EVOLUTION OF GEOLOGICAL INTEPRETATIONS IN THE ALPI APUANE METAMORPHIC COMPLEX, AND THEIR RELEVANCE FOR THE GEOLOGY OF THE NORTHERN APENNINES

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ABSTRACT

It is presented here, after a short introduction on the geology of the Alpi Apuane metamorphic complex, a review of the most important tectonic concepts that where developed in the Alpi Apuane area or that from here were applied to the geology of the Northern Apennines. Worth to mention are the discussions about the notion of large thrust sheets in the nappe building of the Apennines, the indroduction of the structural analysis methods of deformed rocks, the discussion about the transport and emplacement direction of the higher tectonic units of the Northern Apennines nappe stack, the recognition of recumbent km-scale folds developed during extension. The quite comprehensive reference list gives credits to most of main studies have undertaken in the area, especially from a tectonic point of view.

INTRODUCTION

The Alpi Apuane area is the largest tectonic window in the Northern Apennines, where deformation and nappe superposition resulting from Tertiary collisional tectonics may be studied in detail. Because of the good exposures the area assumed in the past a key role in unravelling the tectonic structure of the entire Northern Apennines, many different hypotheses proposed during the years to explain the geolgy of the Northern Apennines are strongly based on field observations from this area.

In this review paper, we first present an overview of the geology of the Alpi Apuane metamorphic complex, i.e. of the metamorphic units that outcrops in the central part of the Alpi Apuane tectonic window, and then we illustrate the evolution of the geological interpretations of the area and their relevance in understanding the geology of the Northern Apennines.

2 GEOLOGY OF THE ALPI APUANE AREA

We deliver here an overview of the geology of the Alpi Apuane metamorphic complex and its surrounding. The following field-guides provide a deeper insight about the regional geology of the area:

- 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 Goscientists, 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.
- Carmignani, L., Conti, P., Meccheri, M. and Molli, G. (2004). *Geology of the Alpi Apuane Metamorphic Complex (Alpi Apuane, Central Italy).* 32nd

International Geological Congress, Florence August 2004. Excursion Guide Book, Post-Congress Field Trip.

Within the Alpi Apuane region different tectonic units derived from the Tuscan domain (Apulia microplate) are traditionally distinguished (fig. 1):
- the Tuscan nappe;
- the Massa unit;
- the "Autochthon Auct." unit.

2.1 The Tuscan nappe

The Tuscan nappe (fig. 2) 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 known as 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 shows a variable thickness between 2000-5000 m.

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 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 thick Middle to Upper Triassic cover (fig. 2). The pre-Mesozoic basement is formed by ?Upper Cambrian-?Lower Ordovician phyllites and quarzites, Middle Ordovician metavolcanic and metavolcanoclastic rocks associated with metasandstones and phyllites and rare Silurian Orthoceras-bearing metadolostones and black phyllites.

The Mesozoic cover sequence consists of a metasedimentary Middle-Upper Triassic sequence ("Verrucano fm.") characterized by the presence of Middle Triassic metavolcanic rocks. 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 "Autochthon" Auct. unit

The "Autochthon" Auct. unit is made up by a Paleozoic basement unconformably overlain by the Upper Triassic-Oligocene metasedimentary sequence (fig. 2). 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 with intercalated mafic volcanic rocks, ?Middle Ordovician metavolcanics and metavolcanoclastics, ?Upper Ordovician quartzic metasandstones and phyllites, Silurian black phyllites and Orthoceras-bearing metadolostones,?Lower Devonian calcschists. Also the basement rocks in the "Autochthon" Auct. unit recorded a pre-Alpine deformation and greenschist-facies metamorphism as the Massa unit, 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 dolomites ("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 turbidite 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 alii*, 1986; Di Pisa *et alii*, 1987; Jolivet *et alii*, 1998; Molli *et alii*, 2000b).

The regional tectonic setting of the Alpi Apuane is well known and generally accepted by researchers belonging to different geological schools. 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

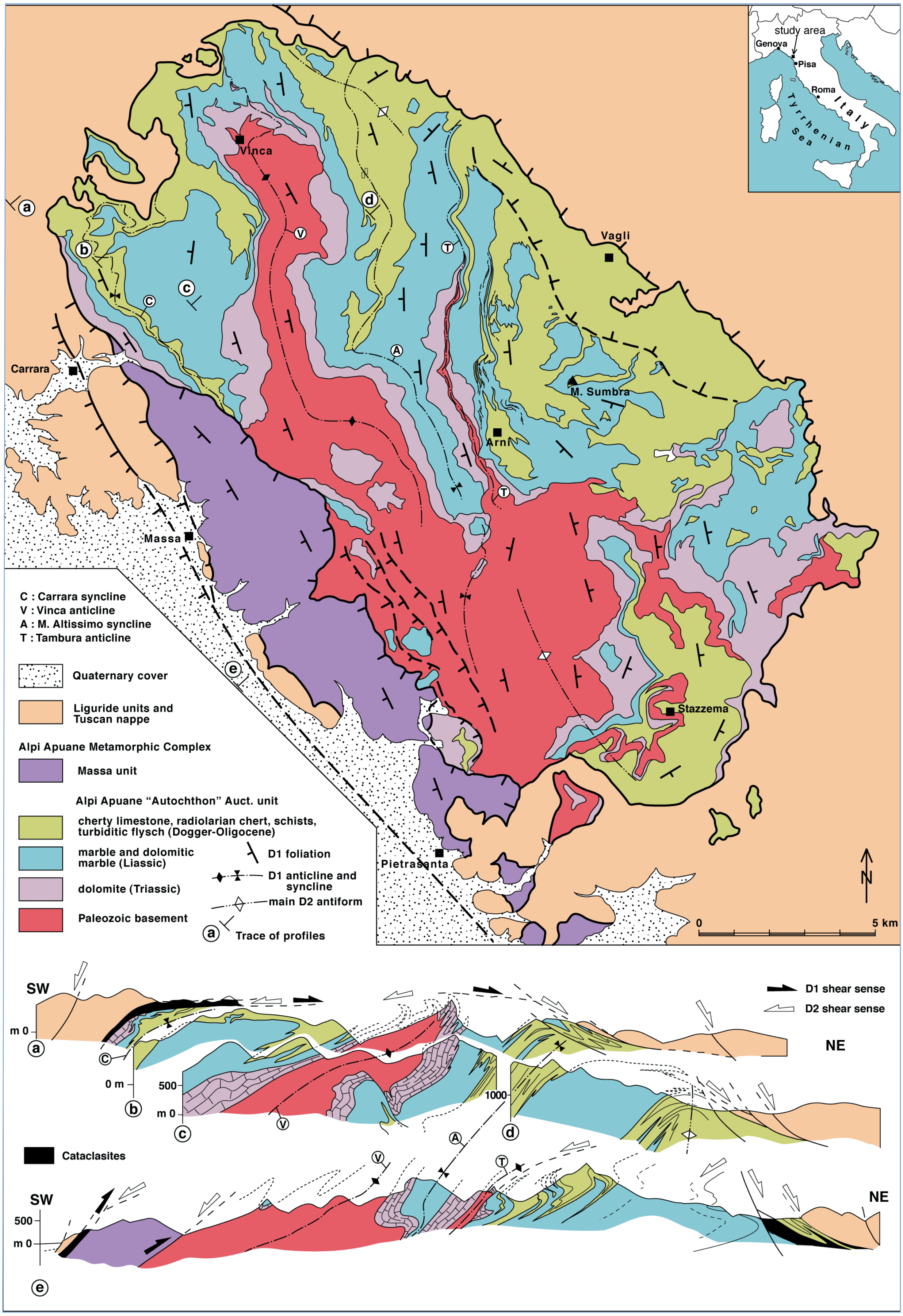

Fig. 1 - Geological sketch map of the Alpi Apuane area

debate focuses 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 have been recognized: the D1 and D2 events (Carmignani & Kligfield, 1990). They are classically regarded as the result of the progressive deformation of the Northern Apenninic continental margin during collisional and late to post-collisional processes.

D1 nappe emplacement occurred with development of km-scale NE-facing isoclinal folds, SW-NE oriented stretching lineations (L_1) and a greenschist regional foliation (S_1). In more detail, the D1 event may be subdivided into an "early folding" phase and a later "antiformal stack" phase. The first one produced recumbent isoclinal folds and an associated flat-lying axial plane foliation, while in the latter local isoclinal folds and metric to plurimetric-scale shear zones with top-to-east/north east sense of movement formed.

During D2 event 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 (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 metaconglomerates.

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. Paleozoic basement rocks core the two main anticline structures, whereas Mesozoic metasediments are present in the core of synclines (fig. 1).

A nearly 90° change in orientation of D1 fold axes is described from the WSW to ENE across the Alpi Apuane. 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 alii*, 1993a). 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 kinematics data allowed to interpret the D1 history as the result of (1) underthrusting and early nappe stacking within the Apenninic accretionary/collisional wedge (fig. 3B); (2) "antiformal stack phase" in which further shortening and a crustal scale duplex are realized (fig. 3C). The original paleotectonic setting and its lateral heterogeneities strongly controlled the development of D1 structures.

2.3.2 D2 structures

Different generations of later structures referable to the post-nappe D2 deformation event overprint all the D1 structures and tectonic contacts. Typical D2 structures are syn-metamorphic, variously sized high strain zones and well developed fold systems mainly associated with a low dipping to sub-horizontal axial planar foliation (S_2) of crenulation type. Upright kinks and different generations of brittle faults, which accomodate the most recent tectonic history, mainly represent late stage D2 structures.

