Field Trip Guide Book - P38

Volume n° 5 - from P37 to P54

32nd INTERNATIONAL GEOLOGICAL CONGRESS

GEOLOGY OF THE ALPI APUANE METAMORPHIC COMPLEX (ALPI APUANE, CENTRAL ITALY)

Leader: L. Carmignani

Associate Leaders: P. Conti, M. Meccheri, G. Molli

Florence - Italy
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Front Cover:
Panoramic view of the Northern Alpi Apuane

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Introduction

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). This guide-book includes an outline of the tectonic and sedimentary evolution of all the tectonics units outcropping in the Northern Apennines and a description of itineraries and stops.

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

- Carmignani, L., Gattiglio, M., Kaelin, O. and Meccheri, M. (1987). Guida all'escursione sul Complesso Metamorfico delle Alpi Apuane. Final Excursion of the "Summer School di Geologia e Petrologia dei Basamenti Cristallini", September 1987. Tipografia Editrice Pisana, Pisa, 110 pp.
- Boccaletti, M., Pieri, M., Turrini, C. and 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, 81 pp.
- Carmignani, L., Disperati, L., Fantozzi, P.L., Giglia, G. and Meccheri, M. (1993). Tettonica Distensiva del Complesso Metamorfico delle Alpi Apuane - Guida all'Escursione. Gruppo Informale di Geologia Strutturale, Siena, 128 pp.
- Molli, G. (2002). Field Trip Eastern Liguria/Alpi Apuane. Gordon Research Conference on Rock Deformation. Il Ciocco, Barga, Italy, 58 pp.

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

- 1:50000 map scale sheets: 249 - Massa Carrara, 250 - Castelnuovo Garfagnana, 260 - Viareggio, 261 - Lucca;
- 1:25000 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 (1:10000) topographic map of the Alpi Apuane area can be obtained from 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., Dallan, L., Federici, P.R., Giglia, G., Nardi, R. and Raggi, G. (1971). Carta geologica d'Italia a scala 1:100.000, Foglio 96 - Massa. Servizio Geologico d'Italia, Roma.
- Trevisan, L., Brandi, G.P., Dallan, L., Nardi, R., Raggi, G., Rau, A., Squarci, P., Taffi, L. and Tongiorgi, M. (1971). Carta geologica d'Italia a scala 1:100.000, , Foglio 105 - Lucca. Servizio Geologico d'Italia, Roma.
- Zaccagna, D. (1890-1920). Carta Geologica delle Alpi Apuane a scala 1:25.000. Servizio Geologico d'Italia, Roma.
- Carmignani, L. (1985). Carta geologico-strutturale del Complesso Metamorfico delle Alpi Apuane, Foglio Nord, Litografia Artistica Cartografica, Firenze.
- Carmignani, L., Conti, P., Disperati, L., Fantozzi, P.L., Giglia, G. and Meccheri, M. (2000). Carta Geologica del Parco delle Alpi Apuane, scale 1: 50.000, Parco Regionale delle Alpi Apuane, Massa.

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

Regional geologic setting

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. 1a). According to most authors this units also suffered the Cretaceous-Paleogene tectonics phases well documented in the Alps (Fig. 1b).

The Tuscan-Umbria domain represent the continental margin of the Adria (Apulia) plate (Fig. 1a) and is formed by an Hercynian basement with its Mesozoic-Tertiary cover.

Eastward motion (in present day coordinates) of the Briançonnais microcontinent formerly belonging to the European plate (Fig. 1c), led to collision and deformation (Fig. 1d) 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

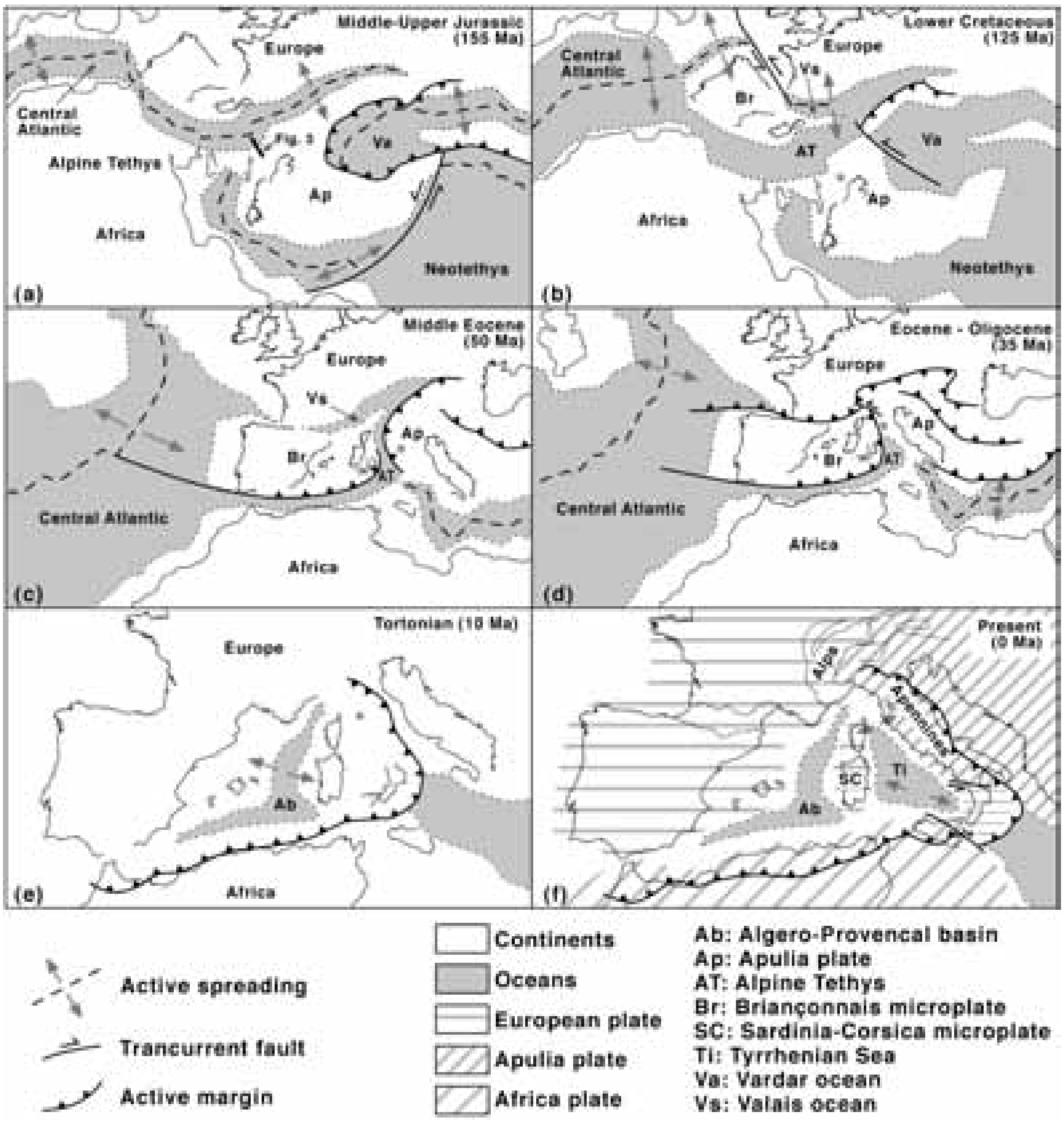

Figure 1 - Plate reconstruction for the western Mediterranean area , after Stampfli et al. (2001), modified.

first in the Algero-Provencal basin and then in the Tyrrhenian Sea (Fig. 1e, f), contemporaneous with eastward migration of subduction, collision zone and deformation (Fig. 2).

Therefore, in the Northern Apennines we find today rocks of the Apulia margin covered by the Ligurian units, first strongly deformed and metamorphosed during the collisional tectonic phases, and then affected by extensional tectonics, normal faulting, uplift and exhumation.

Before discussing the tectonic features of the area, we first review the stratigraphy of the tectonic units outcropping in the Alpi Apuane area.

Stratigraphy

A palinspastic reconstruction of the Apulia continental margin in the late Jurassic is illustrated in Fig. 3.

We distinguish the ocean-derived *Ligurian domain*, a remnant of the Alpine Tethys (Elter et al., 1966; Elter & Pertusati, 1973; Elter, 1975; Bortolotti et al., 2001; Marroni et al., 2001), furthermore separated into:

a) *Internal Ligurian Domain*, characterized by the

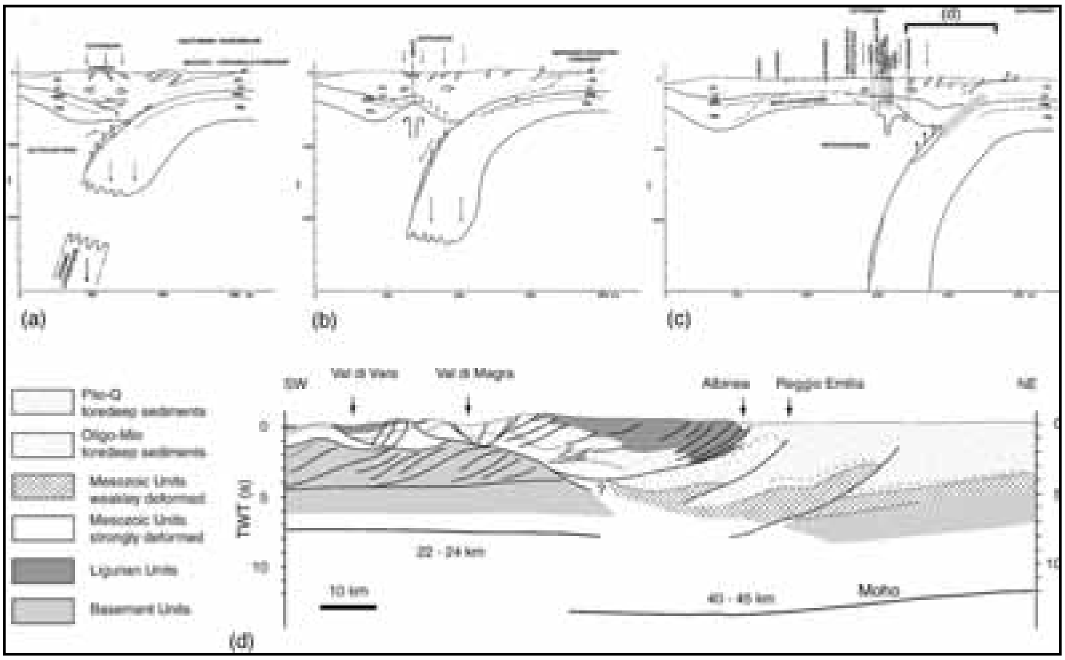

Figure 2 - Neogene-Quaternary geodynamic model for the Corsica-Northern Apennines orogenic system, after Serri et al. (1993). (a) Interpretative section at the Lower Miocene. (b) Interpretative section at the Langhian-Early Tortonian. (c) Interpretative section at the Quaternary. (d) Cross section from La Spezia to Reggio Emilia, north of the Alpi Apuane, after Argnani et al. (2003).

presence of Jurassic ophiolites and their upper 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);

b) *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”. 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 (Fig. 3).

Moving toward the continent the “Subligurian Domain” is distinguished, an intensely deformed Paleogenic sequence (Canetolo Unit) whose original extent 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, from W to E (in present day coordinates) the following domains can be recognized, now outcropping in different tectonic units: the Tuscan Domain, the Umbria Domain, the Lazio-Abruzzi platform.

In the Tuscan domain we can further recognize (Fig. 3):

1 - The Inner 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.

2 - The External Tuscan Domain (“Autochthon” Auct. 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. This unit now outcrops below the Tuscan Nappe.

3 - The Massa Unit, structurally interposed between the Tuscan Nappe and the “Autochthon” Auct., is exclusively made of rocks from Paleozoic to Triassic age and could represent the original substratum of the Tuscan Nappe or derive from an intermediate domain.

We will not visit the Umbro-Marchean domain or the more external carbonate platform during the excursion.

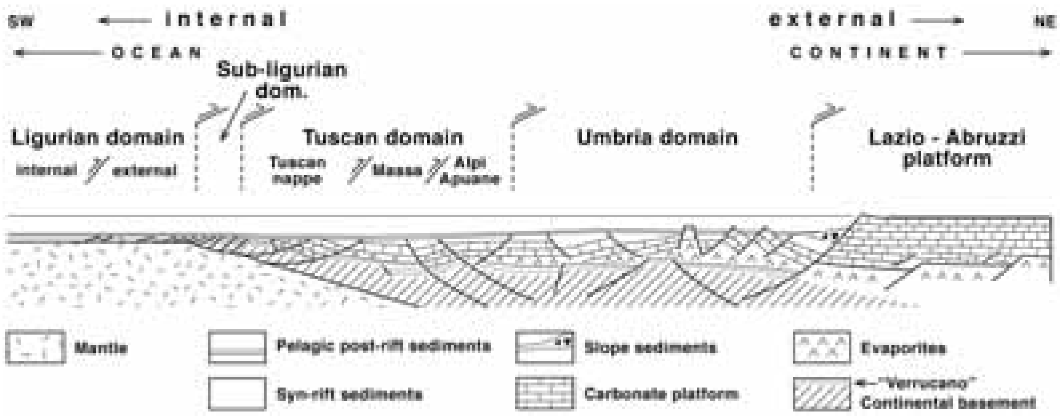

Figure 3 - Palinspastic reconstruction of the western continental margin of Apulia during the late Jurassic (after Bernoulli, 2001, modified). Internal and external is referred to the top-the-NE transport direction of the Tertiary tectonics. Location of this section is approximately located in Fig. 1a.

During the excursion we will focus on tectonics and stratigraphy of the Tuscan Domain (Tuscan Nappe and the "Autochthon" Auct. unit) in the area of the Alpi Apuane. (Fig. 4).

Stratigraphic evolution of the Tuscan Domain

The continental origin of the Tuscan Domain is testified by the pre-Mesozoic rocks, the Tuscan Paleozoic basement, substrate of the Tuscan successions (review in Conti et al., 1991a; Pandeli et al., 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 (Gattiglio & Meccheri, 1987; Conti et al., 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 al., 1986).

