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Late tectonic evolution of the Northern Apennines: the role of contractional tectonics in the exhumation of the tuscan units

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Abstract

Structural analysis performed in the continental tuscan units of the Northern Apennines (Italy) highlight the presence of transversal and parallel structures, with respect to the main trend of the belt (NW-SE), affecting the tectonic nappe pile. These structures, following the main synmetamorphic phases associated to isoclinal folds with axial plane foliations, are upright folds, brittle and brittle-ductile shear zones. Nearly upright folds are related to NW-SE and NE-SW directions of shortening.

The two perpendicular directions of shortening, associated with a contraction setting, induced the vertical growth of the metamorphic domes enhancing the process of exhumation of the metamorphites.

The presence of later NE-verging brittle-ductile shear zones crosscutting both systems of folds testifies that contraction long lasted during the orogenesis.

Fluid inclusion analyses, performed in syntectonic veins coeval with NW-SE trending upright folds, point out that, after the first tectonic phase, pressure values decrease supporting that this tectonic unit was exhuming during the development of upright folds

Post-collisional extensional tectonics gave rise to collapse folds and low- and high-angle normal faults in the latest stages of deformation.

Keywords: Northern Apennines; Later folds; Strike-slip fault; Brittle-ductile shear zones; Metamorphic domes

1. Introduction

The polyphase structural evolution of the Northern Apennines has been highlighted since many times and most of the modern tectonic studies focused on the structures due to the NE-SW directed compression and to subsequent extensional tectonics [1, 2 and references therein]. Most models suggest that contraction forces ceased after the thickening stage of the belt, when exhumation and erosion began. However, it is shown in other recent and ancient orogens that contraction is often active after thickening and may play an important role in the exhumation of the metamorphic units [3-4-8]. Post-collisional tectonics is still debated, being attributed either to extensional [2, 9,10] or to contractional tectonic setting [11-14]. In addition, the transition from contractional to extensional tectonics and the mechanisms of construction of the belt are still debated [10,13-17].

Geological mapping and combined new meso and microstructural analyses in the Tuscan units of the Northern Apennines (Tuscan Nappe, Massa Unit s.l. and Apuane Unit) led to the recognition of a complex tectonic evolution characterized by the development of more tectonic phases than the classical two-stage deformation model [2, 18-20]. The D_1 deformation phase, linked to the development of

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tight to isoclinal folds with syn-metamorphic fabrics, is followed indeed by further deformation phases. These are related to the development of structures consisting of both folds and faults linked to orogen-parallel and orogen-perpendicular contraction. Just very few data on orogen-parallel shortening related structures have been documented in the Northern Apennines so far [21-22], even if transversal structures, represent common features in other orogenic belts, such as the Variscan belt [7, 23-26]. Our studies have been focused on the post D1 tectonic evolution of some of the main tectonic units of the Northern Apennines: the Tuscan Nappe, the Monti Pisani Unit and the Apuane Unit cropping out in some key areas (Fig. 1a). The new achieved data permit a comparison between the structural evolution of the Tuscan Nappe and the underlying metamorphic units.

The aim of this paper is to document the widespread presence of tectonic structures, such as folds, brittle and ductile/brittle shear zones, that may be related to both orogen-parallel and orogen-perpendicular shortening, as far as to discuss their role in the tectonic evolution of the belt and in the development of the metamorphic cores of the Northern Apennines.

2. Geological setting

The Northern Apennines is a fold-and-thrust belt derived from the collision between the Corsica-Sardinia Block and Adriatic Plate during late Oligocene-Miocene times [27-31].

During the collisional event the different tectonic units, belonging to both an oceanic domain (Ligurian Domain, [32-33]) and an epicontinental margin (Tuscan Domain) were transported towards the East [34] (Fig. 1b), with the development of hinterland-to-foreland propagating thrusts, overturned folds and reverse faults. The younging from West to East of deformed sediments testified that the progression of deformation occurred in the same direction [35-37].