According to classical interpretations (Carmignani *et alii*, 1978; Carmignani & Giglia, 1979; Carmignani & Kligfield, 1990) a complex mega-antiform with Apenninic trending axis (nearly N 130°-170°), and corresponding to the entire width of the Alpi Apuane window, was realized as result of the D2 history. All around the antiform, second order asymmetric folds facing away from the dome crests are described and, at scale of the whole Alpi Apuane, reverse drag-folds having "S" and "Z" sense of asymmetries can be observed on the southwestern and northeastern flanks, respectively. These minor structures form series of folds at different scale (from centimetres to kilometres) 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 by many authors, and possibly different generation of D2 structures are developed in different tectonic context:

- 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; b) interference patterns between two folding phases at high angle or two high angle synchronous folding produced through one–directional contraction in a multilayer with different mechanical properties; c) domino-like rigid blocks rotations with antithetic shear during progressive eastward thrusting;
- they produced as reverse drag folds overprinting complex highly non-cylindrical D1 sheath folds during late rebound by vertical isostatic reequilibration of former thickened crust;
- they born as passive folds related to distributed shear within kilometric scale shear zones accommodating crustal extension.

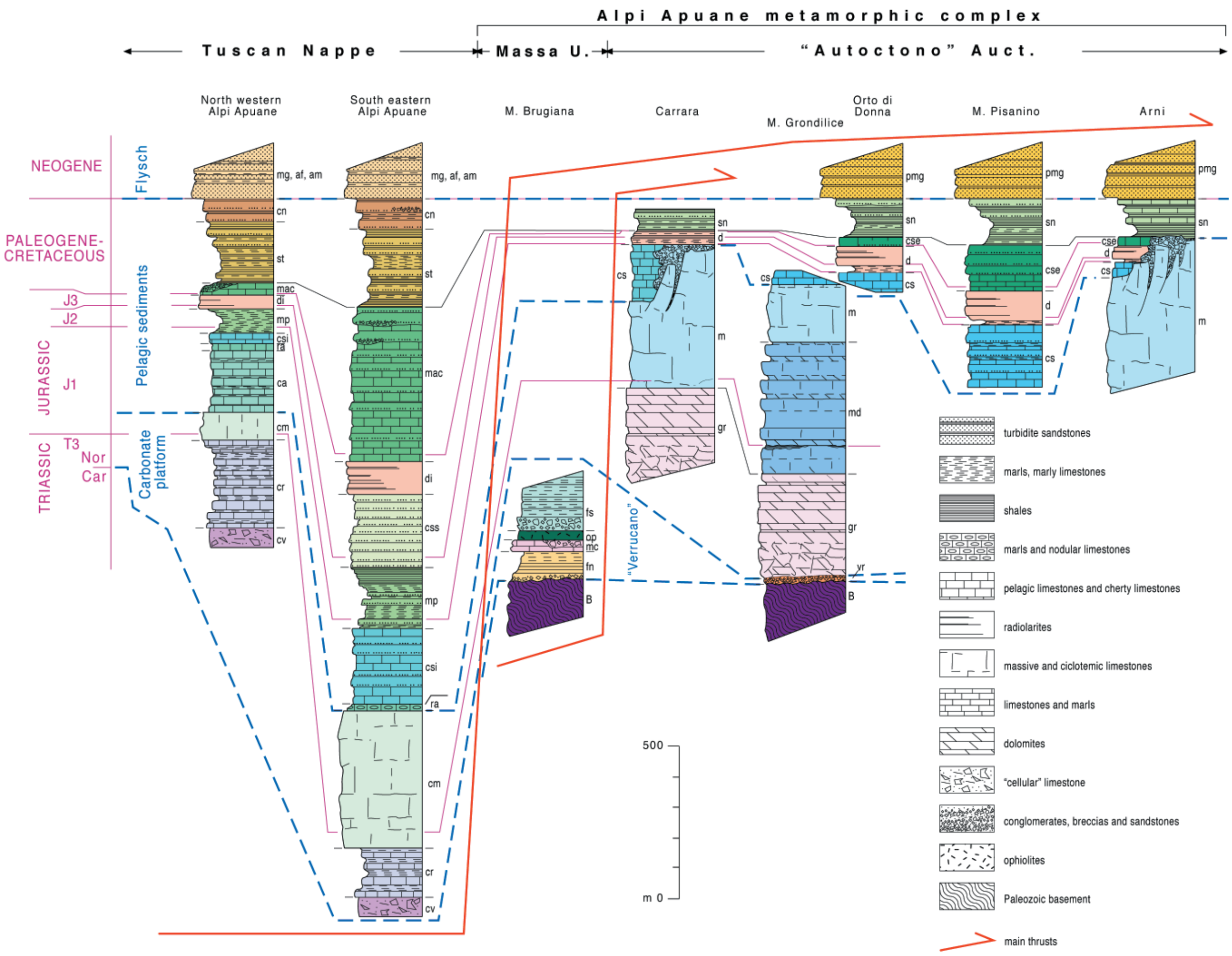

Fig. 2 - Stratigraphic sequences of the Tuscan units in the Alpi Apuane region.

2.3.3 Deformation-metamorphism relationships

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

In the Massa Unit the chloritoid grew since the early stage of the D1 foliation development. In fact, post-tectonic growth of chloritoid on D2 crenulation cleavage was never observed and 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, where it is also included in chloritoid crystals. Therefore, a syn-kinematic growth during the early stage of the D1 foliation development may 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 (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.

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 Pseudoacigno Fm., which contains 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 may be constrained using apatite fission tracks suggesting that between 5 and 2 Ma (ABBATE *et alii*, 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 may be further constrained by sedimentary record, since north and north-east of the Alpi Apuane region the basin fill of the Lunigiana and Garfagnana tectonic depressions contains Upper-Middle Pliocene conglomerates with metamorphic clasts derived from the Alpi Apuane metamorphic units (BARTOLINI & BORTOLOTTI, 1971; FEDERICI & RAU, 1980; BERNINI & PAPANI, 2002; ARGNANI *et alii*, 2003; BALESTRIERI *et alii*, 2003).

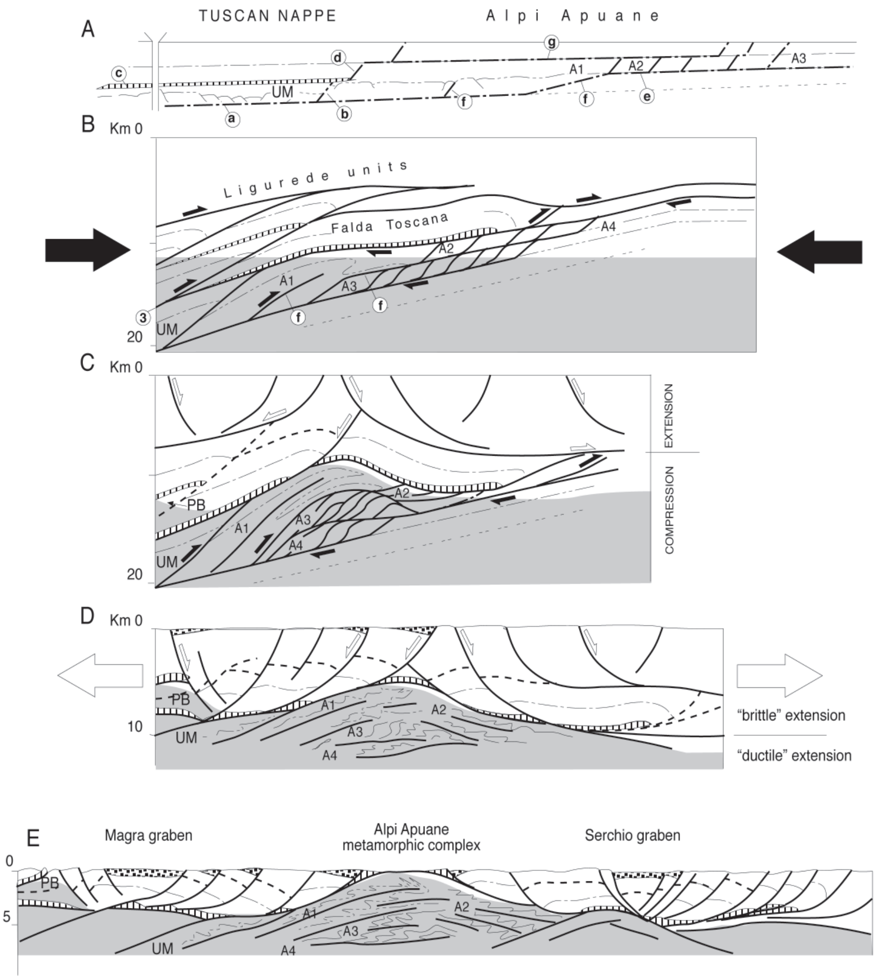

Fig. 3 - Tectonic evolution of the Alpi Apuane metamorphic complex (after CARMIGNANI & KLIGFIELD, 1990).