The continental sedimentation was later re-

Figure 4 - Tectonic units in the Italian northern Apennines.

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

Geological Setting of the Alpi Apuane

Within the Alpi Apuane region different tectonic units derived from the Tuscan domain are traditionally distinguished (Carmignani & Giglia, 1975; Carmignani & Kligfield, 1990) :

- the Tuscan nappe;
- the Massa unit;
- the “Autochton Auct.” unit
- the Panie and Stazzema-slice units;

The Tuscan nappe

The Tuscan nappe (Fig. 5) 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 with silici-clastic foredeep turbidites of the Macigno (upper Oligocene-lower Miocene).

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

Peak metamorphic conditions does not exceed the anchizone/subgreenschist facies conditions with estimated temperature around 250-280°C on the basis of vitrinite reflectance (value around 5.1), illite cristallinity, isotope studies and fluid inclusion analysis (Cerrina Feroni et al., 1983; Reutter et al., 1983; Carter & Dworkin, 1990; Montomoli et al., 2001).

The Massa unit

The Massa unit, exposed in the south-west part of the Alpi Apuane, is characterized by a pre-Mesozoic basement and a middle to upper Triassic cover (Fig. 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 with 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 al., 1986; Jolivet et al., 1998; Franceschelli & Memmi, 1999; Molli et al., 2000b).

"Autochthon" Auct. unit

The "Autochthon" Auct. unit is made up of a Paleozoic basement unconformably overlain by the Upper Triassic-Oligocene metasedimentary sequence (Fig. 5).

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 clearer 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 volcanoclatic deposits (Gattiglio & Meccheri, 1987; Conti et al., 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 al., 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-rocks 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 down-drowning of the former carbonate platform. The Oligocene sedimentation of turbiditic metasandstones ("Pseudomacigno") closes the sedimentary history of the domain.

The Alpine metamorphism in the Apuane unit is characterized by pyrophyllite + chloritoid + chlorite + phengitic muscovite in metapelites. Peak-metamorphic conditions have been estimated by this assemblages in the range of 0.4-0.6 GPa and 350-450 °C (Franceschelli et al., 1986; Di Pisa et al., 1987; Jolivet et al., 1998; Molli et al., 2000b). Di Pisa et al. (1985) first recognized 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 recently been confirmed and used to interpret part of the microstructural variability in marbles (see below).

The regional tectonic setting of the Alpi Apuane is well known and generally accepted by researchers belonging to different geological schools (Fig. 6). 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 al., 1978; Carmignani & Giglia, 1979; Carmignani & Kligfield, 1990; Storti, 1995; Cello & Mazzoli, 1996; Jolivet et al., 1998; Molli et al., 2000b).

In the Alpi Apuane metamorphic units two main polyphasic tectono-metamorphic events are recognized: the D1 and D2 events (Carmignani & Kligfield, 1990), which are classically regarded as a progressive deformation of the inner Northern Apenninic continental margin during collisional and late to post-collisional processes.

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.

D1 structures

A main planar anisotropy (D1 foliation) of L-S type can be recognized in all the metamorphic units as the axial plane foliation of isoclinal decimetric to kilometric scale folds. 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

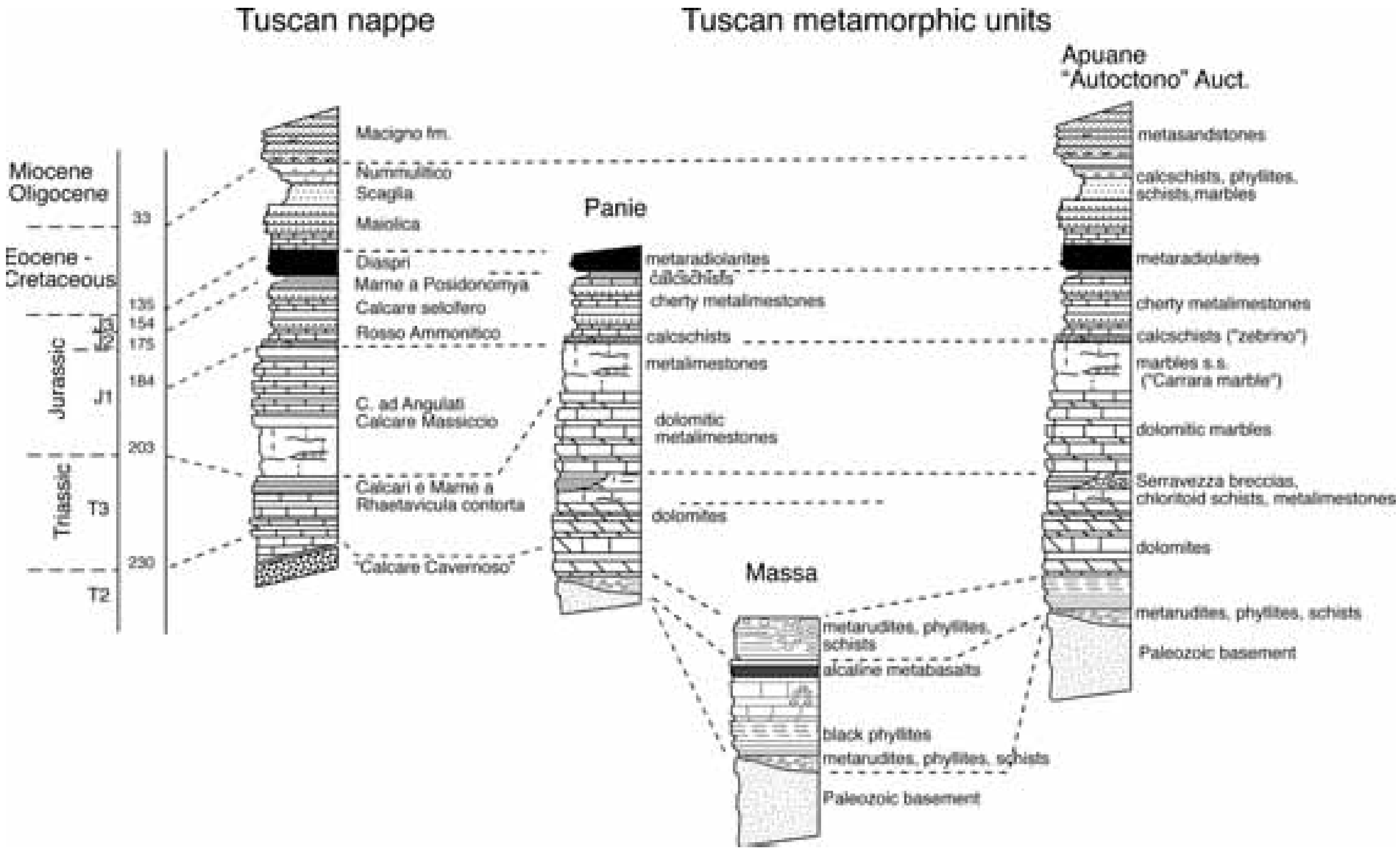

Figure 5 - Stratigraphic sequence of the Tuscan units in the Alpi Apuane region.

metaconglomerates.
Finite strain data from deformed marble breccias, reduction spot and strain fringe indicate X/Z strain ratios of from 4:1 to 13:1 with an average of 7:1. The finite strain ellipsoid varies from the field of flattening to constriction with aspect ratios K between 0.14/0.64 in the west to 0.15/3.34 in the east (Kligfield et al., 1981; Schultz, 1996, our data).
In the "Autochthon" Auct. unit kilometric scale D1 isoclinal fold structures can be observed from west to east, these 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. 6).
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 al., 1978). D1 fold axes in the western area (Carrara) mainly trend NW-SE and are sub-horizontal with a D1 lineation plunging down-dip within the main foliation at 90° from fold axis. In the eastern region fold axes are parallel to sub-parallel to the down-dip stretching lineation and highly non-cylindrical sheath folds appear (Carmignani & Giglia, 1984; Carmignani et al., 1993). This relationship has been proposed as an example of passive rotation of early formed folds into the extension direction during progressive simple shear.

Interpretation of D1 history

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. 7B); (2) "antiformal stack phase" in which further shortening and a crustal scale duplex are realized (Fig. 7C). The development of D1 structures is strongly controlled by the original paleotectonic setting and its lateral heterogeneities.

D2 structures

All the D1 structures and tectonic contacts are overprinted by different 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 fold systems mainly associated with a low dipping to sub-horizontal axial planar foliation (S2) of crenulation type. Late stage D2 structures are mainly represented by upright kinks and different generations of brittle faults, that accommodate the most recent tectonic history.
According to classical interpretations (Carmignani et al., 1978; Carmignani & Giglia, 1979; Carmignani & Kligfield, 1990) a complex mega-antiform with an 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 south-western and north-eastern 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.

Interpretation of D2 history

The tectonic meaning of D2 structures has been the 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 al., 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, 1979); c) domino-like rigid blocks rotations with antithetic shear during progressive eastward thrusting (Jolivet et al., 1998);
- they produced as reverse drag folds overprinting complex highly non-cylindrical D1 sheath folds during late rebound by vertical isostatic re-equilibration of former thickened crust (Carmignani & Giglia, 1979);
- they are born as passive folds related to distributed shear within kilometric scale shear zones accommodating crustal extension (Carmignani & Kligfield, 1990; Carmignani et al., 1994).
Possibly different folding mechanisms were contemporaneously active during D2 deformation. We point out here that all major km-scale D2 fold show a facing direction that is opposite to dip of the main high-angle normal faults that border the Alpi Apuane window. In the northern Alpi Apuane major D2 folds

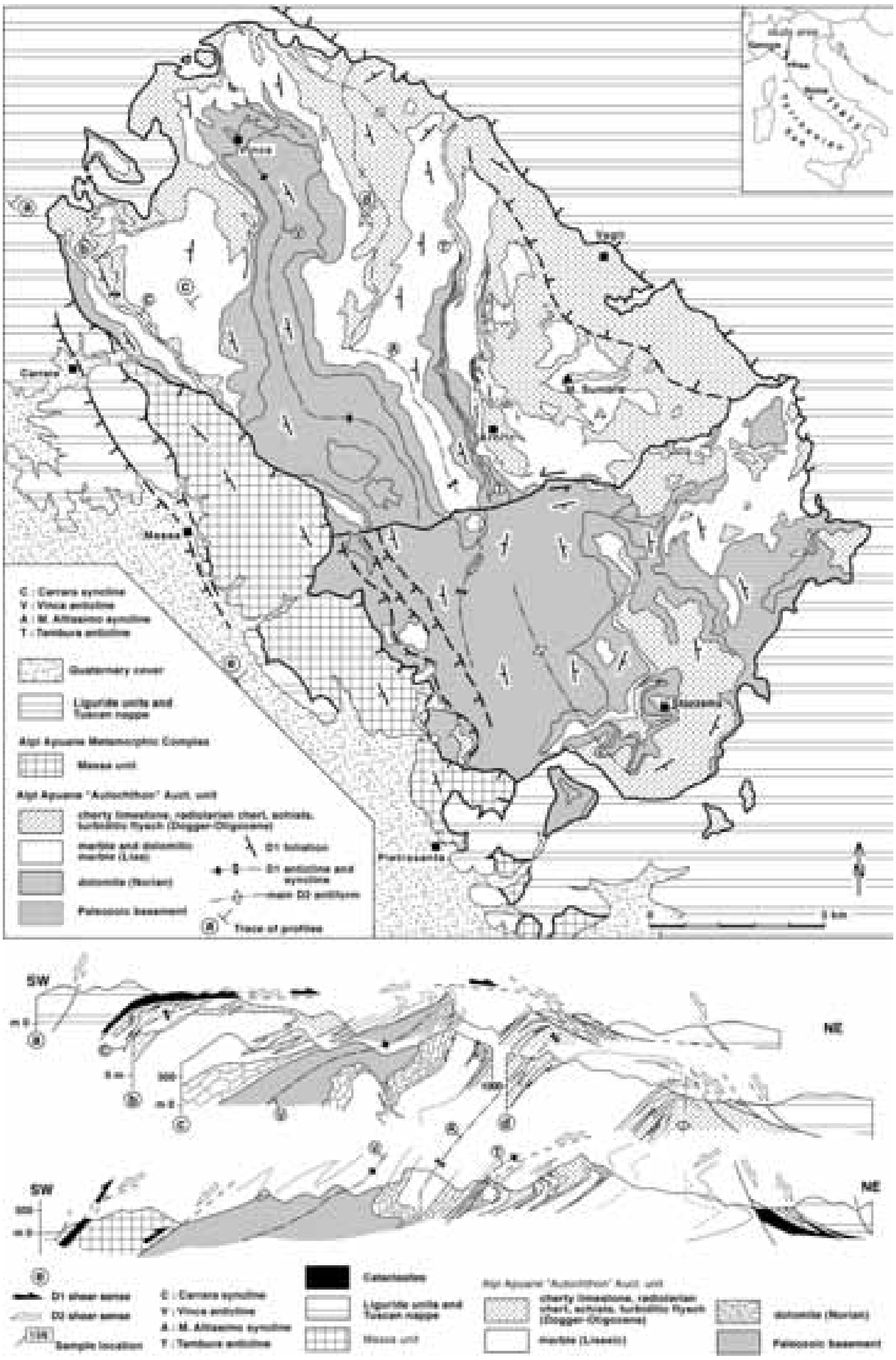

Figure 6 - Tectonic map of the Alpi Apuane area.

face SW and the main border fold is located in the Garfagnana valley and dips NE. In the southern Alpi Apuane main D2 folds in the Stazzema area face NE and here the main high-angle border faults are those of the Versilia area dipping SW. Due to this different D2 kinematic evolution between the northern and southern Alpi Apuane, a sinistral strike-slip zone developed in the central Alpi Apuane (Fig. 6).

