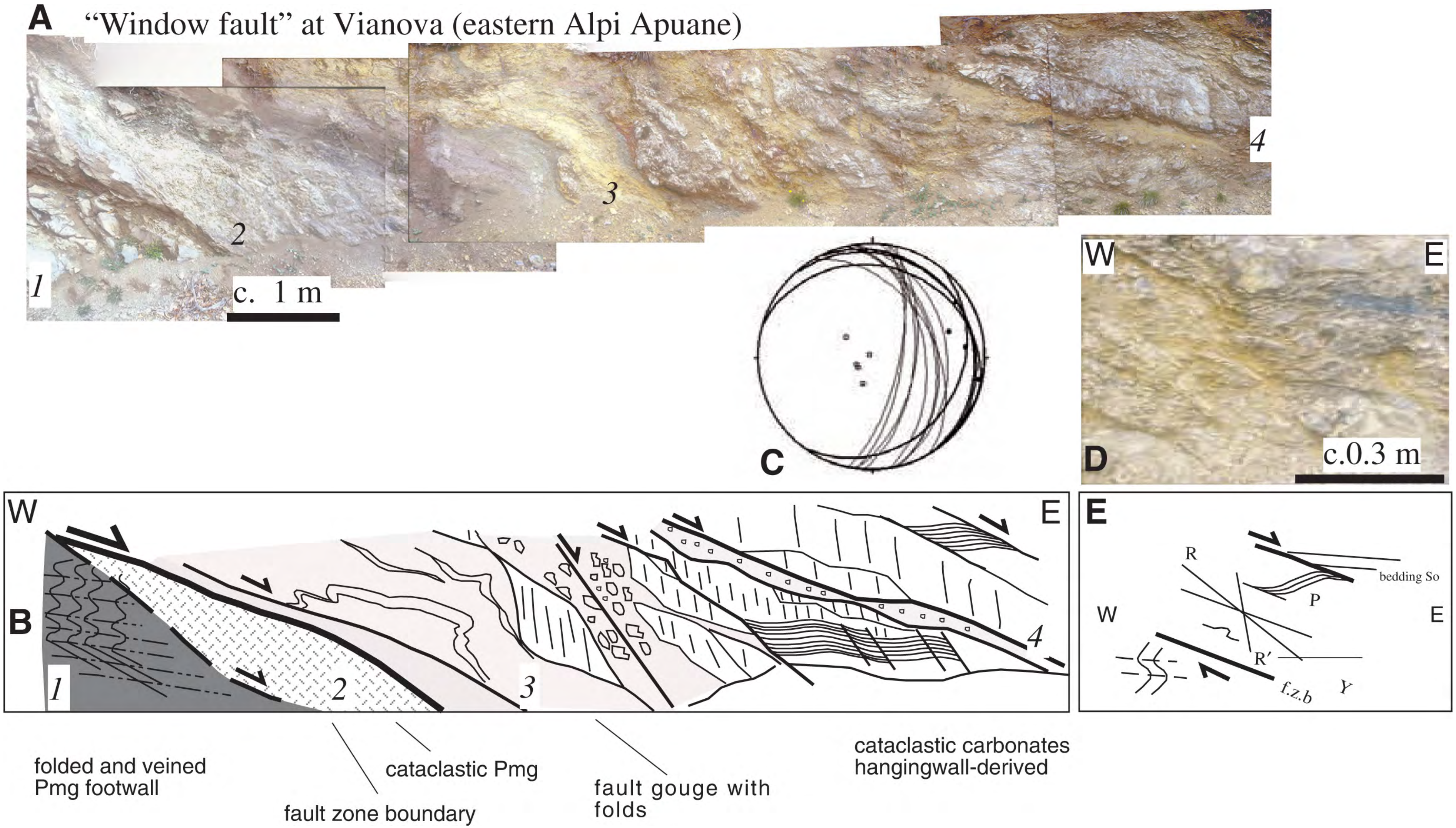


Fig. 38 – Stop 3.4. (A) General view (scale bar 1 m) and schematic representation (B) of the structural elements of the tectonic "window fault" between the not metamorphic Tuscan Nappe and metamorphic Apuane core, a fault that is observable at Vianova (road toward Capanne di Careggine) eastern Apuane. (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).

Day 4 : Minucciano - Orto di Donna

Itinerary

Castelnuovo Garfagnana – Minucciano – Orto di Donna.

Themes

Tectonics of the northern Alpi Apuane, Quaternary deposits.

Geological overview

During the fourth day of excursion we will cross the northern part of the Alpi Apuane (Fig. 39). Along the itinerary we will study the overlying recent post-tectonic deposits and the internal deformation of this portion of the metamorphic unit.

Stop 4.1

Locality: Minucciano.
Topics: Quaternary deposits and their relationships with recent uplift of the Alpi Apuane..

Along a road cut south-east of Minucciano are exposed Middle Pleistocene fluviatile conglomerates with sand intercalations, with pebbles mostly belonging to the "Macigno" formation of the Tuscan Nappe (Bartolini & Bortolotti, 1971; Bernini & Papani, 2002). Bedding in conglomerates gently dips toward NE.

In this outcrop the conglomerates rest on the "Macigno" formation, that westward is cut by a NE dipping normal fault. The conglomerates are located in the hangingwall of this normal fault. Although the contact is not exposed, we think that activity of the fault was later than conglomerate deposition. This fault is linked with the NE-dipping main fault systems that border the estern side of the Alpi Apuane Metamorphic complex and that is responsible for the recent uplift of the metamorphic rocks. Assuming this relationships between conglomerate dep- osition and faulting we get a very recent age (Pleistocene) for the uplift of the Alpi Apuane area.