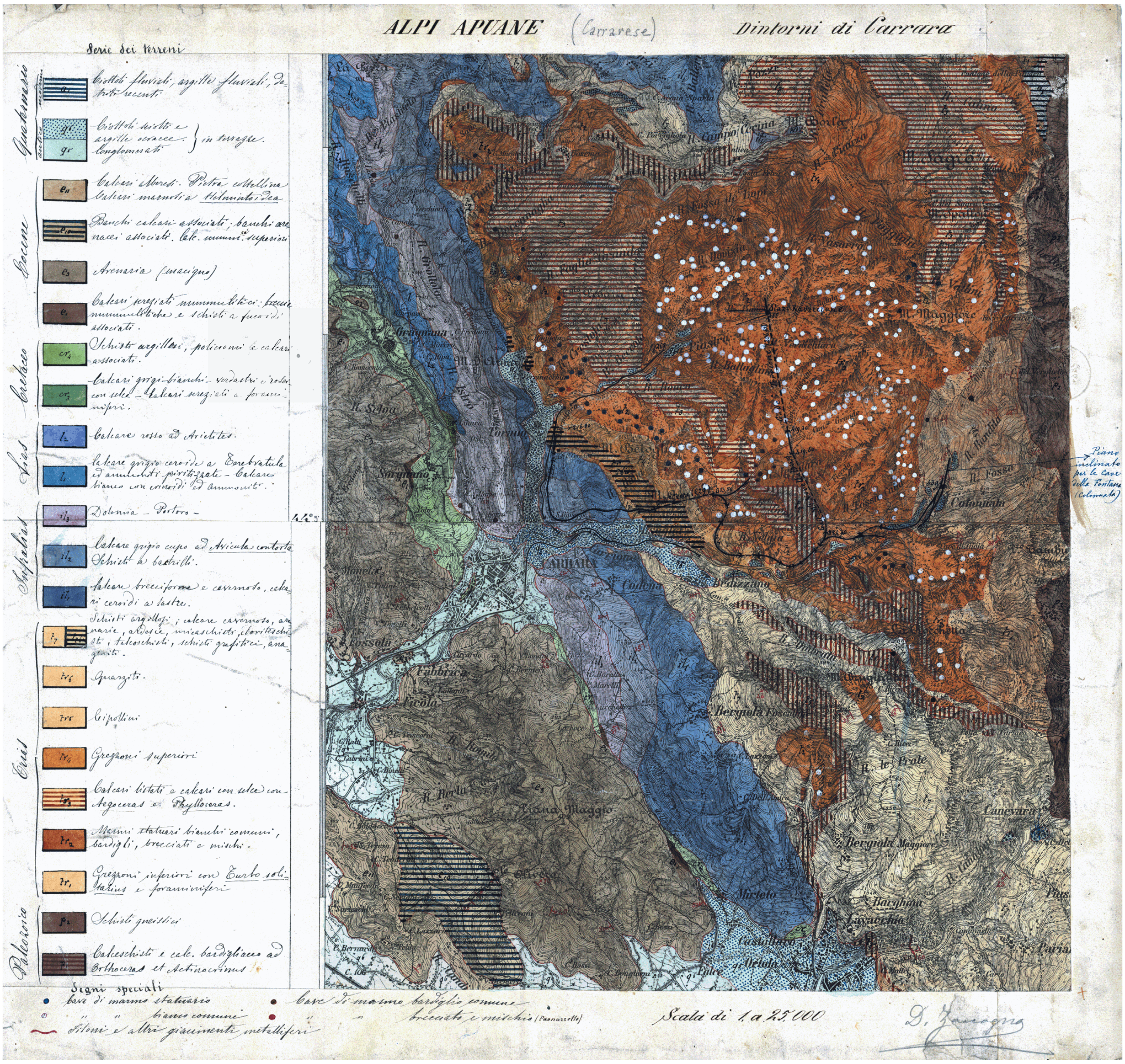

Fig. 4 - Geological map of the area NE of Carrara by Domenico Zaccagna (realisation age unknown, from the library colletion of the Servizio Geologico Italiano, Roma). Note the indications of marble commercial varieties and marble quarries location.

3 AUTOCHTHONOUS AND ALLOCHTHONOUS INTERPRETATIONS

The geological investigations in the Alpi Apuane area started in 1800 with studies of REPETTI (1820), SAVI (1833; 1863), GUIDONI (1829; 1840); COCCHI (1871; 1872), COQUAND (1874; 1874-75), DE STEFANI (1874-75; 1880b; 1880a; 1881b; 1881c; 1881a; 1887; 1889), MENEGHINI (1880; 1881; 1886) and LOTTI (1880; 1880; 1881a; 1881b; 1882b; 1882a).

However the most impressive contribution to the geology of the Alpi Apuane comes however from the work of DOMENICO ZACCAGNA. Between late 1800 and early1900 he mapped the whole Alpi Apuane at the 1:25.000 scale and published numerous papers, maps at various scale, and cross sections (fig. 4, fig. 5a, fig. 6). His geological maps and papers are wealthy rich of detailed information and still today the field observations he made are worth considered by modern authors (ZACCAGNA, 1880; LOTTI & ZACCAGNA, 1881; ZACCAGNA & LOTTI, 1881; ZACCAGNA, 1895, 1896, 1897, 1898b, a, 1904, 1920, 1925, 1932, 1933, 1937, 1938).

All the work of ZACCAGNA (and all early authors) was strongly influenced by the geological ideas of his time, and he was strongly devoted to an autochthonous interpretation of the geology of the area. Although the Alpi Apuane tectonic window is characterized by thrusting of the Tuscan nappe, with fossil-rich Rhaetian limestones at the basis onto the metamorphic rocks, ZACCAGNA didn't recognised any thrust, and interpreted all the rocks at the basis of the Rhaetian limestone, at that time not acknowledged as metamorphic and fossil poor, as Permian-Triassic in age (see legend of geological map of fig. 5a). This led to a complicated stratigraphic succession in his maps, with frequent and sudden lateral variation of rock types, now interpreted as hinge zones of km-scale isoclinal folds. The firm "autochthonous" interpretation of ZACCAGNA matured in the late 1800 when this view was usual in all the mountain chains in Europe. He retained this interpretation in all his works and maps and in his final basic work published in 1932 (ZACCAGNA, 1932).

At the beginning of the 1900, the new concept of the thrust tectonics came out and slowly consolidated, following the works of LUGEON, ARGAND, TERMIER, STEINMANN and DE LAUNAY in the Alps. In the second decade of 1900 LENCEWICZ (1917) reinterpreted the maps of ZACCAGNA and LOTTI and he is the first to represent in a geological map the overthrust of the Tuscan Nappe (that he indicated as "Falda di Sicilia") on the Alpi Apuane metamorphic complex (that he indicated as "Falda di Calabria"). He also defined the uppermost Liguride units and gave them the name of "Falda superiore". Around the 1930's non-Italian geologists (TILMANN, 1926; DE WIJKERSLOOTH, 1930; STAUB, 1932; TEICHMÜLLER, 1932; DE WIJKERSLOOTH, 1934; TEICHMÜLLER, 1935) proved thrusting and nappe superposition in the Northern Apennines. These authors separated the continuous stratigraphic succession of Zaccagna in two tectonics units, which are today still widely accepted (although with different unit names). They are:

a) "TOSCANIDE I", the lowermost, includes the metamorphic rocks of the Alpi Apuane. It is further divided in a lower autochthonous unit and a upper tectonic unit made of mostly Triassic continental deposits ("Schuppen Zone von Massa" of STAUB, 1932);

b)"TOSCANIDE II", the overlying unit, it is the non-metamorphic Mesozoic-Tertiary succession. The two units show clear stratigraphic correspondence and similarities.

All the above mentioned authors that first accepted the ideas of thrust tectonics in the Northern Apennines indicated a top-NE trasport direction for emplacement of all tectonic units, with the noteworthy exception of STAUB. He postulated (STAUB, 1932) an "Adriatic" origin and top-W emplacement of the "Toscanide II" onto the "Toscanide I" and, in general, for all the tectonic units of the Northern Apennines. This belief derived from correlations with tectonic units of the Alps, STAUB correlated the metamorphic "Toscanide I" with the Pennine units of the Alps and the "Toscanide II" with the Apulia derived (Austroalpine) Dinaride units; in this scenario the "Toscanide II" must have a westward tectonic transport, following the emplacement of the Apulia continent on the Europe continent during collision as evidenced in the Alps.

In the meantime Italian geologists gave credit for an allochthonous intepretations for the tectonic units of the Northern Apennines too. We cite here the works of MERLA (1932) and BONATTI (1938) both based not on large scale considerations but on detailed field work and new observations. BONATTI (1938) put forward an accurate description of the metamorphic rocks oucropping in the Alpi Apuane and agreed with the presence of two tectonic units in the area. He recognised the presence of similar formation ("Macigno" and "Pseudomacigno") in the two units, and questioned the widespread eteropies proposed by ZACCAGNA between formations of very different depositional environment. The occurrence of a regional scale overthrusting of an upper non-metamorphic tectonic units ("Toscanide II" or "Falda Toscana") onto metamorhic rocks was finally proved by the work that IPPOLITO and BURCKHARDT carried out in the 1942-1943 years and published some years later (IPPOLITO, 1946a, b, 1948, 1950). From now large scale thrust tectonics was widely accepted in the geology of Tuscany and of the Northern Apennines in general (TREVISAN, 1950; MERLA, 1951; TREVISAN, 1955).