Deformation-metamorphism relationships

The presence of index minerals (chloritoid 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 al., 1997) can be observed in syn- to post tectonic relationships with the D1 foliation. The chloritoid mainly predates the D2 crenulation (which mechanically rotates it) in the uppermost geometrical levels of the unit, e.g. at Campo Cecina. On the contrary, at deeper structural levels (Forno valley, inland of Massa) chloritoid can be observed in clear syn- to post-tectonic relationships with the sub-horizontal D2 crenulation cleavage testifying a different thermo-mechanical history in different geometrical positions within the same unit.

Age of deformation

In the metamorphic units of the Alpi Apuane the youngest sediment involved in the syn-metamorphic deformation is the Pseudo-Macigno containing microfossils of Oligocene age (Dallan Nardi, 1976). Moreover, available K-Ar and Ar-Ar dates (Kligfield et al., 1986) suggest that greenschist facies metamorphism and ductile deformation within the region began about 27 Ma (late Oligocene) and were over by 10-8 Ma (late Miocene). The younger history can be constrained using apatite fission tracks suggesting that between 5 and 2 Ma (Abbate et al., 1994) 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 records, since north and north-east of the Alpi Apuane region the basin fill of the Lunigiana and Garfagnana tectonic depressions contains upper-middle Pliocene conglomerates with metamorphic clasts derived from the Alpi Apuane metamorphic units (Bartolini & Bortolotti, 1971; Federici & Rau, 1980; Bernini & Papani, 2002; Argnani et al., 2003; Balestrieri et al., 2003).

The Alpi Apuane marbles

In the Alpi Apuane region marbles derive from stratigraphically different levels, the Liassic marbles however are the thickest succession and represents the world-wide known white variety called “Carrara marble”. The “Carrara marble” is extensively used both as building stones and for statuary (this use dates as far back as the Roman age) as well as in rock-deformation experiments (Rutter, 1972; Casey et al., 1978; Spiers, 1979; Schmid et al., 1980; Schmid et al., 1987; Wenk et al., 1987; Fredrich et al., 1989; De Bresser, 1991; Rutter, 1995; Covey-Crump, 1997; Pieri et al., 2001a; Pieri et al., 2001b) where it is widely used because: a) it is an almost pure calcite marble; b) it shows a nearly homogenous fabric, with no or weak grain-shape or crystallographic preferred orientation; c) it usually develops a large grain-size. All the above features can be found in large volumes of marbles cropping out in the Carrara area, i.e. in the north-western part of the Alpi Apuane region, however on the scale of the Alpi Apuane region a variability of microstructure has been described.

In 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 north-western Alpi Apuane area in the surroundings of the town of Carrara (Fig. 6). 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 studies appearing since the sixties (D’Albissin, 1963; Di Sabatino et al., 1977; Di Pisa et al., 1985; Coli, 1989).

Marble-types and their microstructures

In the Alpi Apuane three main groups of marbles

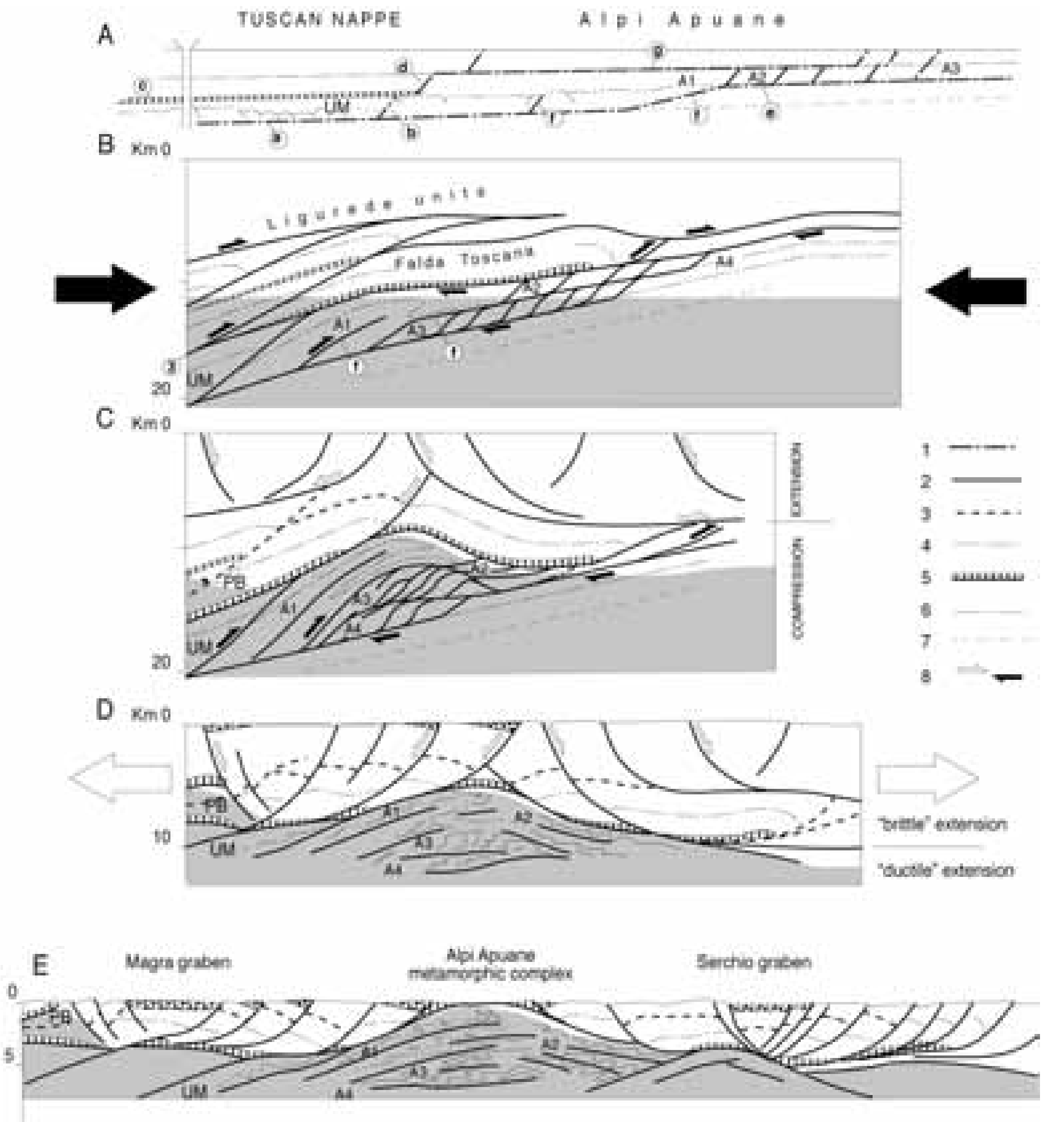

Figure 7 - Tectonic evolution of the Alpi Apuane region.

can be distinguished according to their mesoscopic features: the white-light grey, 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 called "Nuvolato" and "Bardiglio". These three main groups encompass more than fifty different commercial varieties quarried in the Alpi Apuane region (ERTAG Regione Toscana, 1980).

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 (1) static recrystallization (type A), (2) dynamic recrystallization (type B, further subdivided into two types B1 and B2), and (3) reworking during the late stage of deformation (type C). 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 descriptions in Molli & Heilbronner Panozzo, 1999; Molli et al., 2000a).

Annealed microfabric (type-A microfabric)

This type of microfabric is characterized by equant polygonal grains (granoblastic or "foam" microstructure, Fig. 8), 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 minor parasitic folds also developed. The presence of such microstructures within D1 folds indicates that the grain growth which produced type A microfabric occurred after the main D1 folding phase, and obliterated all earlier syntectonic microstructures associated with folding. However, the presence of a texture in some samples has been related to the pre-annealing deformation history (Leiss & Molli, 2003).

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

Dynamically recrystallized microfabrics (type-B microfabrics)

Within type-B microfabrics two end-members of microstructures can be recognized: a) microstructures exhibiting strong shape preferred orientation, coarse grains and lobate grain boundaries (type B1); b) microstructures with shape preferred orientation, smaller grain size and predominantly straight grain boundaries (type B2). Fig. 8 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.

Twinned microfabric (type-C microfabric)

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

Microfabric evolution and tectonic history

The variability of statically and dynamically recrystallized microfabrics in the Liassic Alpi Apuane marbles has been inserted in the following evolutionary tectonic model. During the early D1 stage (main regional deformation phase, Fig. 8a), 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. 8b). 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. 8c), further shortening was accomplished. In this phase, dynamically recrystallized microstructures (type B1 microfabrics) were produced in localized, meter to decameter-thick shear zones, where earlier type A annealed fabrics were reworked. These shear zones accommodate the transport of the originally deeper westernmost tectonic levels toward NE in higher positions within the nappe stack. The D2 history was associated with further exhumation in retrograde metamorphic conditions (Fig. 8d). During this event, narrow millimeter- to decimeter-thick shear zones developed in the higher levels of the Alpi Apuane metamorphic complex (Carrara area), whereas folding occurred at lower levels (Arni area). The temperature was lower during D2 deformation than during D1, but high enough to produce syntectonic recrystallization (type B2 microfabric). This is testified by fine-grained calcite in D2 shear zones, and recrystallized calcite grains elongated parallel to the axial surface of D2 folds. The difference in the temperature during the D2 event (380°C in the east, 340°C in the west) can

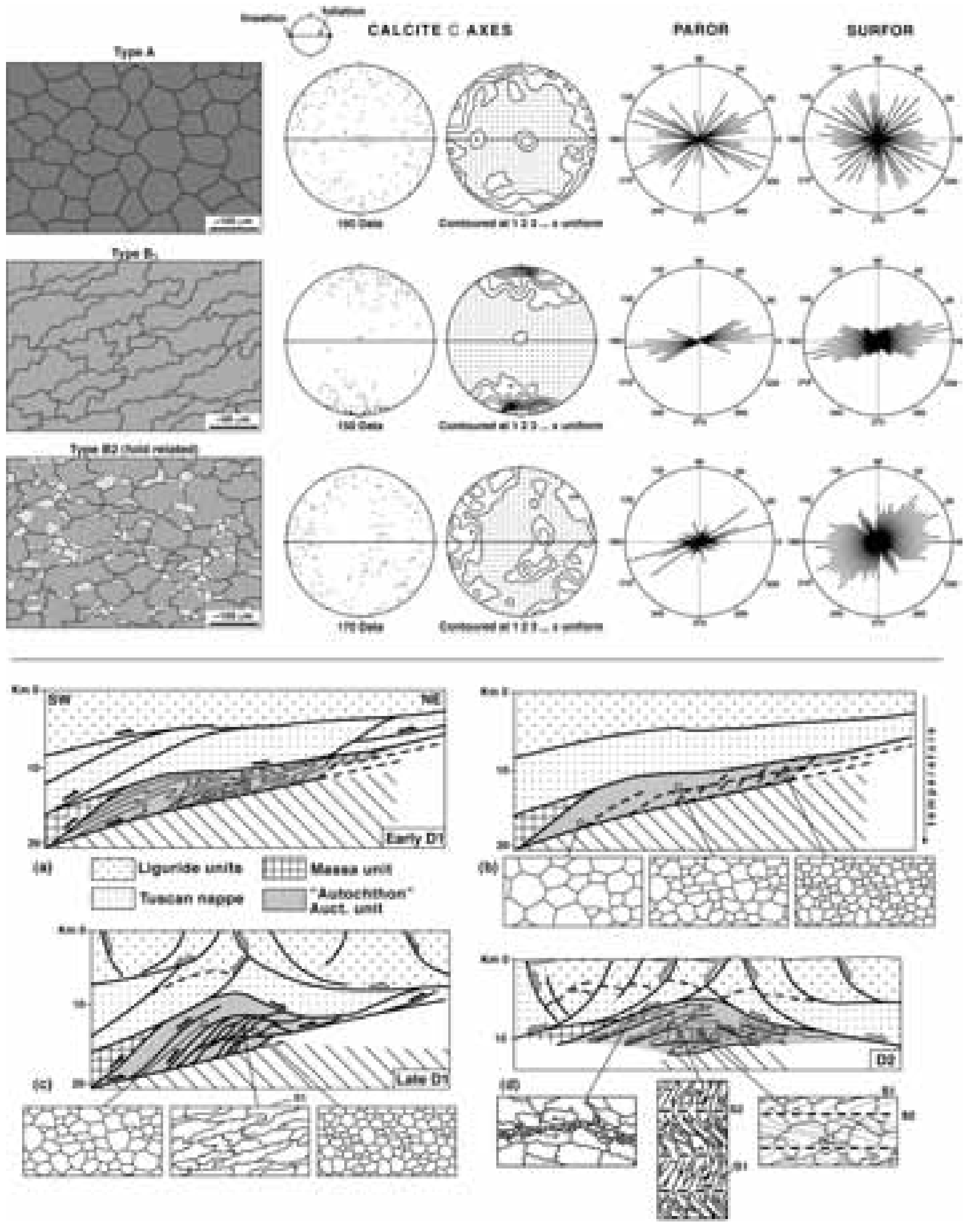

Figure 8 - Line drawing of microstructures, c-axis orientation (from universal stage measurements) and results of PAROR and SURFOR analysis for calcite microfabric of type-A and type-B. Number of grains analysed with PAROR and SURFOR routines is more than 200. Lower: development of the Alpi Apuane structure(after Carmignani & Kligfield, 1990, modified) and marble microstructure. (a) D1 main folding phase, with top-NE nappe emplacement. During this phase main foliation and km-scale isoclinal folds developed. (b) After D1 phase annealing occurred, with complete obliteration of earlier microfabric. In marbles polygonal granoblastic microstructures develop (type-A microfabrics). (c) D1 antiformal stack phase, with final NE transport along thrusts. Annealed microstructures are passively transported toward NE or reworked in shear zones along thrusts (type-B1 microfabrics). (d) D2 deformation led to extension and exhumation. D1 features are folded or cut by later shear zones or along low angle normal faults. Earlier microstructures can be reworked in D2 shear zones or along D2 fold axial planes (type-B2 microfabrics). From Molli et. al. 2000.

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. 8d). 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.