Stop 4.2

Locality: Orto di Donna.
Topics: D1 and D2 deformation on the metamorphic unit.

South of the "Rifugio Donegani" the D1 M. Contrario anticline and the D1 M. Contrario syncline crop out. In the core of the anticline Liassic cherty limestones outcrops, in the syncline core Cretaceous-Oligocene "Scisti sericitici" are present.

Just south of the "Rifugio Donegani" the cherty limestones of the anticline core are exposed, in the normal limb calcschists and cherts outcrop, in the inverted limb the calcschists are locally laminated. In the cherty limestones D1 folds are present, evidenced by folded chert layers. The folds have strongly dipping fold axes NE-SW directed, parallel to the D1 stretching lineation; we interpret this geometry as the result of fold axes rotation in the tectonic transport direction during D1 deformation (sheath folds). Map scale D1 folds in this area show a sheath-like geometry too, with opposite facing direction on both closure of sinclines and anticlines.

In this stop we can see also the superposition of D2 deformation on D1 structures. The D1 axial plane foliation (S1) of the M. Contrario anticline is refolded by D2 folds with subhorizontal axial plane, facing SW. This D2 folds develop a slaty cleavage foliation in calcschists.

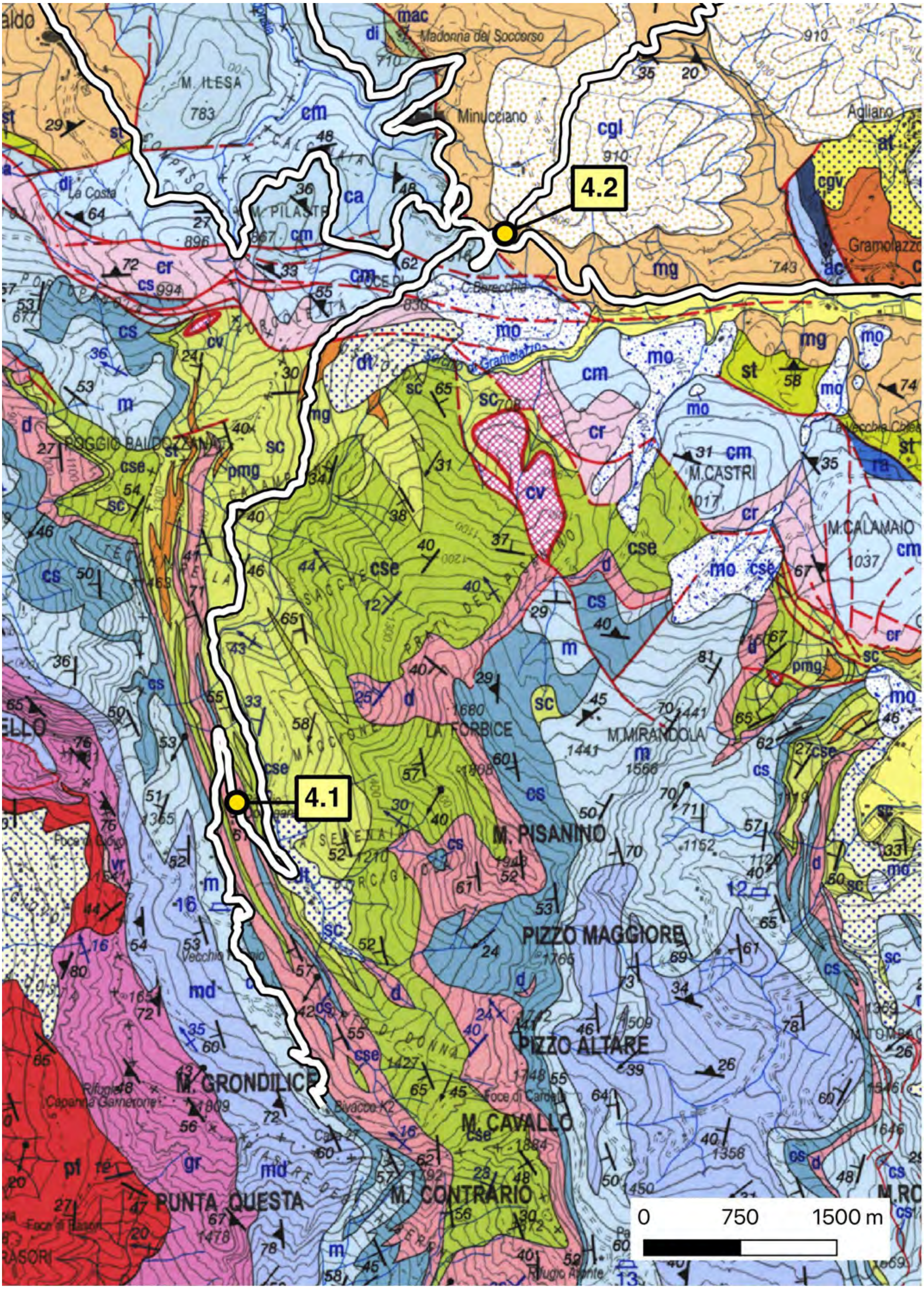


Fig. 39 – Stops during the fourth day of excursion.

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