4 DEFORMATION AND TECTONIC STYLES

IPPOLITO (1950) clearly illustrated the different style of deformation between the Tuscan Nappe and the Alpi Apuane metamorphic complex and indicated as

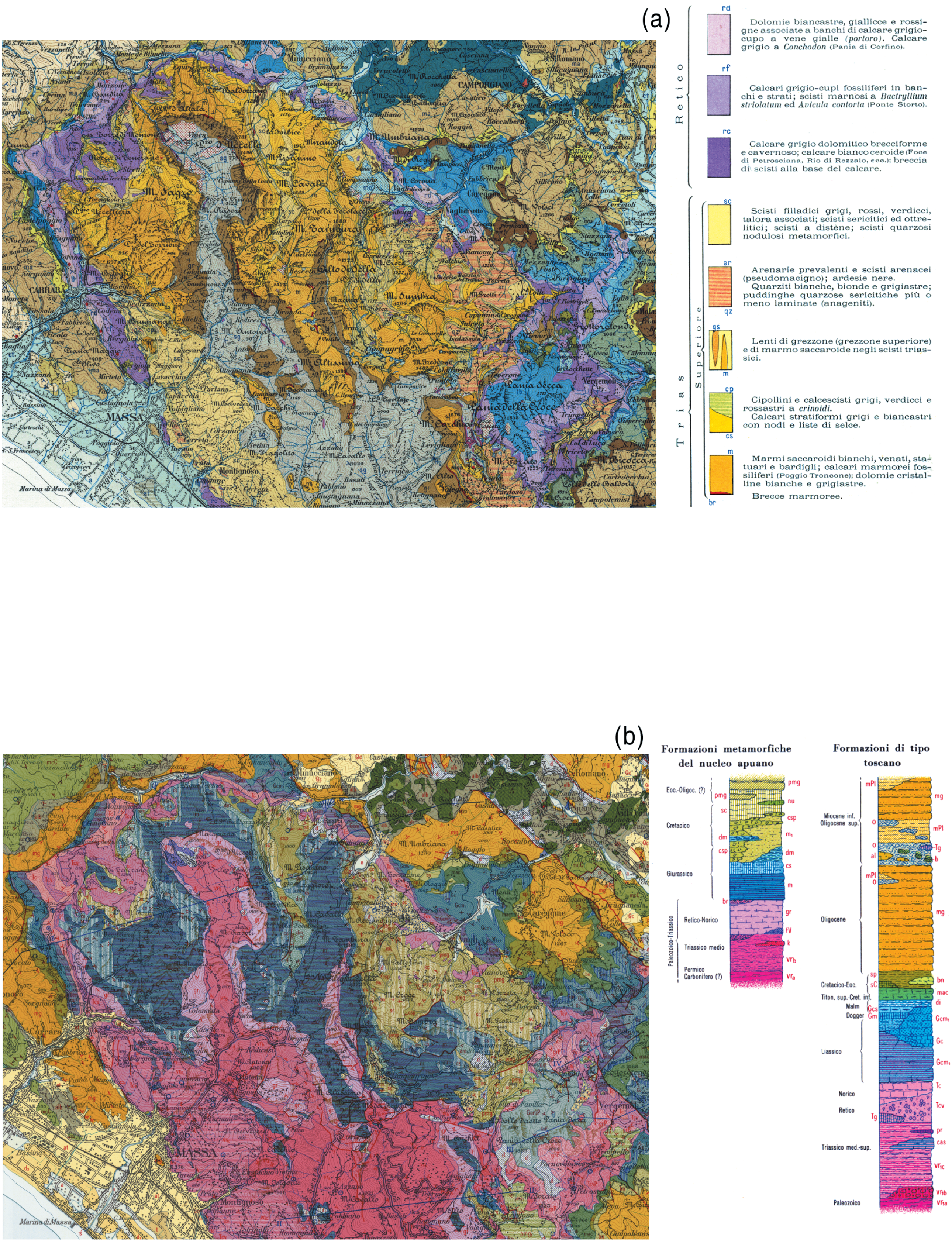

Fig. 5 - The two editions of the sheet 96 - "Massa" of the Geological Map of Italy at the 1:100,000 scale, by the Servizio Geologico Italiano. The first edition (a) is mapped by ZACCAGNA between 1879 and 1910 and is published in 1923. The second edition (b) is edited by TREVISAN *et alii* and is published in 1970.

"fluidale" the tectonic style of the metamorphic rocks. He also gave prominence to one the most important problems of the Alpi Apuane geology, namely the presence of opposite facing folds in the central part of the Alpi Apuane (known as "problema della doppia vergenza" in the Italian geological literature). As evident also in Zaccagna cross sections, the central part of the Alpi Apuane shows folds with opposite facing direction over a limited area (fig. 7, fig. 8a). This poses a major problem with an unique transport direction for the overlying Tuscan Nappe. This problem will be discussed in the next chapter as it found its solution about 40 years later, thanks to the modern methods of structural geology.

Strongly deformed rocks were recognised in the Stazzema area where tectonic slivers of phyllites and dolomites outcrop, Trevisan (1955) indicated this area as the eastern continuation of the Massa zone ("Scaglie parautoctone dello Stazzemese"). Some years later, the work of Valduga (1957) in the northeastern part of the Alpi Apuane evidenced the km-scale Carrara isoclinal syncline with transposition of the main foliation in cherty limestones rocks ("Calcare Selcifero" Fm.) along the axial plane of the syncline. Authors that substantially contribute to unravel the tectonic structure are Maxwell (1956), Nardi (1961; 1962a; 1962b; 1963a; 1967), Giglia (1967) and Boccaletti (1968). Contemporaneous palaeontology studies completely demonstrate the analogy between the successions of the metamorphic and the non-metamorphic unit (Trevisan, 1959; Nardi, 1963b, c; Sguazzoni, 1963; Nardi, 1967; Sguazzoni, 1968; Dallan Nardi, 1976). First radiometric ages of metamorphic parageneses were also produced (Giglia & Radicati di Brozolo, 1970). The great advance in geology interpretation at the end of 1960s is very well illustrated in the second edition of the sheet "Massa" of the Geological Map of Italy at 1:100,000 scale edited by Trevisan *et alii* in 1970 (fig. 5b).

5 THE CONTRIBUTION OF STRUCTURAL GEOLOGY

Between 1960 and 1970 British geologists provided strong ompulse in structural geology studies, especially in studying polyphasic deformation, foliation and lineation development and mechanisms of folding. New techniques of structural geology investigations led to significant advance in understanding deformation of rocks and tectonics of metamorphic orogenic belts in particular.

This new age of structural analysis yield to an important increase of knowledge in the Alpi Apuane (Haccard *et alii*, 1972; Carmignani & Giglia, 1975; Carmignani & Giglia, 1976; Carmignani & Giglia, 1977; Carmignani *et alii*, 1978; Carmignani & Giglia, 1979; Kligfield, 1979; Boccaletti & Gosso, 1980; Carmignani *et alii*, 1981; Kligfield *et alii*, 1981; Boccaletti *et alii*, 1983; Cerrina Feroni *et alii*, 1983). These studies led to the recognition:

a) of ubiquitous isoclinal NE-facing folding, up to km-scale, originated during top-NE emplacement of the overlying Tuscan Nappe;
b) that the main foliation recognizable in the field it is of metamorphic origin and is the axial plane foliation of the isoclinal folds;
c) of the complete transposition of bedding parallel to axial plane foliation of isoclinal folds;
d) that isoclinal folds are often strongly non cylindrical (sheath folds), developing complicate facing direction patterns in the field;
e) that axes of sheath folds are parallel to the widespread stretching lineation, SW-NE oriented; high values of the X:Z ratio of the strain ellipsoid oriented parallel to the stretching lineation are also documented;
f) that the main foliation is polyphasic refolded by later tectonic events; the Alpi Apuane metamorphic complex is at large scale an antiform but is the refolding of the main foliation (not the bedding) that develops the antiform.

5.1 The problem of the "*doppia vergenza*"

Since the works of Zaccagna and Lotti, it is widely accepted that bedding in the western Alpi Apuane mostly dips toward SW, and toward NE in the eastern Alpi Apuane. In their maps and cross sections axial planes of major folds shows the same opposite attitude too (fig. 6, fig. 8a), strongly influenced (Lotti, 1881a)1 by the fold structure depicted by Escher and Heim in the footwall of the Glarus thrust in the Helvetic nappes of eastern Switzerland (fig. 8b). In this view, the folds of the western Alpi Apuane show a northeastward facing that well agrees with a top-NE thrusting of the Tuscan Nappe. The fold of the eastern Alpi Apuane shows consequently a southwestward facing direction: this is a major problem with a top-NE thrusting of the overlying tectonic unit. This problem of folds with opposite facing direction in the same area is known in the Italian literature as the problem of the "doppia vergenza" (double vergence) (Carmignani & Giglia, 1983).

Staub, whose cross-sections highlighted the problem (1932), considered the main NE-facing fold as "backfolds" developed after the main southwestward-directed deformation. Maxwell (1956) introduced the idea of a contemporaneous "double provenance" for the upper Tuscan Nappe, idea sporadically reintroduced by some authors also in recent years. Giglia (1967) first claims for a general top-NE transport direction during main folding in the Alpi Apuane metamorphic complex, and attribute to local later backfolding the SW-facing folds, totally reversing the Staub's interpretation.