Field itinerary

The excursion includes the central and northern sectors of the Alpi Apuane. The excursion is divided into three days:
- the first day is dedicated to the relationships between the Metamorphic Complex and the Tuscan Nappe, which will be examined in the area of Campocecina (north of Carrara) and the stratigraphy and structure of the Tuscan Nappe at Castelpoggio;
- the second day focus on the structure developed in the central part of the Metamorphic Complex. We drive through the central Apuane Alps, showing the examples of superposition of compressional and extensional uplift-related structures;
- the third day is devoted to tectonics of the eastern Alpi Apuane, relationships between the Metamorphic unit and the Tuscan nappe, Quaternary deposits and recent evolution of the Alpi Apuane area.

DAY 1

Itinerary: Carrara - Campocecina - Carrara
Themes: The relationship between the Metamorphic Complex and the Tuscan Nappe north of Carrara.

From Carrara we move towards Castelpoggio and arrive at Campocecina. Following the itinerary we first cross the non-metamorphic Tuscan sequence (from the "Macigno" to the oldest levels), and then enter the metamorphic sequence which is here folded in the Carrara Syncline. We will reach the normal limb of the syncline, and later on our return, we will make six stops along one of the most classic geological sections of the Apuane Alps [Zaccagna, 1932 #3910; Ippolito, 1950 #4176, whose structure and stratigraphy are also illustrated in works by Valduga (1957), Elter (1958) and Decandia et al. (1968). The area is basically made up of tectonic units with varying dip towards the Tyrrhenian Sea and superpositioned in this order, 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 in well delineated folds on all scales and in their pervasive axial plane schistosity. In the Tuscan Nappe instead, this phase is only evidenced by the foliation in anchizonal facies (Pertusati et al., 1977; Cerrina Feroni et al., 1983), which is well developed 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

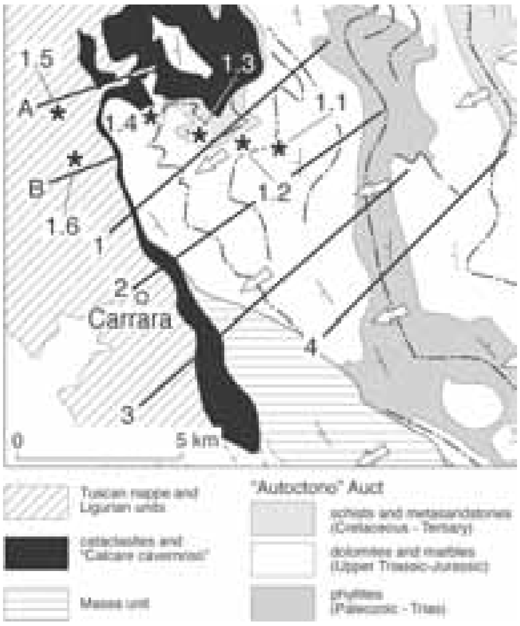

Figure 9 - Tectonic sketch map of the area north of Carrara. First day stops and traces of Fig. 10 sections are located.

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 Upper Triassic - Eocene formations (Fig. 9 and Fig. 10). As can be seen in the cross-section in Fig. 10 (sections A and B), the "Calcare Cavernoso" and the "Macigno" are not involved in the fold: these two formations limit a W-verging extensional shear zone.

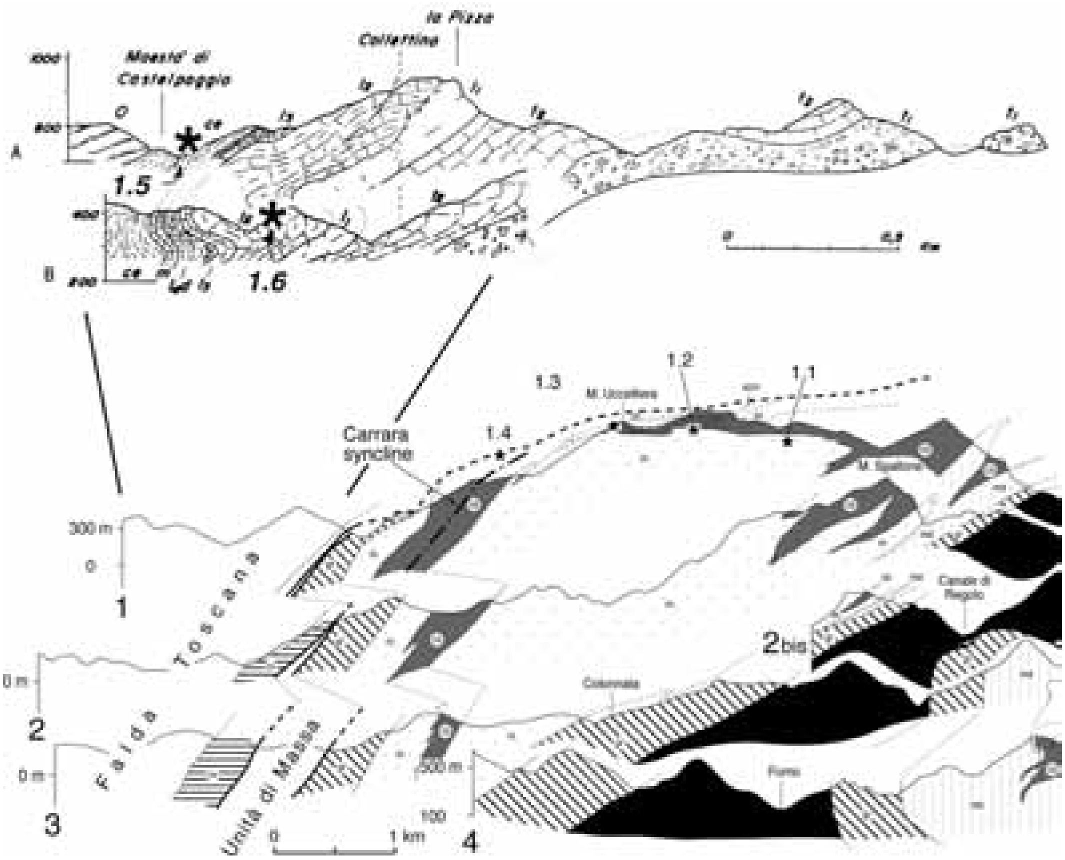

Figure 10 - Geological cross section in the area of Fig. 9. A and B sections after Decandia et al., 1968. t1: "Calcare cavernoso", t2: Rhaetavicula contorta limestones, l1: "Calcare massiccio", l2: Angulati limestone, l3: "Rosso Ammonitico, Posidonia marls, m: cherts, ce: Scaglia, o: "Macigno" flysch. Legend for sections 1-3: B: Paleozoic basement, gr: dolomites (Norian-Rhetian), md: dolomitic limerstones (Lower Liassic), m: marbles (Lower Liassic), cs: cherty limestones (Liassic), sc: "Scisti sericitici", scm: nummulite limestones, cv: "Calcare cavernoso".

Stop 1.1:

Interference between NE-facing structures of the D1 phase and SW-facing D2 phase along the M. Uccelliera - M. Borla ridge.

The Carrara Syncline (Fig. 10), whose core contains Sericitic Schist and arenaceous metalimestone of the Early Cretaceous-Early Oligocene, is well exposed in this area. Other outcropping formations are:

a) Marble: white metalimestones and/or veined with variously-sized lenses of breccia; just upstream from 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.

b) Cherty limestone: metalimestones with layers and nodules of whitish quartzite. The metalimestone generally derives from calcilutite, but varieties 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 grain size, produced by erosional mechanisms connected to the synsedimentary block-faulting tectonics during the Early Liasssic.

c) 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.

d) Sericitic Schist Auct. ("Scisti sericitici") and Nummulite limestone Auct. s.l: these are green, to a lesser extent violet-grey, silty phyllite; in the upper portion they contain levels of white marble and metasandstone, and polygenic breccia.

Along the M. Borla crest we can see Calcare Cavernoso klippes, which will be observed in detail W of Campocecina (near Capanne Ferrari); these klippes represent the base of the Tuscan Nappe, which tectonically cuts the overturned limb and the core of the Carrara Syncline (Fig. 10).

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 road cut at Foce di Pianza, we observe two of these parasitic folds (a Marble-cored anticline and, below, a syncline with a Cherty Limestone core: Fig. 11) on the normal limb of the main structure. These parasitic folds are refolded by a late 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. The next stop (Stop 1.2) will be at the site of this interference.

We leave this viewpoint; along the road cut 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.).

Stop 1.2:

Interference between D1 and D2 folds above the Morlungo quarries.

The road cut shows a wide variety of structural details of the interference between the D1 and D2 phases: S1-S2 foliation overprinting and intensely deformed D1 folds asymmetry, systematic indicate the SW-vergence of the D2 deformation. On the cut above the road we see an example of a sedimentary dyke at the top of the Marble, filled with resediment similar to that which constitutes the Morlungo bank.

We continue towards Stop 1.3.

Stop 1.3:

Panorama of the basal tectonic contact of the Tuscan nappe between M. Ballerino and Capanne Ferrari and of the non-metamorphic sequence of the Carrara area.

Looking to the NE, we see the Tuscan Nappe overlying the Metamorphic Complex. Viewing the W we see rocks of the Tuscan Nappe which dips toward the coastal plain, and in the distance, the above-lying Ligurian Units. Geological section A in Fig. 10 illustrates the geological structure along this profile, which from NE to SW encompasses:

- Mt. Ballerino, whose peak is made of “Calcare Cavernoso”;
- to the W we see other “Calcare Cavernoso” klippes which allow us to easily reconstruct the Tuscan Nappe basal contact up to the road near Capanne Ferrari, at the site of our next stop;
- further to the W, in the distance the steep slope which rises up to the summit of La Pizza is made of Upper Triassic and Jurassic limestone, forming a SW-dipping slope;
- in the next morphological saddle, Maestà di Castelpoggio, the Tuscan “Scaglia” formation crops out;
- further in the distance, the peaks to the W of La Maestà di Castelpoggio are made of “Macigno”;
- in the background, before the Magra River Valley, the Ligurian Units s.l. crop out.

To the NW, beyond the ridge in the foreground, the tectonic depression of the Lunigiana opens.

We continue our descent by bus for about 2 km, crossing the Sericitic Schist.

Stop 1.4:

Contact between the Metamorphic complex and the Tuscan Nappe at Capanne Ferrari

The Tuscan Nappe is separated from the Metamorphic Complex by polygenic breccia of variable thickness (Fig. 9 and Fig. 10) which contain clasts belonging to the formations of both tectonic units. Among these, clasts and blocks of dolomite and dolomitic limestone, strongly fractured, are often abundant.

There has been much debate on the geological significance of this breccia, which is everywhere at the basis of the “Calcare Cavernoso”. There are basically two divergent opinions regarding the origin of this breccia:

a) the breccia is of sedimentary origin, marine of the Tertiary age (Dallan Nardi & Nardi, 1973; Dallan, 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 this breccia;

b) 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

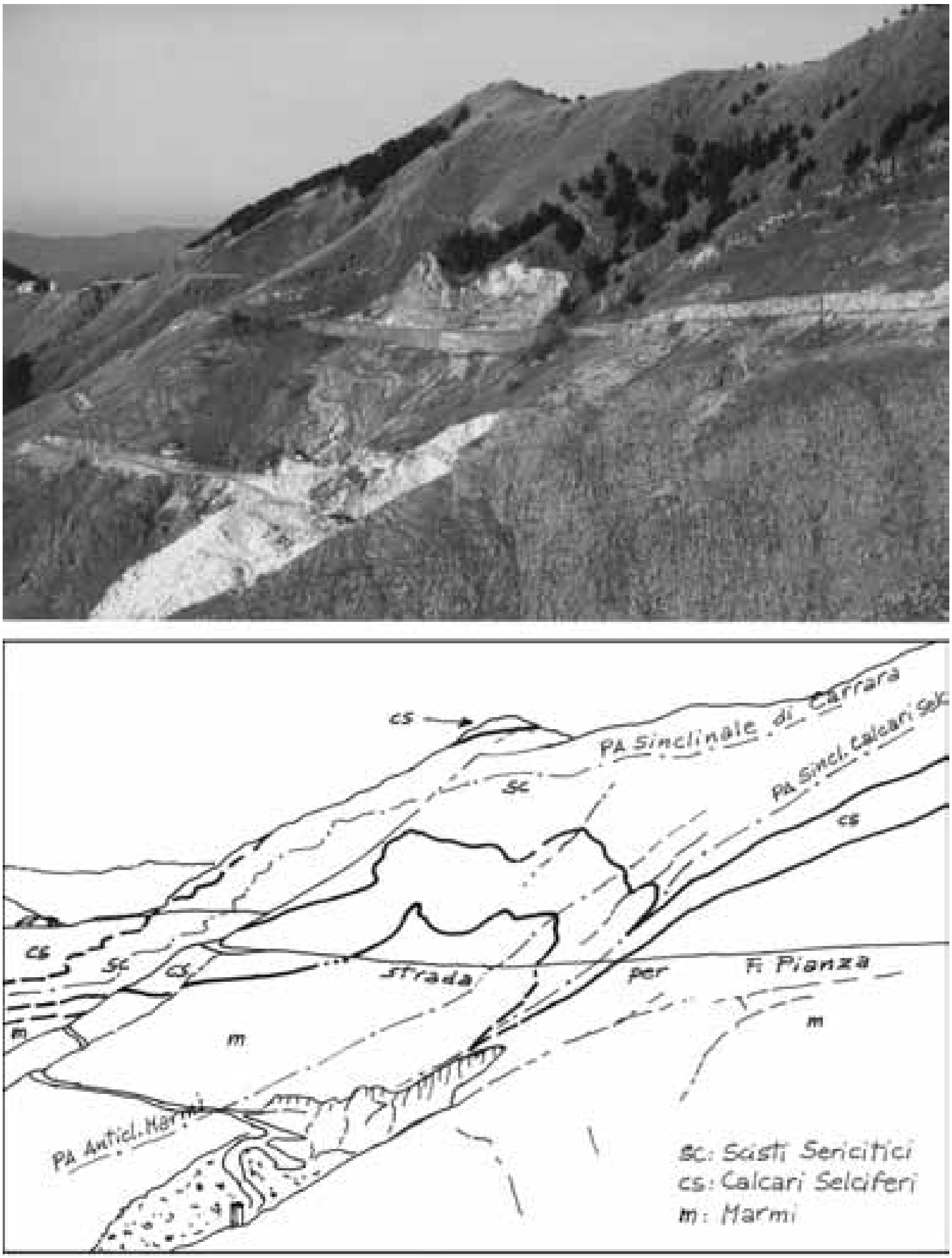

Figure 11 - View of the Murlungo-Zucco del Latte area. Parasitc folds of the normal limb of the D1 Carrara syncline are deformed by the D2 Murlungo synform and antiform.