The problem of the "doppia vergenza" was then solved when the modern methods of structural analysis became available. A key area for investigations about this topic is the area near the village of Arni, in the central Alpi Apuane. Structural investigations in this area (fig. 7, Carmignani & Giglia, 1979, 1983;

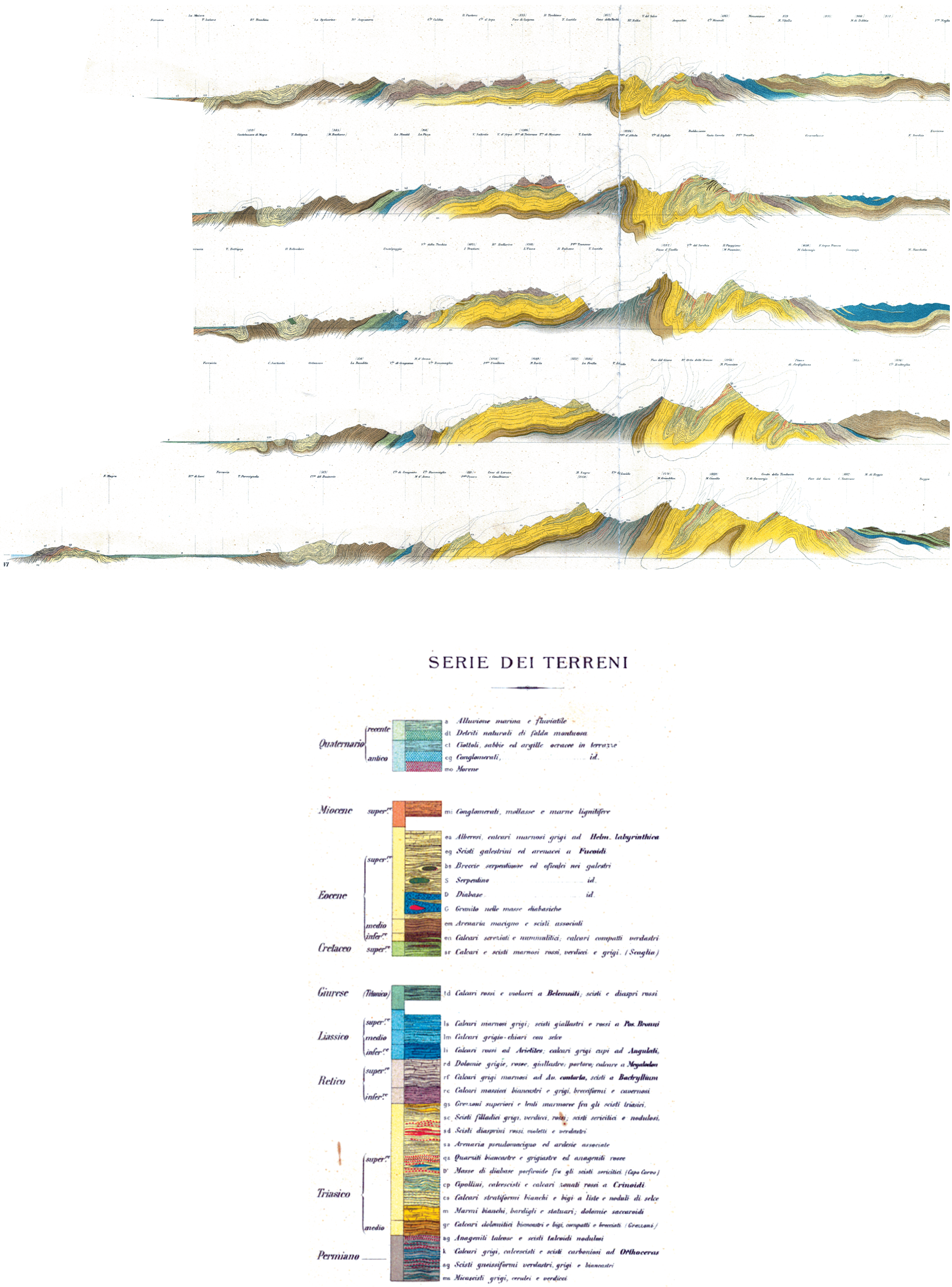

Fig. 6 - Geological cross section in the Alpi Apuane by Domenico Zaccagna. Note the opposite attitude of axial planes in the central part of the area.

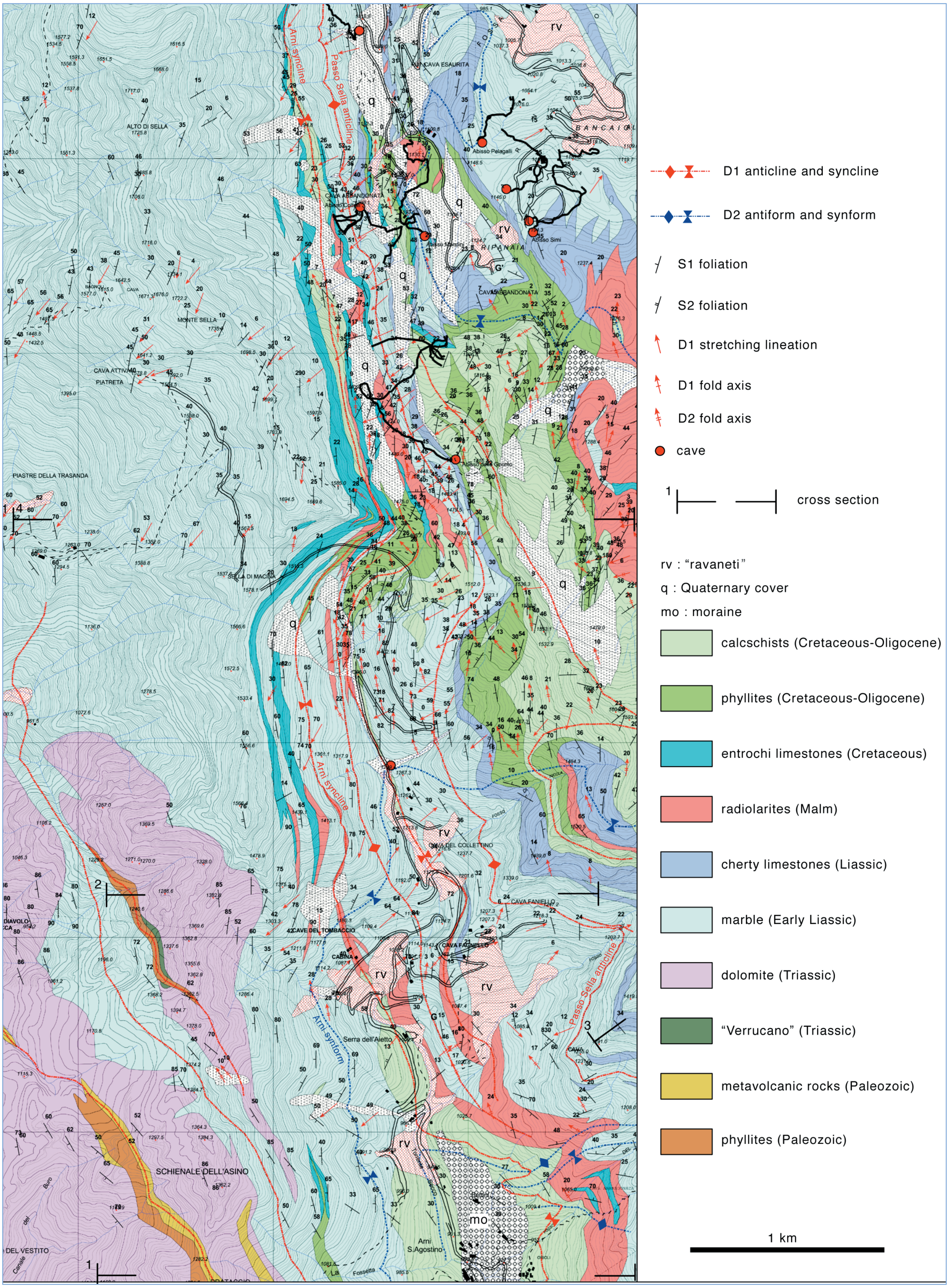

Fig. 7 - Geological map of the Arni area.

Carmignani *et alii*, 1993b) led to recognition of a first generation of isoclinal non-cylindrical folds, linked to the D1 deformation, refolded by later km-scale D2 folds with NE trending fold axes. In fig. 8c is illustrated the structure of the area: all D1 folds are NE facing and the main foliation in the field is the axial plane foliation of these folds, D2 folds are SW facing and deform all the earlier features. This tectonic setting led to close juxtaposition of NE facing D1 folds with SW facing D1 folds in the same cross section, as visible in fig. 8c; the SW facing D1 folds are those located in the inverted limbs of the D2 folds. A sketch for development of refolded D1 facing is illustrated in fig. 8d and fig. 8e

Therefore in the Alpi Apuane a "double" direction of nappe emplacement does not exist. The opposite facing directions often recognisable in the field is due to interference between different generation of fold, both developing km-scale inverted limbs. Later on evidence of large-scale folds refolding the main foliation was found in other outcrops of metamorphic rocks in Tuscany. Again, the geological investigations in the Alpi Apuane contribute to the understanding of the geology of the whole Northern Apennines.