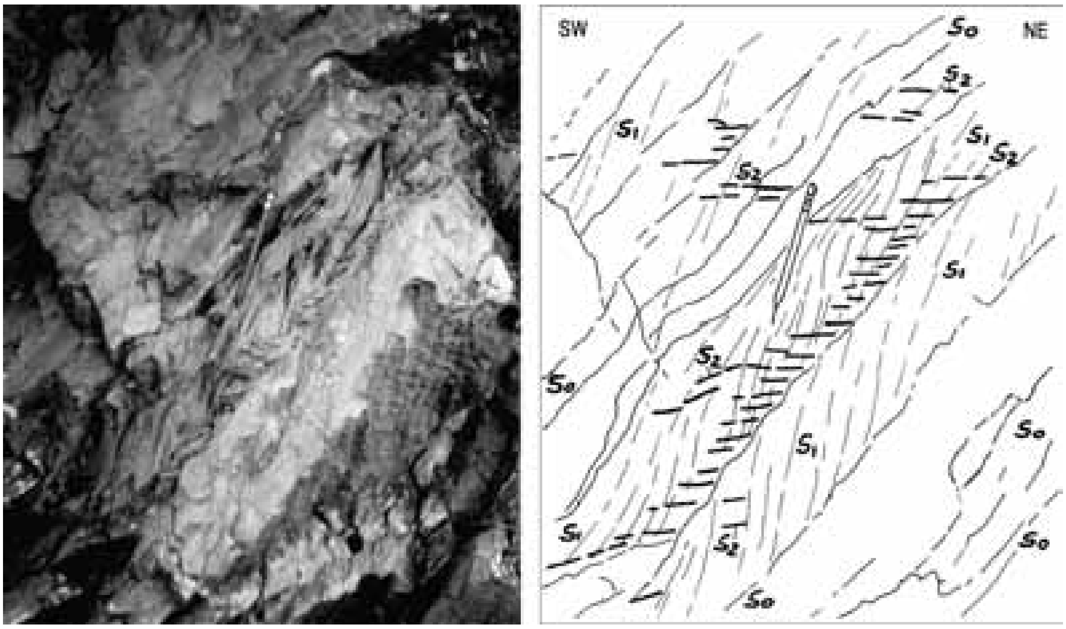

Figure 12 - S0, S1 and S2 interference in the road cut at La Maestà di Castelpoggio. S0-S1 relationships indicate a top-NE facing for D1 fold, S0-S2 relationships indicate top-SW facing for D2 fold.

phases.
The diverging interpretations for the origin of this rock are surely due to its complex history. In fact, any hypothesis must take into account its tectonic evolution during the syn- and post- collisional movement of the Tuscan Nappe, and the subsequent deep karstification it underwent; the latter is evidenced by data on oxygen isotope ratios obtained from the breccia matrix, which indicates a continental environment (Cerrina Feroni et al., 1976).
We continue in the direction of the La Maestà locality, crossing the contact between the Tuscan Nappe and the Metamorphic Complex, and finally entering in the non-metamorphic succession.

Stop 1.5:
The S0-S1-S2 interferences in the Tuscan "Scaglia" formation.

Near La Maestà the north-western end of the Foce fault brings a restricted outcrop of "Diaspri" (chert) formation in contact with the Tuscan "Scaglia" formation (Fig. 10). In this area, where the more pelitic formations of the Tuscan Nappe sequence crop out, the interference among structural elements of the NE-verging compressional phase and of the SW-verging extensional phase is evident. In particular, in the "Scaglia" along the road we see examples of S2-S1-S0 interference, with reciprocal attitude relationships as outlined in Fig. 12. Taking into account that the stratigraphic sequence is normal, the S0-S1 angular relationships indicates the NE facing direction. These angular relationships are maintained in all of the Tuscan Nappe in the Carrara area, and as further confirmation of the SW-to-NE emplacement of the Tuscan Nappe, the same ratios are present on the entire outcrop located on the eastern flank of the Metamorphic Complex (e.g. the valley of the Edron Stream valley, Vagli).
On average the S1 dips more horizontally 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 coarse cleavage in the axial planes of slight undulations which deform S0 bedding and S1 foliation; the cleavage planes are subhorizontal and have an attitude similar to that of the late schistosity in the metamorphic formations of the Carrara area.
As will be seen in the next stop, this cleavage is axial plane of the large reclined Castelpoggio fold. Along the western flank of the Apuane Alps, it is the best example of a ductile structure connected to W-verging extensional shear zones.

Stop 1.6:
The Castelpoggio fold

We walk along a stretch of road which cuts the “Calcari ad Angulati” formation. Along the first stretch we cross the normal limb of the Castelpoggio Fold (Fig. 10, section A), in which the SW-dipping S0 bedding maintains the previously observed relationships (Stop 1.5) with the S1 plane (Fig. 12). The hinge area is not well-exposed, while the overturned limb crops out along the road cut: here the S0-S1 system is overturned so that the bedding is subhorizontal and the S1 dips to the W (Fig. 13C).

A panoramic view of the entire structure and its relationship to the underlying Metamorphic Complex can be seen from the hairpin turn (see the composite section in Fig. 10 A). To the NE, the “Calcare Cavernoso” Auct. carbonatic horizon lies on the Metamorphic Complex along a slightly SW-dipping contact. On the wooded slopes of the Tecchia valley this contact strongly dips without overturning; this attitude is reached instead in the formations of the Tuscan Nappe.

The structure of Castelpoggio is therefore an S-shaped fold with a NW-SE axis which dips slightly NW. It developed in a W-verging normal shear zone located between the “Calcare Cavernoso” and the “Macigno”.

We descend back to Carrara.

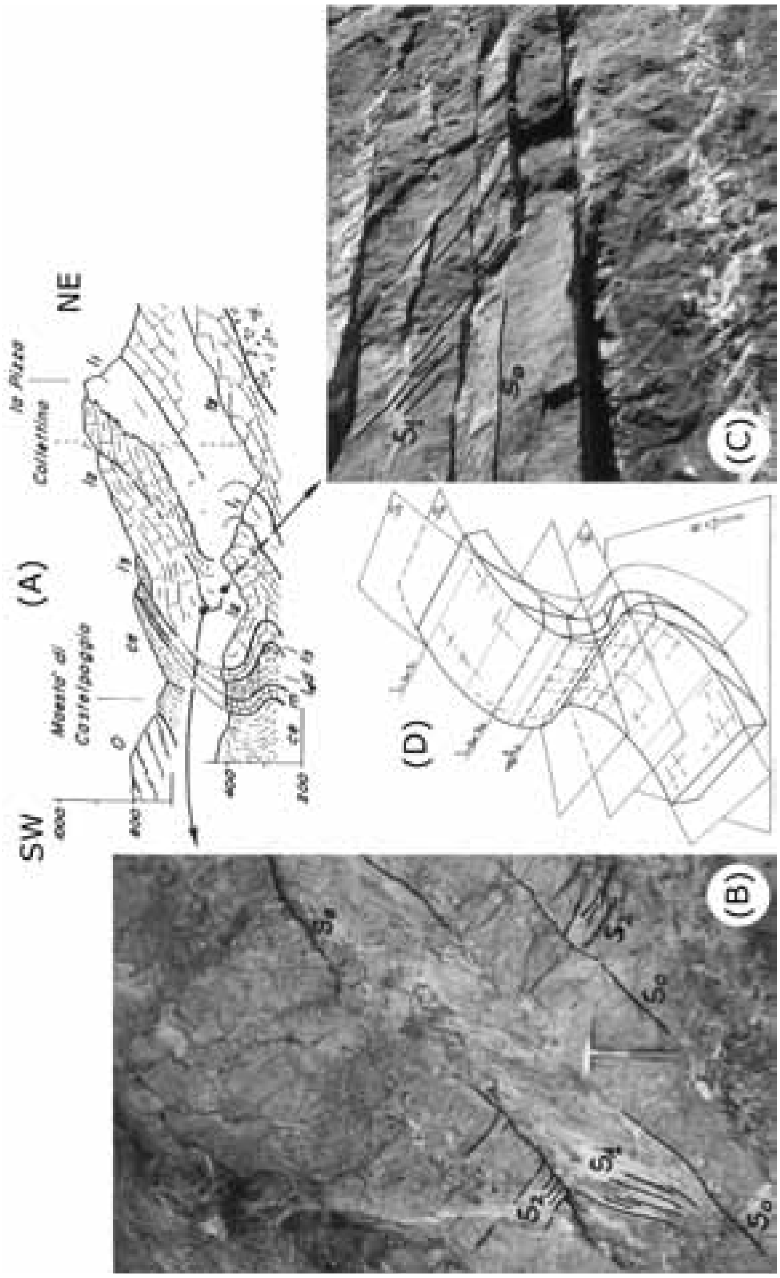

Figure 13 - (a) Detail of the Fig. 10 sections in the Castelpoggio area. (b) S0-S1-S2 relationships in the normal limb of the D2 Castelpoggio fold. (c) S0-S1 relationships in the inverted limb of the Castelpoggio fold, are opposite respect to the normal limb. (d) Sketch diagram of bedding and foliations relationships.

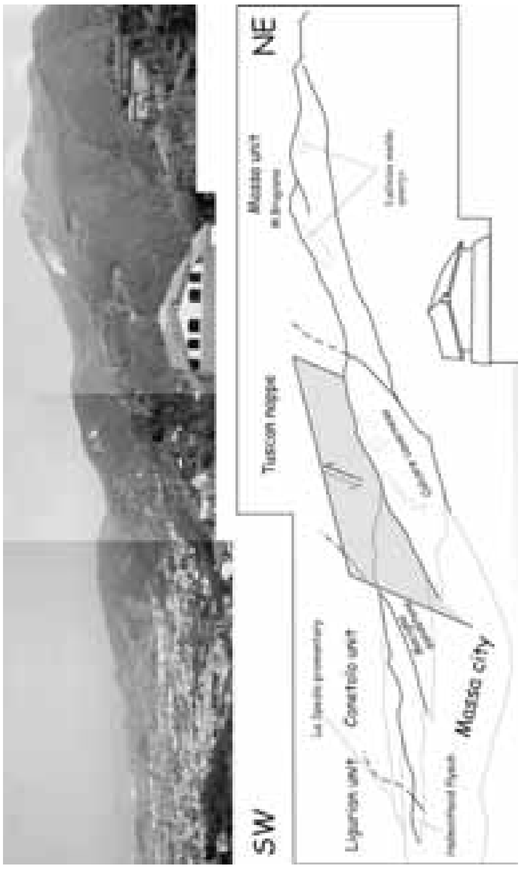

Figure 14 - Panoramic view from San Carlo near Massa. Stop 2.1.

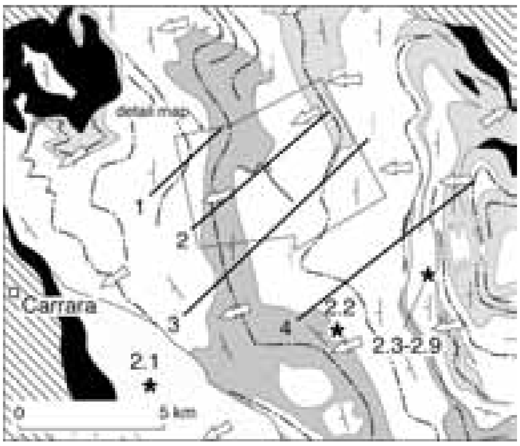

Figure 15 - Tectonic sketch map of the central Alpi Apuane. Second day stops and traces of Fig. 17 sections are located. Dotted line ("detail map") indicate the area of Fig. 18. See Fig. 9 for legend.

DAY 2

Itinerary: Massa - Pian della Fioba - Arni.
Themes: Large scale, folded structures in the central Alpi Apuane.

Stop 2.1:

Panoramic view from San Carlo Terme.

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. 14). The superimposition 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:

Panoramic view of the natural section between M. Sagro and M. Tambura from Pian della Fioba.

From the road toward Passo del Vestito, we reach one of the most suggestive geologic panoramic views in the central Alpi Apuane (Fig. 15), already illustrated in Zaccagna's section in 1881. It is one of the most complete natural sections of the Vinca Anticline. The natural section visible at this stop extends from M. Brugiana to M. Tambura (Fig. 16). The sections of Fig. 17 show the geology between M. Spallone and M. Tambura.

The panorama is characterized by two main ridges. First the Mandriola crest (above the town of Resceto, section 3 of Fig. 17) is developed. Toward the NE it joins at M. Cavallo; in the distance from east to west the ridge includes the peaks of the mountains: Tambura, Cavallo, Contrario, Grondilice, Rasori, Sagro, Spallone (the central part of the panorama is represented in sections 1 and 2 of Fig. 17). The axes of the structures dip shallowly (10 to 20 °) northward and therefore from north to south deeper parts of the structure crop out:

The normal limb of the D1 Vinca anticline crops out in the relief of M. Spallone-Sagro, and is moderately inclined westward and, from east to west includes Grezzoni, Dolomitic marbles, Marbles (east edge of Sagro and M. Spallone) and Cherty limestone (peak of M. Sagro and M. Spallone) (section 1 of Fig. 17). The core of the anticline is made of phyllite and volcanic rocks of the Paleozoic basement, crops out at the crest of M. Rasori between M. Sagro and M. Grondilice (section 1 of Fig. 17) and further south toward the Forno valley from our observation point .