5.2 Recumbent folds during extension

In the time span between 1970 and 1980, structural geology investigations focused mainly to unravel tectonic features resulting from collisional tectonic and crustal shortening. Above all, the studies concerned polyphasic folding in metamorphic basements, strain analysis in deformed rocks, microfabrics development in dynamically recrystallized fault rocks, balanced cross sections in fold and thrust belt, etc.. In the Northern Apennines, this led to the production of large number of studies on development of foliations, fold axes, stretching lineations and folding superposition during compressional tectonics. At that time all these tectonics features were considered to be exclusive of compressional tectonics. On the other hand, not very much consideration was paid to study the structures resulting from crustal extension and exhumation of rocks

Trevisan (1950) published the first pioneering work in the Northern Apennines on exhumation and tectonic denudation on the tectonics of the Isola d'Elba in the Tuscan archipelago. However, only those structures developed in the brittle field (as high angle normal faults, cataclasites, veins, tectonic joints, etc.) were regarded for many years as the only tectonic structures developed during extension. Again, geological investigations in the Alpi Apuane pointed out that km-scale isoclinal folds, reverse and recumbent folds, subhorizontal schistosity and mylonite zones are not only expression of horizontal shortening, but they may also develop during extensional tectonics, with a vertical shortening direction.

The occurrence of large scale reverse D2 folds following the main (D1) collisional tectonics in the Alpi Apuane metamorphic complex was established in the late 1970 (Carmignani & Giglia, 1979). Anyway, only few years later they were definitely established as developed in a regional context of extensional tectonics that affected the Northern Apennines since late Miocene (Carmignani & Kligfield, 1990). Two main different ways of development of D2 recumbent folds are recognised in the Alpi Apuane metamorphic complex (Carmignani *et alii*, 1993b): a) folds developed in shear zones, and b) folds developed in shear zones confined by less competent rocks.

The first class of folds formed in D2 shear zones where rocks with minor or no viscosity contrast are present (marble, cherly limestones, calcschists, etc.), suffering a progressive simple shear deformative history (fig. 9a). The D2 shear zones are characteristic "normal" shear zones, i.e. the shear zones boundaries are not horizontal and the upper part of the shear zone moves downwards. The folds usually are similar folds, asymmetric, with strongly thinned inverted limbs, the axial plane foliation is always evident and often is the main foliation recognizable in the field. The D2 folds in the Arni area, already mentioned in fig. 8b, are an example of such mechanism of folding. Large-scale recumbent D2 folds in the Carrara and Stazzema area show this geometry.

A second class of folds develops when shear zones present layers of rocks with significant higher viscosity than surrounding rocks (for example phyllites between quartz rich rocks), that progressively die out (fig. 9b, Dennis & Secor, 1987; Rykkelid & Fossen, 1992); the folds development is confined between the layers of less competent rocks. The upright folds are due to strain compatibility issue, as a pure shear component of deformation is required in the central part of the shear zone to accommodate higher simple shearing in upper and lower less competent rocks (fig. 9c). As deformation proceeds rock heterogeneities and instabilities may led to an overall simple shear deformation (fig. 9d), and overturned and recumbent folds may develop. In the Alpi Apuane km-scale folds with such geometry are found north of Massa, in the Frigido valley (fig. 9e, f).

5.3 Gravity driven tectonic features

At present, the identification of the regional tectonic setting responsible for the overall extension of the Alpi Apuane constitutes one of the main problems to solve in the area. In the past, many ideas were presented, as extension contemporaneous with thrusting in an orogenic wedge, or extension in a core complex like exhumed crust. Recent field work in the area indicate a very young (Quaternary) age for uplift of the Alpi Apuane metamorphic complex. This needs to integrate the Alpi Apuane uplift and extension in the recent extensional tectonics well documented in southern Tuscany (Decandia *et alii*, 1993) and in the Northern Apennines north of the Alpi Apuane (Bernini & Papani, 2002; Argnani *et alii*, 2003). In the Alpi Apuane and surrounding areas, all larger km-scale D2 folds show a facing direction that is opposite to the dip direction

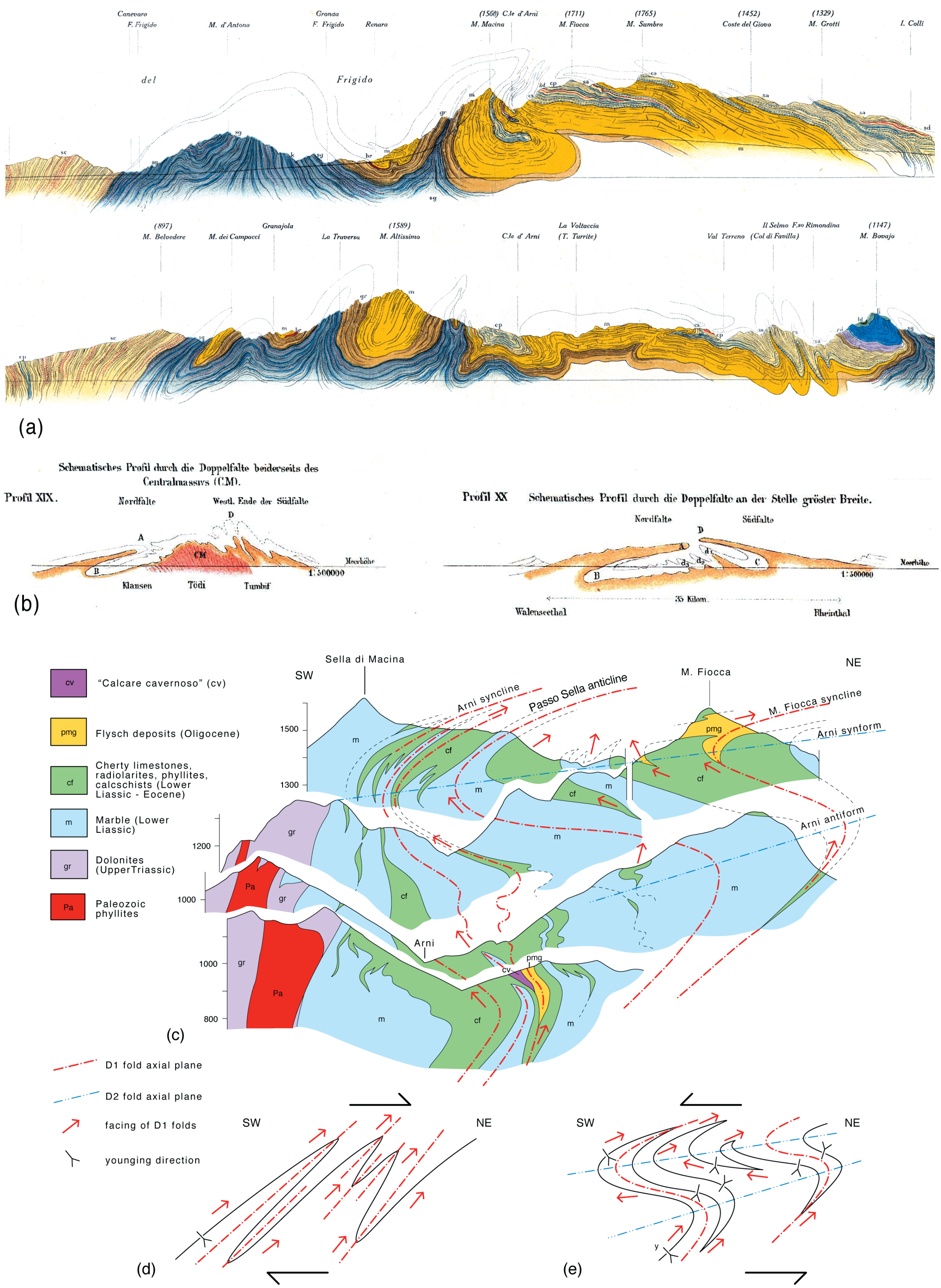

Fig. 8 - (a) Geological cross section in the Arni area, after Zaccagna (1898b). This is the most simple (but erroneous) solution possible, without the concepts of polyphase folding and of folds that develops km-scale inverted limbs. (b) Geological sections across central Swiss Alps, after Heim (1878). On the right is the "double fold" interpretation of the Glarus thrust. (c) Geological cross sections in the Arni area, after Carmignani *et alii* (1993b). (d) Facing directions of folds after D1 deformation. (e) Refolding of D1 folds and D1 facing directions due to D2 deformation.