The overturned limb of the Vinca anticline crops out

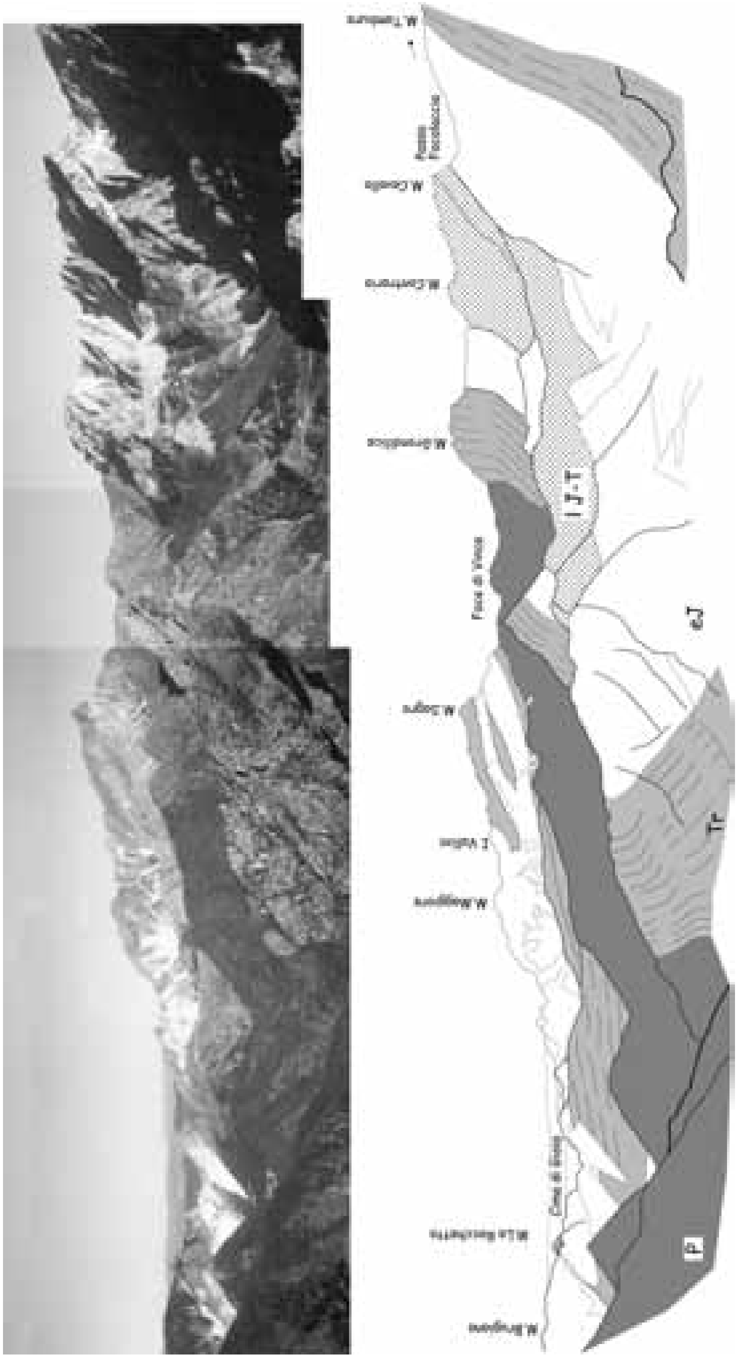

Figure 16 - Panoramic view from Pian della Fioba. Stop 2.2..

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 (section 2, 3 of Fig. 17)

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 extreme eastern side of the panorama at Campaniletti (section 4 of Fig. 17).

The effects of the post-collisional tectonics are quite evident also on 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 of the overturned limb of the Vinca Anticline is produced by activity of D2 extensional shear zones in the less competent formations of the Orto di Donna syncline (Cretaceous-Eocene Phyllite and calcschist) and the Vinca anticline (Paleozoic phyllites) that superpose and interfere with the earlier (D1) structures. The most objective representation of this interference is shown in the profile of Fig. 18, constructed normal to D2 fold axis (gently NW-dipping). In this profile we can see the interruption of

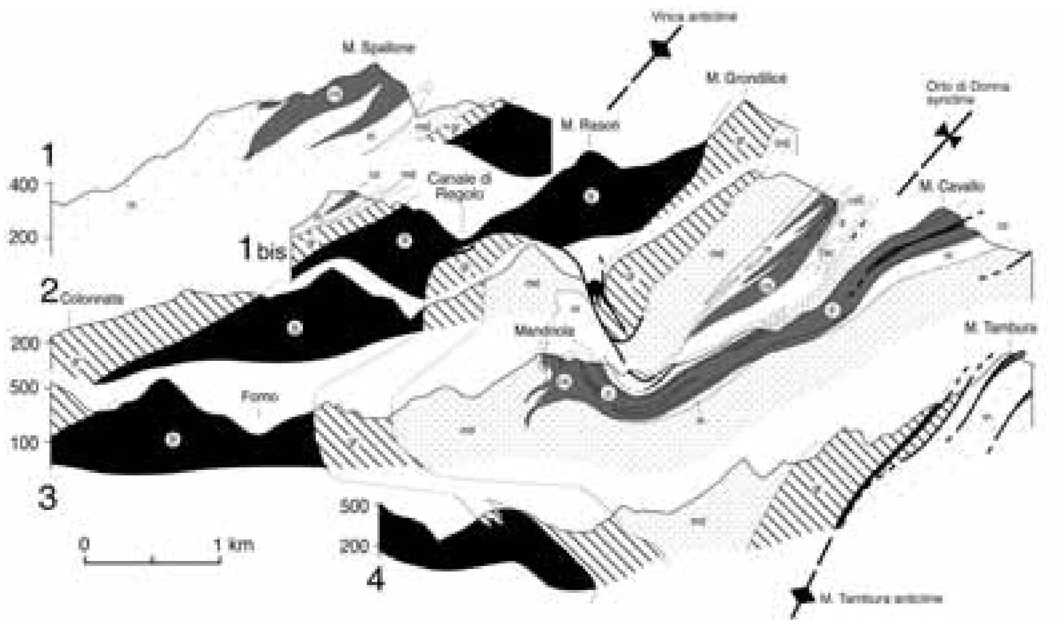

Figure 17 - Geological cross section in the Frigido valley, central Alpi Apuane. See Fig. 15 for section traces. Legend as in Fig. 10.

the Triassic dolomite formation between the hinge of the D2 M. Rasori antiform and the D2 M. Rasori synform. This zone of weakness must certainly have influenced the location of the two D2 folds. These folds have steep axial planes, involve only Triassic dolomites and the upright limbs of the Vinca Anticline and Orto di Donna syncline are not refolded.

The Cretaceous-Oligocene phyllites and calcschists in the core of the Orto di Donna syncline and the Paleozoic phyllites in the core of the Vinca anticline suffered a strong west-verging internal strain, testified by an intense folding at the micro to mesoscale and by a pervasive S2 schistosity. This foliation in the

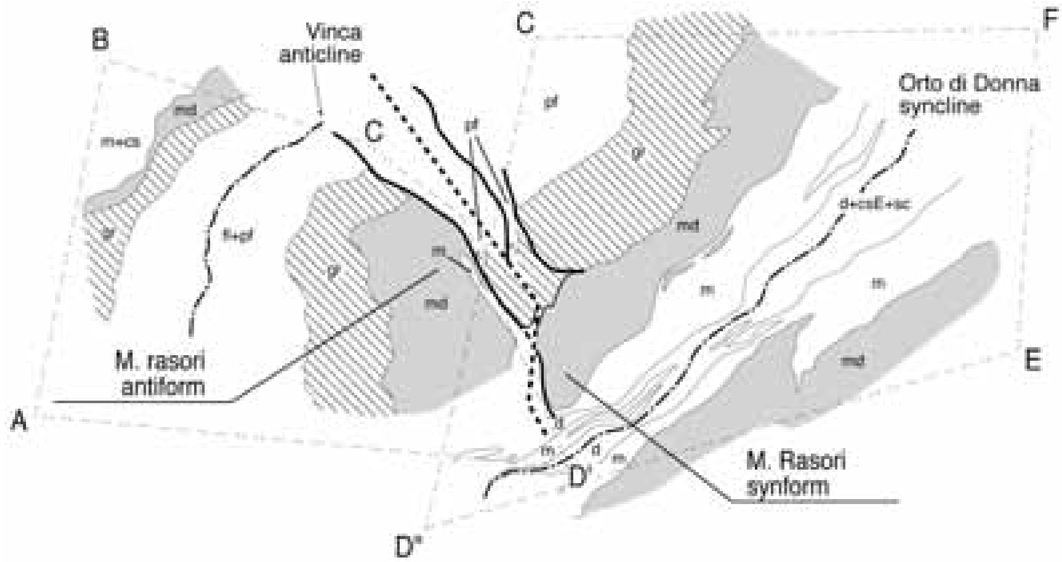

Figure 18 - Profile in the Frigido valley for the detail area indicated in Fig. 15.

Cretaceous-Oligocene phyllite becomes the most evident surface at the outcrop scale. The cores of the two D1 phase folds acted therefore as normal shear zones during the D2 extension.
The transport toward the west that occurred in the "ductile" core of the Orto di Donna syncline and the later ductile faults exhaust toward the west near the closure, in that direction, of the incompetent formations in the hinge of the same syncline. On the contrary, the phyllites in the core of the Vinca Anticline open progressively toward the west, permitting a strong internal deformation in this rocks. A kinematic sketch of the evolution in this area is given in Fig. 19. The top-W transport generated a strong parallel compressional component in the dolomite in the overturned limb of the Vinca Anticline and therefore developed approximately symmetric folds that nucleated in a zone of D1 boudins.
The weak asymmetry toward the west of the M. Rasori antiform and of the M. Rasori synform (Fig. 18) is probably due to the D2 W-verging shear component that affected all the area.

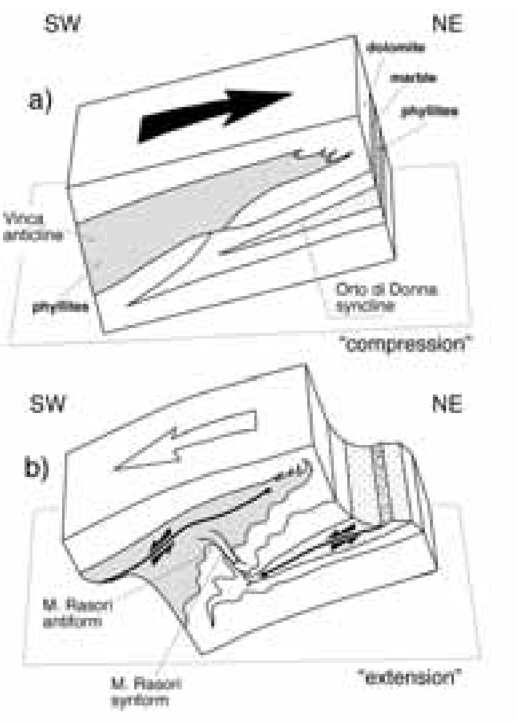

Figure 19 - D1 and D2 deformation interference in the Frigido valley. Late structures in the inverted limb of the D1 Vinca anticline are interpreted as "transfer folds" between two ductile shear zones.

Along the road the contact between the Paleozoic basement and the Triassic cover is exposed, in the normal limb of the Vinca anticline. This contact is strongly inclined toward the west , the basement here consists of Paleozoic porphyritic volcanic rocks, and the contact with the Triassic dolomite is marked by a thin metaconglomerate horizon. The structure at the outcrop scale is characterized by a schistosity that is subparallel to the stratification, well developed in the basement rocks. This foliation is not developed in the competent Triassic dolomite, where the original sedimentary structures are still preserved. The main foliation is the D1 axial plane foliation of the Vinca anticline. A shallowly E-dipping crenulation cleavage develop a shallowly N-plunging lineation. The main schistosity (S1) is attributed to the syncollisional Apennine compression (D1), the crenulation (S2) to the ductile extensional event connected to the denudation and exhumation of the Apuane Metamorphic Complex (D2). In the basement rocks, a second steeply inclined, EW-trending weak crenulation cleavage is developed and cuts all the previous structures. At the valley of the Acerello tunnel, the interference between two crenulations creates small dome and basin structures on the S1 schistosity. This latest crenulation is developed by local late D2 shear zones parallel to the Frigido valley.

Stop 2.3:

Core of the 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 exposed here. The Grezzoni formation (dolomites) of the overturned limb is reduced to a few metres 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 2.4:

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 Apuane Alps. 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. 20). The orientation of the contacts in the Metamorphic Complex, dipping toward the WSW on the western flank of the valley and toward the ENE 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 ten 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 (1881a) makes reference in the last paragraph of his first work.

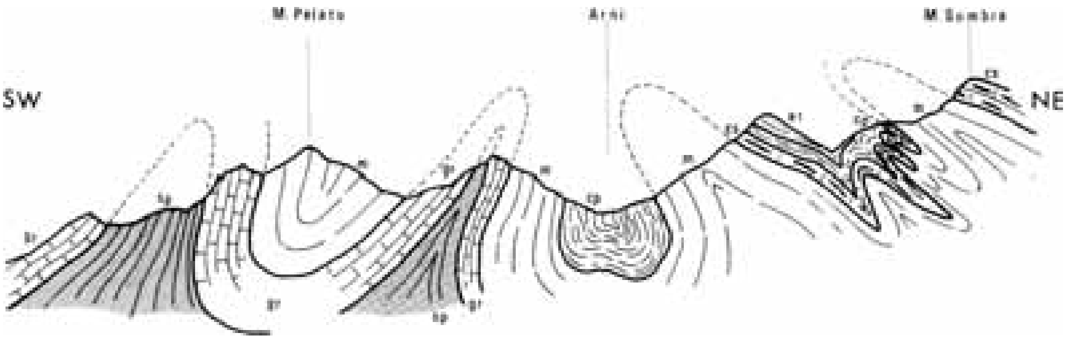

Figure 20 - The structure of the Arni valley after Lotti (1881a, b). sp: Paleozoic phyllites, gr: Triassic dolomites, m: marbles, cs: certy limestones, cp: calcschists, ar: metasandstones flysch .