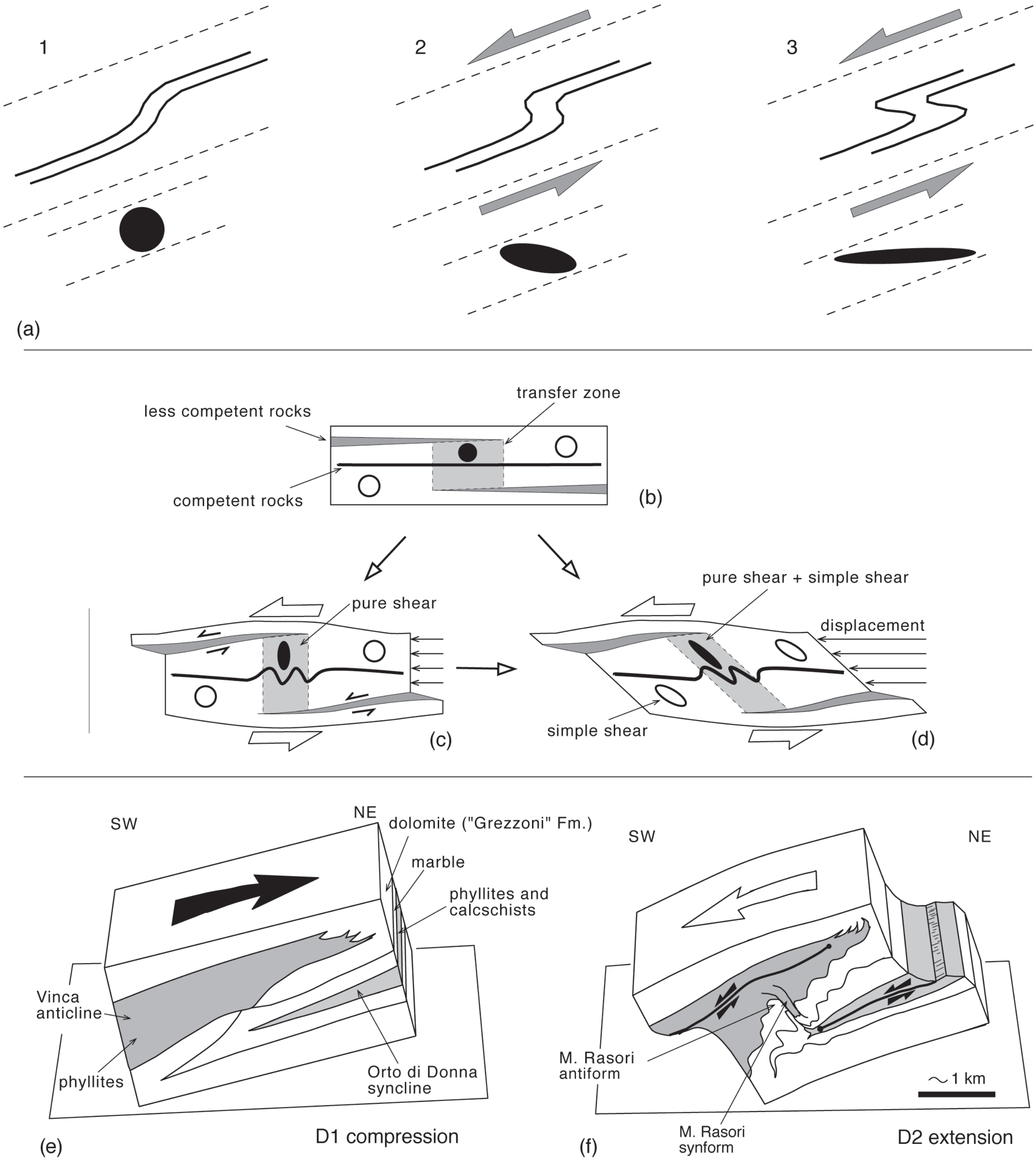

Fig. 9 - (a) Progressive development of recumbent folds in shear zones; typical are inverted limbs thickened at moderate strains (2), thinned at higher strains (3). (b) Development of folds in shear zones containing rocks with high viscosity contrast. (after Rykkelid & Fossen, 1992, modified). (c) Shortening parallel to shear zone boundaries occurs between the two levels of less competent rocks (greyed area), producing upright symmetric folds. (c) Ongoing deformation led to simple shearing, and development of asymmetric reverse and recumbent folds. (e) Sketch diagram of the D1 anticline and syncline structure of the norther Alpi Apuane, anticlinea are core by Paleoizoic phyllites, syncline contains phyllites and calcschists; the limbs are represented by the competent dolomite rocks of the "Grezzoni" Fm. (f) Geometry of the same structures after D2 extension. Upright and overturned D2 folds developed between the D1 anticline and syncline (after Carmignani *et ali*i, 1993b, modified). The same structure is illustrated in fig. 1, cross section "c".

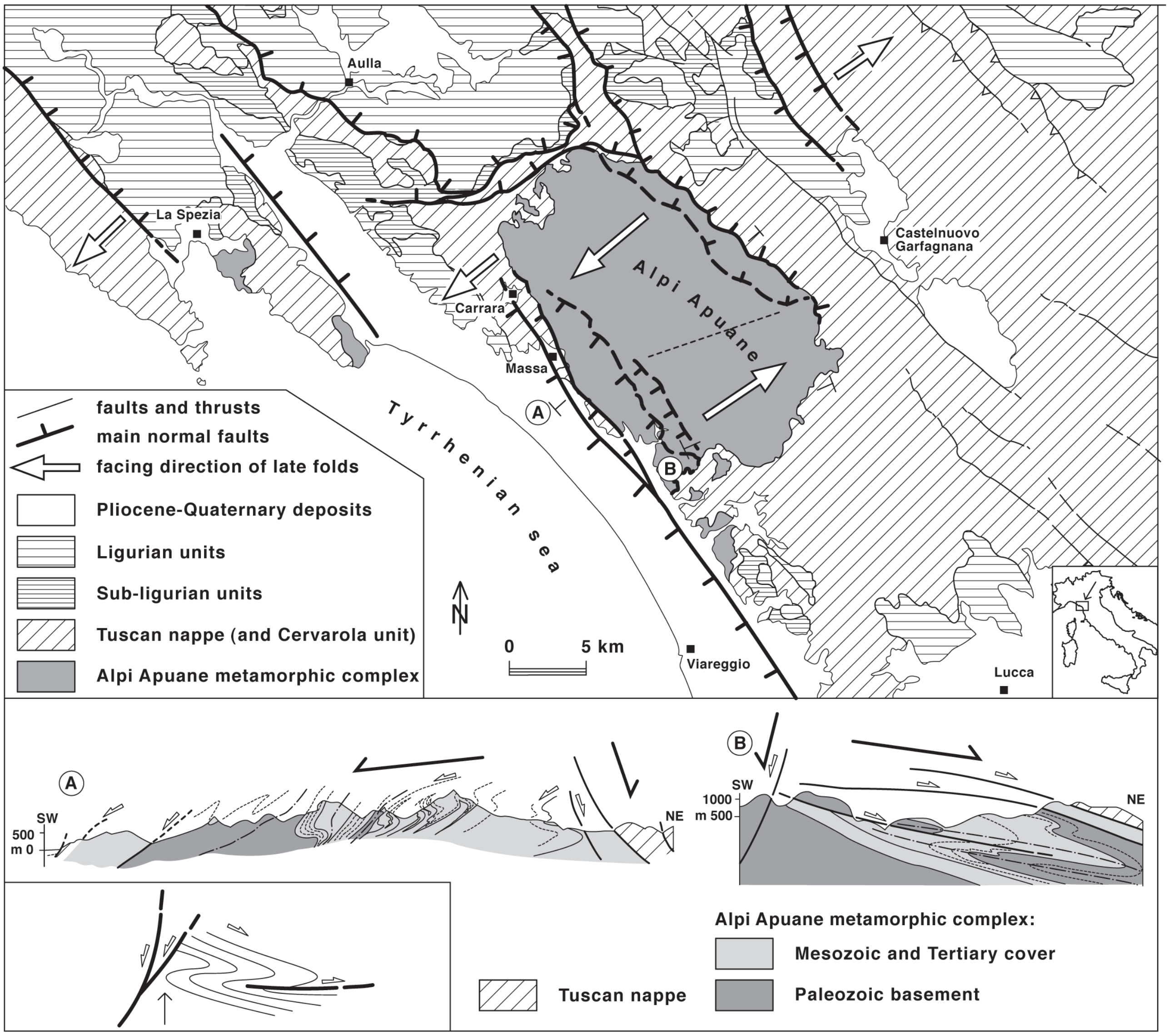

Fig. 10 - Tectonic sketch map of northern Tuscany. The major tectonic lineaments and structures linked with Quaternary uplift are outlined.

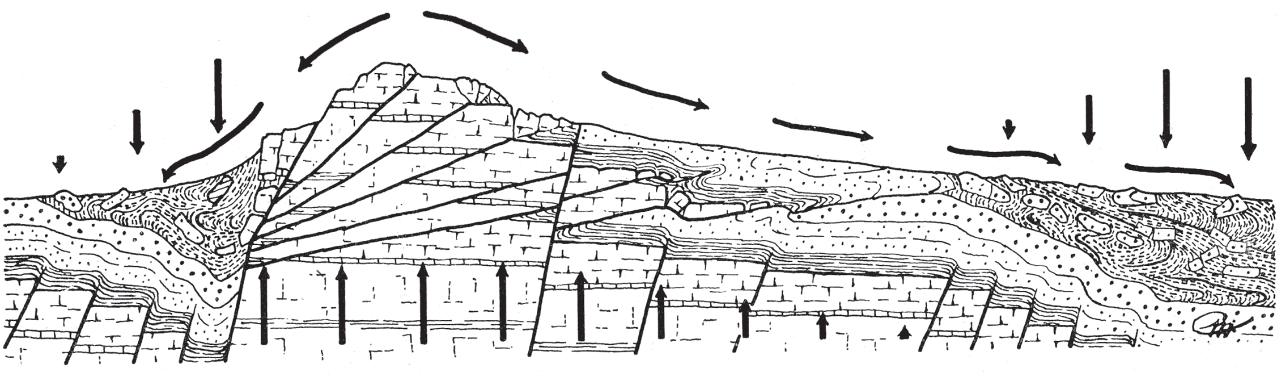

Fig. 11 - Sketch from the Migliorini's work (1948) on the movement of gravity controlled slivers ("cunei composti") in the tectonic evolution of the Northern Apennines.

of the main high-angle normal faults that border the Alpi Apuane window (fig. 10). In the northern Alpi Apuane major D2 folds face SW and the main border fault is located in the Garfagnana valley and dips NE. In the southern Alpi Apuane main D2 folds face NE and here the main high-angle normal faults are those of the Versilia area (between Massa and Viareggio) dipping SW. We suggest that normal faults and folds are closely related and that their development should be more or less contemporaneous: we interpret the folding event as due to gravity tectonics consequent to the uplift of footwall rocks during normal faults activity (see lower left inset in fig. 10). This kind of structures is evident also in the La Spezia area, where late SW-facing folds developed in the footwall of a regional NE-dipping normal fault (La Spezia fault). This also occurs north-west of Castelnuovo Garfagnana (fig. 10), where large faults dip SW (Corfino) and late folds show a north-eastward facing. In this area, the north-eastward transport direction of folds locally may develop thrusts in the overturned limb of the km-scale folds (see lower left inset in fig. 10). These thrusts can be responsible of some "anomalous" nappe superposition found in the area, with emplacement of Tuscan units above Ligurian units. Anyway this interpretation is not new for the Northern Apennines, as it is deeply inspired by the old works on gravity tectonics by Migliorini (1948) (fig. 11).