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 vergence of the Alpi Apuane” resisted until a few years ago. Only in 1979 (Carmignani & Giglia, 1979) was the structure of the Arni valley 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 geologic structure of the area is reported in Fig. 21, Fig. 22, Fig. 23 and Fig. 24.

As shown in the sections of Fig. 22, the Liassic Marble in the overturned limb of the Arni syncline rest in tectonic contact directly on the Paleozoic basement (the Triassic dolomites are reduced to a few discontinuous cataclastic levels).

In detail, the D1 structure is complicated by:

a) D1 folds and ductile thrusting that caused repetitions of stratigraphy;

b) sheath 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 (see diagrams in Fig. 23).

D1 structures are deformed by two large folds that are overturned to the west (Arni Synform and 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. 22), whose

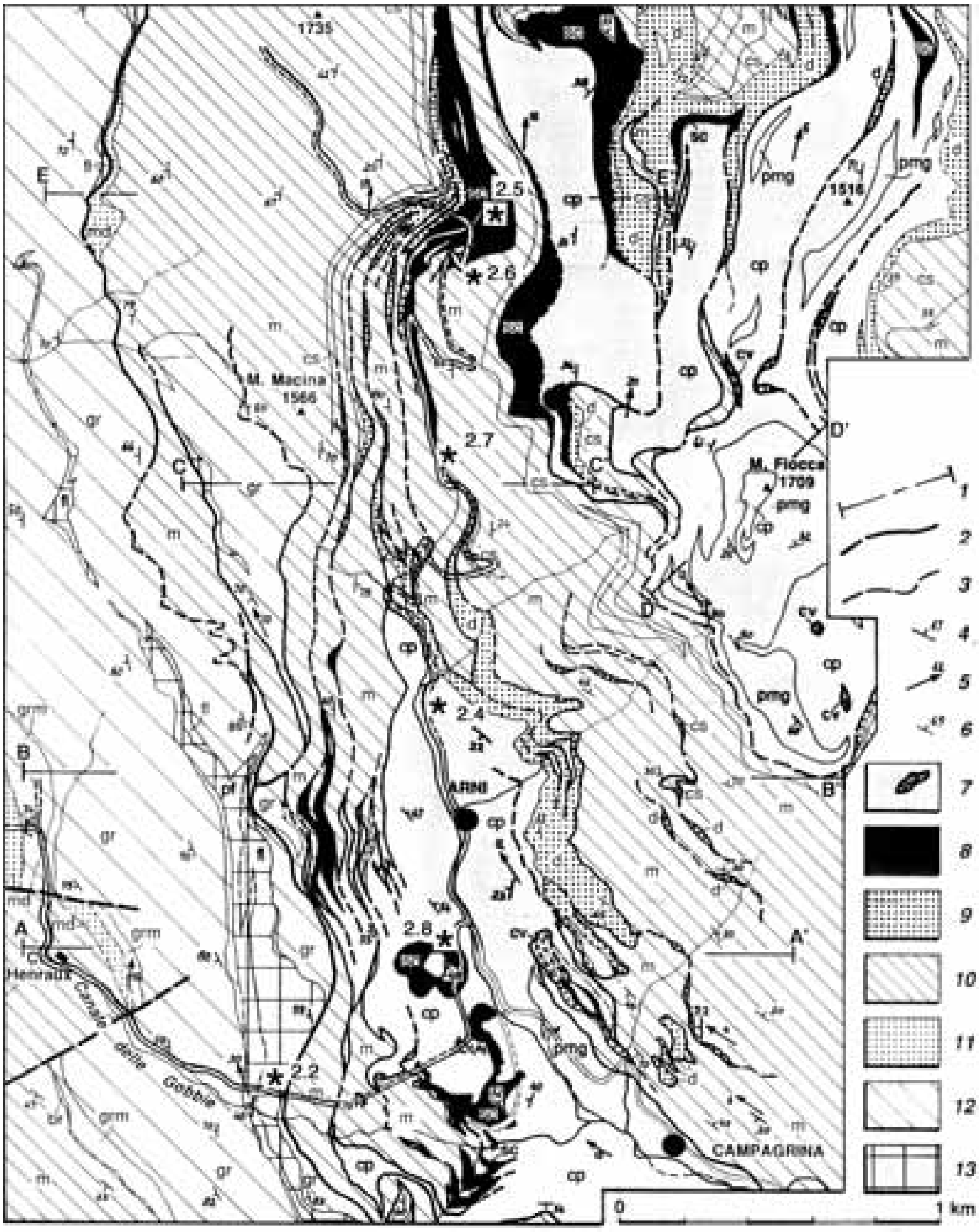

Figure 21 - Geological map in the Arni valley. 1: traces of sections of Fig. 22; 2: faults; 3: tectonic contacts; 4: D2 foliation; 4: D2 fold axis; 6: D1 foliation; 7: "Pseudomacigno" metasandstones (pmg), calcschists (cp), "Calcare cavernoso" (cv); 8: "Scisti sericitici" phyllites (sc); 9: Cherts (d); 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).

overturned limb crops out on the eastern side of the Arni valley and has a width measured normal to the axes of about one km. The kinematics of this structure is consistent with a km-scale normal shear zone, delimited by Grezzoni of M. Tambura and whose lower limit does not crop out.

In Fig. 25 a restored section shows 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 g=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 is 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”).

To summarize, the complex interference pattern of the Arni valley can be understood in terms of:

1) an inhomogeneous E-verging shear deformation during D1 (Fig. 25A);

2) a W-verging shear deformation during D2 (Fig. 25 B, C, D).

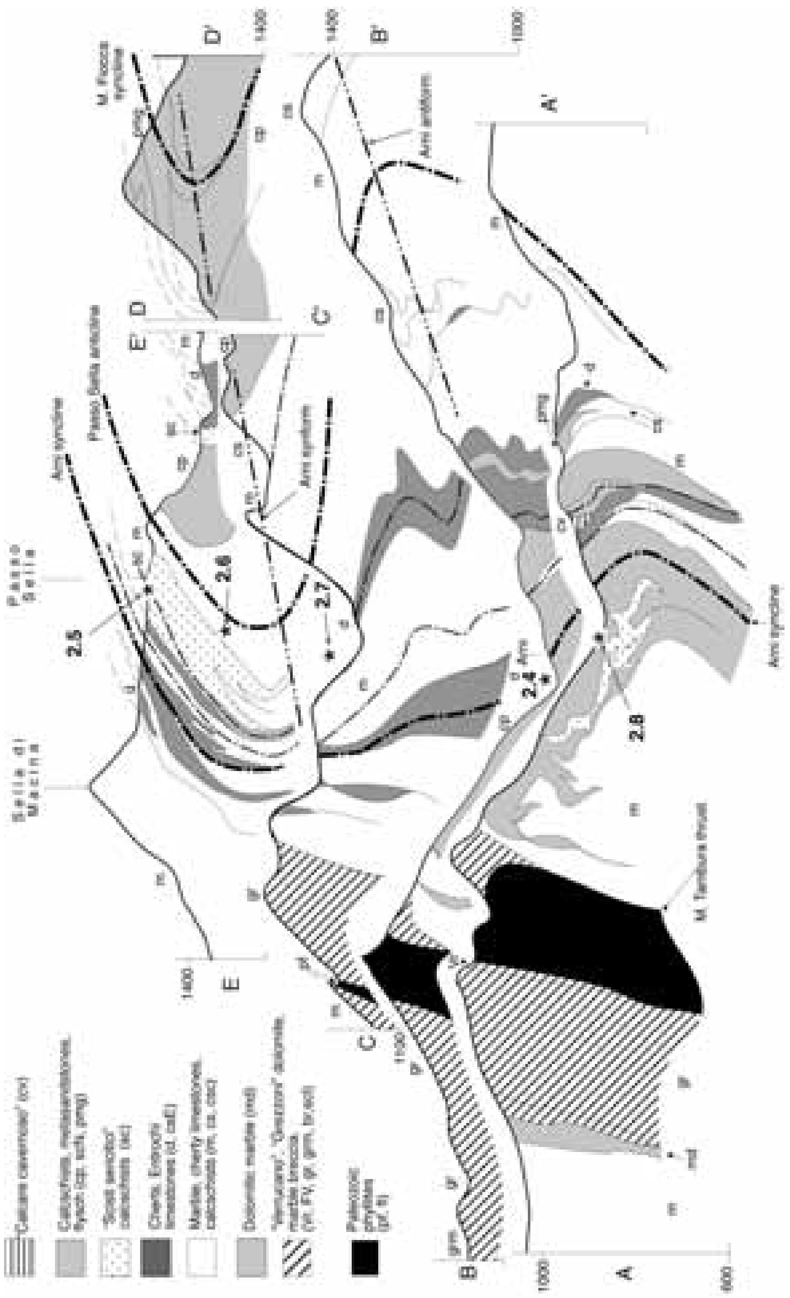

Figure 22 - Geological cross section in the Arni valley. See Fig. 21 for locations.

Stop 2.5:

Panoramic view of the eastern side of M. Sella

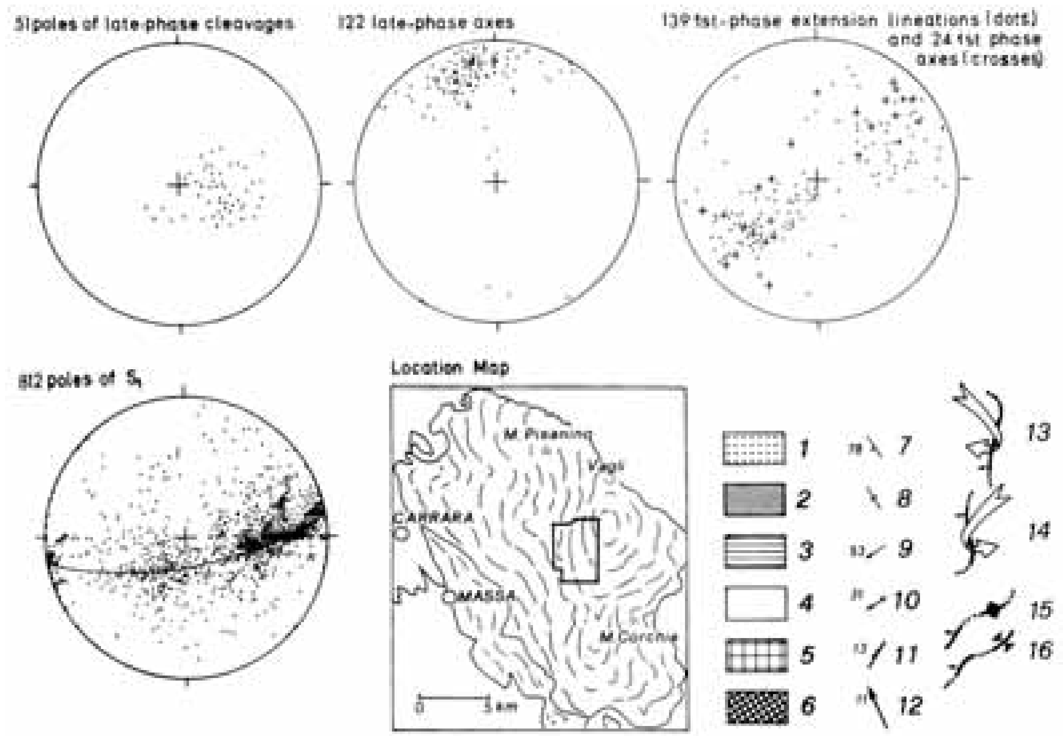

Figure 23 - Stereograms and legend for the geological map of Fig. 24. 1: Metasandstones (Upper Oligocene); 2: Calcschists, cherts, phyllites, (Dogger-Eocene); 3: Cherty Limestones (Middle-Upper Liassic); 4: Marble (Lower Liassic); 5: Dolomite (Upper Triassic); 6: Paleozoic Phyllites; 7: S1 foliation; 8: S1 foliation vertical; 9: D1 stretching lineation; 10: D1 minor fold axes attitude and D1 intersection lineations; 11: S2 foliation; 12 : D2 minor fold axes attitude and D2 intersection lineations; 13: axial plane trace of the Arni synform; 14: axial plane trace of the Arni antiform; 15: Minor D2 antiform axial plane traces; 16: Minor D2 sinform axial plane traces.

- M. Roccandagia.
Toward the north the Arnetola valley opens, where the structure we saw before continues in the Arni valley.
The left side of the Arnetola valley is comprised of a pile of isoclinal structures cored by marble (anticlines) and Pseudomacigno or Sericite Schist (synclines) under the stack of M. Tambura. These isoclinal synclines reach the Sella pass and proceed south toward the Arni syncline.
Descending from the Passo Sella we cross two minor anticlines cored with marble separated by Calcschist and Sericite Schist of the Arni syncline core. The marble cores contain very few minor D2 structures and instead show well-developed S1 and stretching lineations. The Sericite Schist in the cores of synclines are often in direct contact with the breccia containing clasts of marble ("arabescato" marble variety). Because of the deformation and metamorphism, it is difficult to establish if these sequences were complete or incomplete: the sporadic presence of breccia with clasts of grey or red flint seems to suggest a local erosional hiatus.