5.4 Microfabric studies of the Alpi Apuane marbles

The Alpi Apuane metamorphic complex is surely a key area for the development of many geological hypothesis later extended to the whole Northern Apennines, because of its spectacular outcrops and the continuity of rock exposures. However the area is also well known for another peculiarity: the marbles. The marbles from the Alpi Apuane, and in particular the white variety called "Carrara marble", are well known geological materials due to their extensive use both as building stones and for statuaries as well as in rock-deformation experiments. In the latter, Carrara marble is widely used because: a) it is an almost pure (monomineralic) calcite marble; b) it shows a nearly homogenous fabric, with no or weak grain-shape or crystallographic preferred orientation; c) it usually developed a large grain-size; and d) a large amount of literature data about its behaviour under various experimental deformation conditions is available (Rutter, 1972; Casey *et alii*, 1978; Schmid *et alii*, 1980; Schmid *et alii*, 1987; Wenk *et alii*, 1987; Fredrich *et alii*, 1989; De Bresser & Spiers, 1993; Rutter, 1995; Lu & Jackson, 1996; Covey-Crump, 1998; Burlini & Kunze, 2000; Pieri *et alii*, 2001; Barnhoorn *et alii*, 2004).

Therefore the marble of the Alpi Apuane is worldwide accepted as the reference starting material for laboratory investigations dealing with microstructure and crystallographic preferred orientation development in calcite rocks. Although a huge mass of data is available on experimental behaviour of Alpi Apuane marbles, much has still to be done to investigate microfabrics developed in naturally deformed marbles. Contemporaneous with structural geology investigations in the area, studies are today carried out based on both fieldwork and microfabric analysis. They aim to achieve a better understanding of microfabric development in Alpi Apuane marbles and more in general in monomineralic rocks, taking into account the role of the regional deformation history and the position of marbles in kilometre- to metre-scale geological structures (Barsottelli *et alii*, 1998; Molli & Heilbronner Panozzo, 1999; Molli *et alii*, 2000a; Leiss & Molli, 2003).

These studies evidenced that in the Alpi Apuane metamorphic complex after main D1 deformation (fig. 12a, b), thermal relaxation and heating produced statically recrystallized fabrics ("granoblastic") in marbles (fig. 12e). The westernmost rocks in the Alpi Apuane metamorphic complex 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 (fig. 12c), further shortening was accomplished. In this phase, dynamic recrystallized microstructures were produced in localized shear zones reworking earlier annealed fabric. The D2 history was associated with exhumation in retrograde metamorphic conditions (fig. 12d). During this event, narrow millimetre- to decimetre-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 in calcite. This is testified by recrystallized calcite grains elongated parallel to the axial surface of D2 folds (fig. 12f), and fine-grained calcite in D2 shear zones (fig. 12g). All these investigations at the scale of the whole Alpi Apuane area have pointed out a large variability of marble calcite microstructures and crystallographic preferred orientations (fig. 12h) originated during various stages of the dynamic recrystallization, which overprinted the "granoblastic" annealed fabric.

6 CONCLUSIONS

The Alpi Apuane captured the interest of many generations of geologists since 1800. This area is a tectonic window that represents the largest and best-exposed outcrop of metamorphic rocks of the Apennines, where it may be studied the internal structure of the lowest tectonic units of the Northern Apennines and the kinematics of thrusting of all the tectonic units that now form the Northern Apennines nappe stack.

Here many concepts later on extended to whole Northern Apennines, as the notion of large thrust

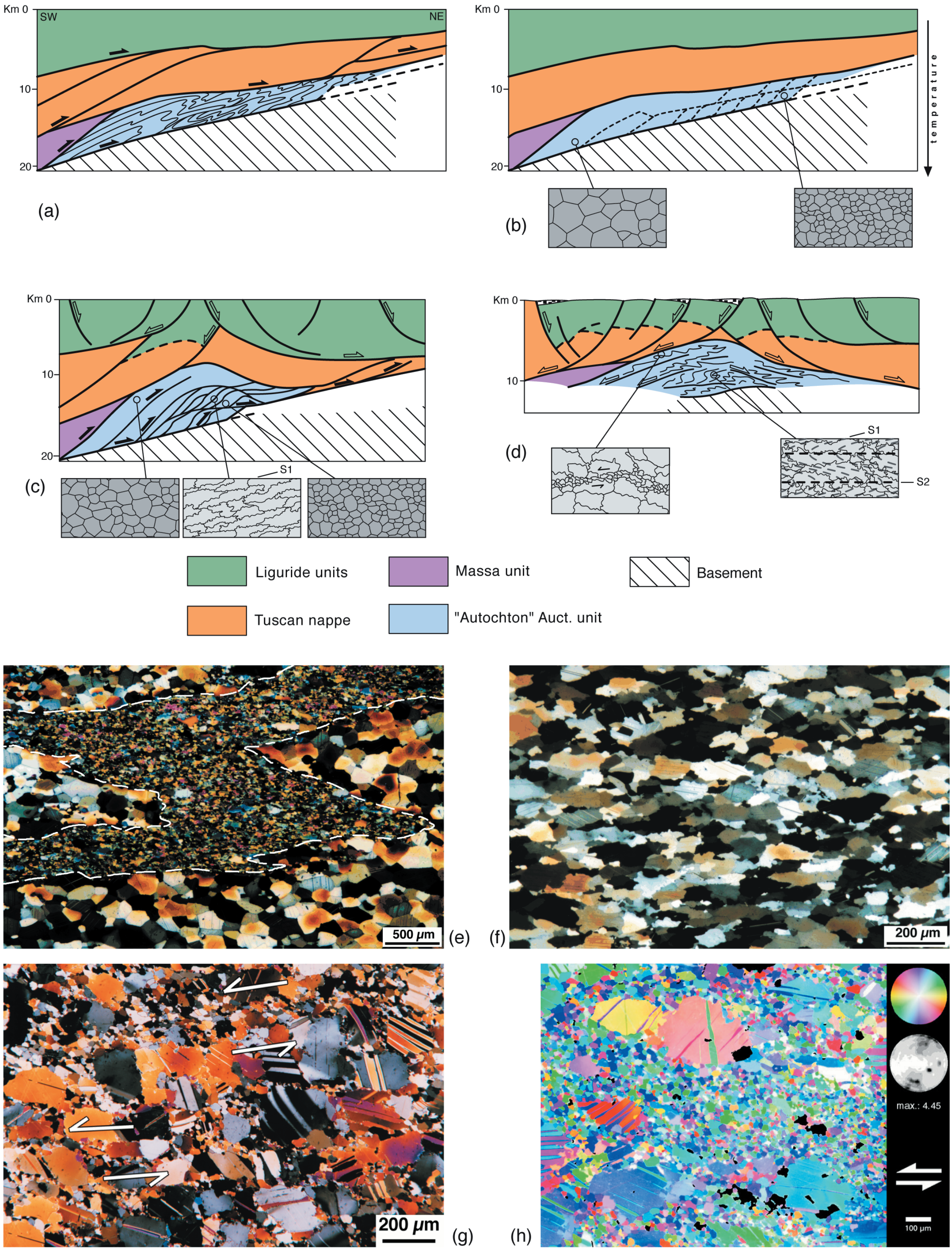

Fig. 12 - Microfabrics in Alpi Apuane marbles (after Molli *et alii*, 2000a). (a) D1 phase, with main foliation and km-scale isoclinal folds developed. (b) After D1 main folding phase annealing occurred, with annealining and complete obliteration of earlier microfabrics. (c) During final D1 NE transport along thrusts annealed microstructures are passively transported toward NE or reworked in shear zones along thrusts. (d) D2 deformation led to folding and shear zones along low angle normal faults. Earlier microstructures are be reworked in D2 shear zones or along D2 fold axial planes. (e) Typical D1 folds, overprinted by annealed microstructure. (f) Shape preferred orientation of 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 recristallization. (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.

sheets in the nappe building of the Apennine, the introduction of the structural analysis of deformed rocks, the discussion about the emplacement direction of the higher tectonic units of the Northern Apennines, the recognition of recumbent km-scale fold developed during extension, the use of microfabric investigations in naturally deformed monomineralic calcite rocks to unravel relationships between microstructure and crystallographic preferred orientation development and deformation history have been developed.

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