Stop 2.6:

The outcrop scale structures along the road descending from Passo Sella

At the first turn, in the core of a small anticline of marble, pronounced elongation lineations are evident. The form of the marble breccia clasts show the strong internal deformation experienced in this zone during the collisional phase (D1).
From this view point, the D1 structure of the high Arni valley is well exposed. The core of the Arni syncline is represented by the "Cipollini," formation (calcschists) bounded by green Sericite schist. Even in the panorama, transport by late ductile shearing (extensional) is visible above all within the Sericite Schist that shows folds with inverted limbs..
Above the Cipollini-cored syncline (Arni syncline) a pile of isoclinal structures is folded together: marbles,

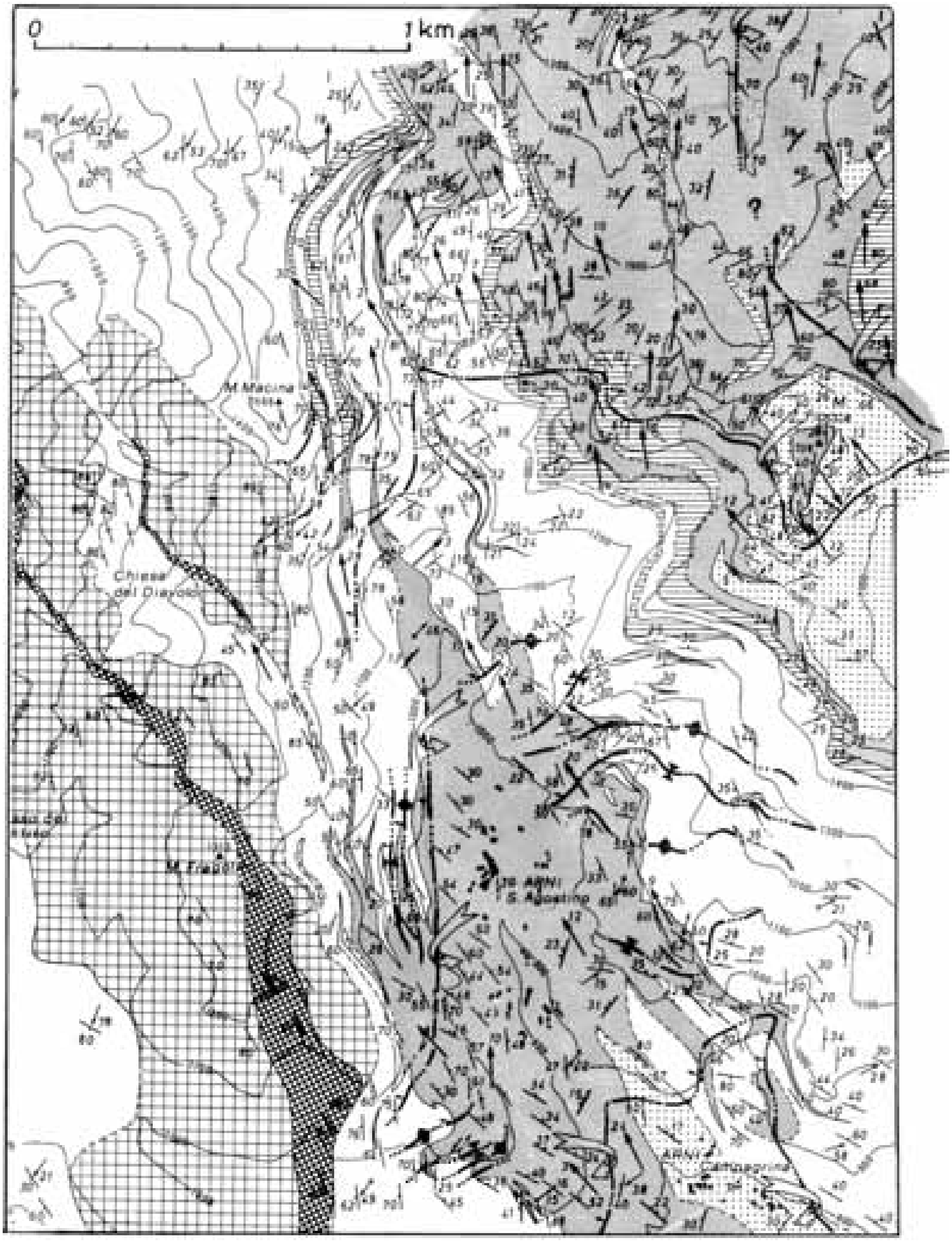

Figure 24 - Structural map of the Arni valley. See Fig. 23 for legend.

cherts, Sericite schist and modest thicknesses of Cherty limestone.

Passing the first two turns, we cross the contact

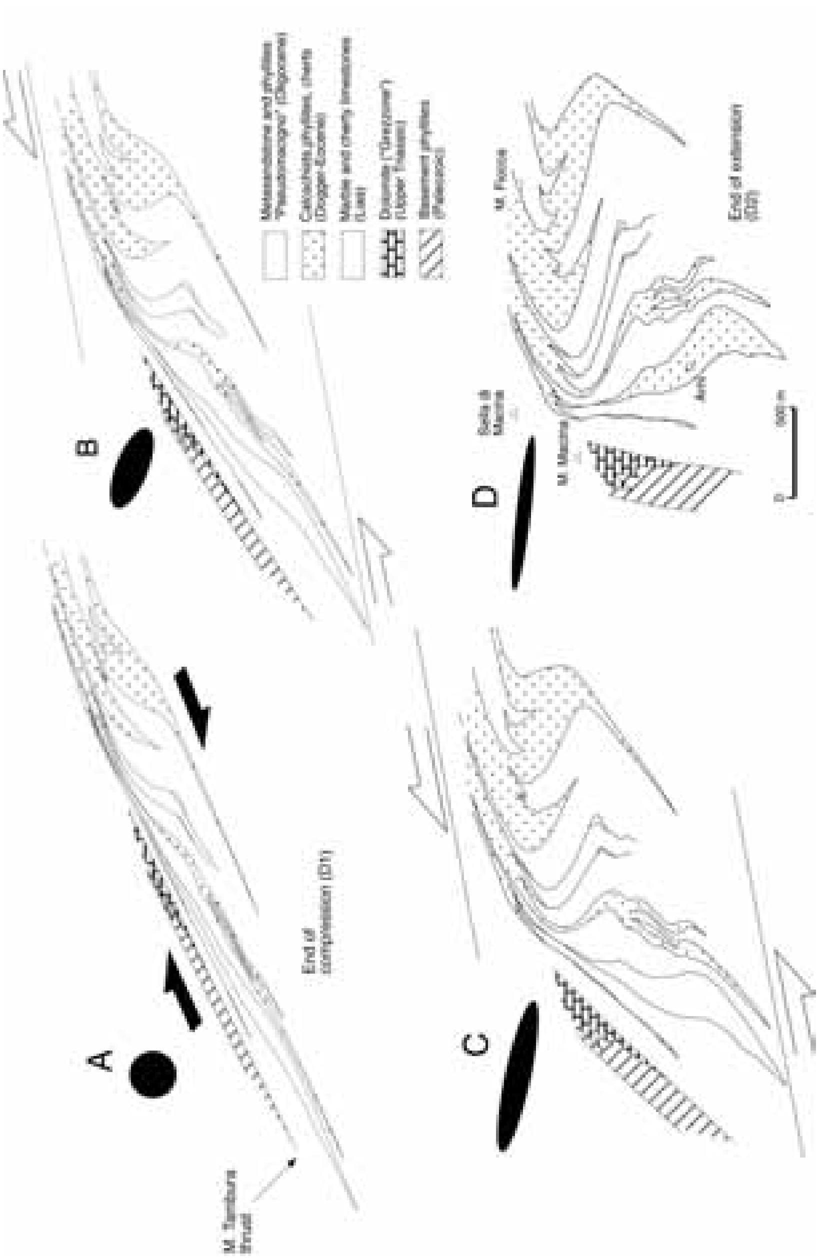

Figure 25 - Reconstruction of the kinematic evolution of the tectonic structures in the Arni valley.

Sericite Schist-Marble. The contact is folded and D1 folds are rotated (approximately with NE oriented fold axes) into parallelism with the extension lineation ("sheath folds").

The road continues within the Marble core of the Sumbra anticline. In this stretch, as we descend, we approach the hinge zone of the Arni synform, so that up high, we pass the S1 inclined toward the west, and toward the bottom, S1 is subvertical. Along all of this stretch steeply dipping D1 extension lineations are well exposed.

Stop 2.7:
Structures in the marble quarry ("Arabescato" and "Arni fantastico")

At the confluence of the main valley with the Fosso del Mantello on the left side of the road, an "arabescato" quarry is open. The quarry walls show that the breccia was tremendously flattened (X-Z ratio up to 12:1).

On the right side of the road, the "Arni Fantastico" quarry exposes tight minor synclines of D1 within the marble, refolded by D2 folds. In this zone, the hinge zone of the Arni synform is developed and D2 minor folds begins to show "M" symmetry.

Going down toward the Canale del Burrone, we enter the lower limb of the Arni synform and the D1 foliation, axial planes of the folds of this phase dip towards the east. The symmetry of the minor D2 folds that had been "S" in part of the valley and "M" at the confluence of the Fosso del Mantello, is now "Z" shaped. We cross the town to the front of the church.

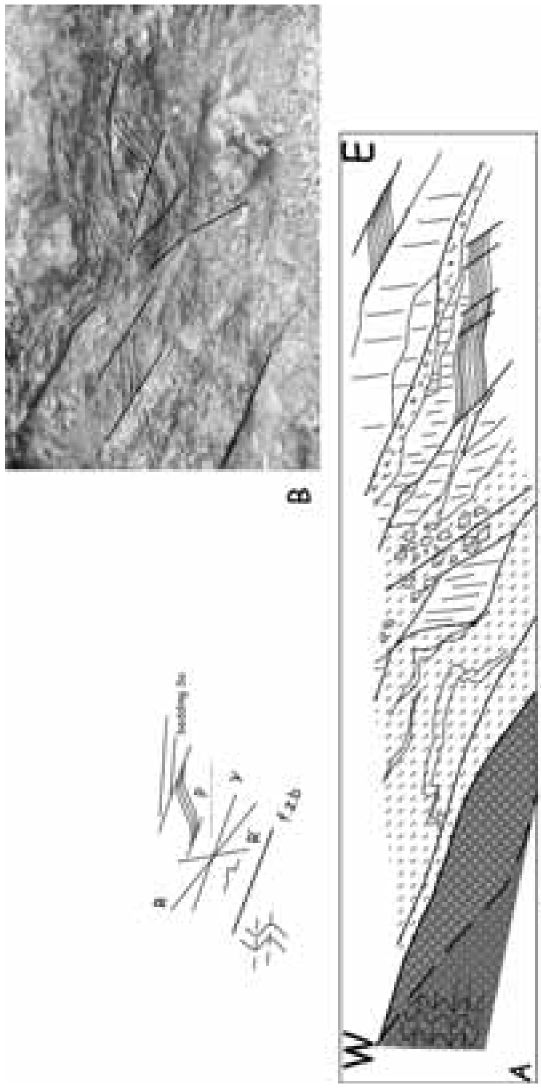

Figure 26 - (a) Schematic representation of structural elements at the Apuane/Tuscan nappe contacts, Stop 3.1. (b) Detail of foliated cataclasites base of Tuscan nappe. Outcrop width: about 20 m

Stop 2.8:

Panoramic view of the hinge zone of the Arni antiform

In front of the town church, along the initial stretch of the road that goes to the Passo del Vestito, on the left side of the valley, we can follow the development of the large D2 structure at depth.

The Arni Synform, studied from the upper limb (Passo Sella) to the lower limb (Fosso del Burrone), develop at depth an antiform of analogous size and style. On the left side of the Arni valley, the hinge of the antiform is well exposed. The "M" zone of the structure is seen in an outcrop of chert where D1 is vertical. From this position it is possible to follow the hinge of the synform, which crops out above the large marble quarry open on the right side of the Fosso del Burrone (Faniello quarry) with the hinge of the antiform, which crops out to the right of the church.

DAY 3

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.

Stop 3.1:

Tectonic contact between the Tuscan nappe and the Metamorphic unit in the eastern Alpi Apuane.

Along the road to Vianova we can observe the contact between the metamorphic rocks and the Tuscan nappe. The Calcare cavernoso is lacking here and the contact is between Liassic carbonates ("Calcari ad Angulati") and the Oligocene metasandstones and slates (PseudoMacigno fm). The contact is characterized by a pluridecametric thick fault zone in which it is possible to distinguish different domains. In the footwall rocks (Pseudomacigno fm.) plurimetric to decimetric-scale D2 folds associated with a sub-horizontal axial planar foliation can be recognized. The metasandstones are affected by well developed vein-systems. The dominant vein-system whose geometry seems to indicate a syn- to late development in respect to folding (Fig. 26) shows en-enchelon arrangement suggesting a top-to-east kinematic. At the top of folded domain a metric thick cataclastic Pseudomacigno can be recognized.

This cataclastic domain is in contact with plurimetric thick fault gouge, showing evidence of confined fluid infiltration testified by the red, violet and yellowish colour of the matrix. The matrix contains clasts with different grain size of footwall and hangingwall rocks and within it decimetric scale folds can be recognized. In spite evidence of non-cylindric fold geometry the vergence of most of these folds is coherent with top-to-east kinematics. The fault gouge is overlain by the cataclastic carbonates at the base of Tuscan nappe. Well developed P-foliations and the different types of Riedel-fracture geometry can be observed, still coherent with general top-to-east kinematics.
Arguments related to geometric relationships between 1) original bedding So, R-R' fractures and P-foliation in hangingwall carbonates; 2) sub-horizontal D2 foliation and fault zone; 3) lack of the Calcare Cavernoso indicating a cut-down section of the fault planes and 4) regional consideration, allowed us to interpret the structure as a low angle normal fault related with the exhumation of the Alpi Apuane metamorphic complex.

Stop 3.2:

D1 and D2 deformation in the Orto di Donna valley.

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 limestone 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 chert 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 synclines 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.

Stop 3.3:

Quaternary deposits and their relationship 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 is cut westward by a NE dipping normal fault. The conglomerates are therefore 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 eastern side of the Alpi Apuane Metamorphic complex and that is responsible for the recent uplift of the metamorphic rocks. Assuming this relationships between conglomerate deposition and faulting we get a very recent age (Pleistocene) for the uplift of the Alpi Apuane area.

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