Radiometric ages for the stacking of the tectonic units are availables for the Apuane Unit (27 Ma, [31]) and for the Massa Unit s.l. outcropping in Southern Tuscany (varying from 31 to 27 Ma; [38]). The tectonic units deriving from the continental margin have been attributed to two different domains: the Internal Tuscan Domain, represented by the Tuscan Nappe [39], and the External Tuscan Domain represented by the Massa s.l. and the Apuane Units.

The Tuscan Nappe, detached at the level of Norian evaporites, is made up by sediments deposited on the continental margin from late Trias to early Miocene. The sequence is represented by platform and pelagic limestones followed by interbedded marls and limestones and with turbiditic sandstones at the top.

The External Tuscan Domain is mainly represented by the Apuane Unit that is composed of a Triassic to Oligocene sequence quite similar to the Tuscan Nappe. The Apuane Unit rests unconformably over a Paleozoic basement [43-44] and it is characterized by a greenschist facies metamorphic imprint [45]. The Massa Unit s.l. is interposed between the upper Tuscan Nappe and the lower Apuane Unit and consists of a Paleozoic to Triassic siliciclastic sequence followed by a carbonatic and argillaceous cover ranging in age from Rhaetian to Malm [22, 46] (Fig. 1b).

The Tuscan Nappe is characterized by a very low-grade metamorphic imprint confined to anchizonal conditions [40-42, 47], associated with the dynamic recrystallization of quartz + calcite ± albite ± illite ± chlorite + opaque minerals during the metamorphic conditions peak.

It is worth noting that the original sequence deriving from the same palogeographical domain (Massa Unit s.l. [36, 43]) during underthrusting and collision has been splitted into a number of different tectonic units [48, 49] that undergone different metamorphic conditions, expecially regarding the pressure values.

Whereas a relatively HP-LT metamorphism has been highlighted in the Massa Unit s.l. outcropping in Southern Tuscany [50-52] and further north on the western side of the Apuane Alps [10, 15, 53], a greenschist facies metamorphism has been detected in the Massa Unit of Monti Pisani [54] even if recently higher pressure values have been determined through fluid inclusion studies [55].

The main mineralogical association in the HP-LT units outcropping in Northern Tuscany is characterized by quartz, white micas, chlorite, chloritoid ± kyanite. Even if most of the authors agree about values corresponding to the peak of metamorphic conditions, that have been estimated around 450-500°C and 0.6-0.9 GPa [10, 15, 56], some debates occurred about the moment in which it was reached. Some authors confined the growth of chloritoid after the first deformation phase but before with respect to the second tectonic phase [13, 54-58] while some others agree that the growth of the chloritoid started earlier in the tectonic evolution, during the first tectonic event [53].

The outcrops of the Massa Unit s.l. located in Southern Tuscany are also characterized by the presence of magnesiocarpholite and pyrophyllite. Peak metamorphic conditions have been estimated between 350-420°C and 0.8-0.10 GPa [10, 50, 52, 59]. The Massa Unit of the Monti Pisani (Fig. 1a) falls down in the pyrophyllite zone of Franceschelli *et al.* [54] and the peak metamorphic conditions occurred around 400°C [60] and between 0.6 and 0.7 GPa [55].

The different thrust slices of the Massa Unit s.l. are characterized also by a different structural evolution. While the Massa Unit cropping out west of the Apuane Alps is characterized by two penetrative synmetamorphic foliations (Author's unpublished data), referred to a composite foliation by Molli *et al.*, in the Monti Pisani area only a synmetamorphic S1 foliation has been recognized both at the meso and microscale. So that we refer to the Massa Unit outcropping in the study area as Monti Pisani Unit.

The underlying Apuane Unit experienced a lower metamorphic imprint with respect to the one of the Massa Unit exposed on the western side of the Apuane Alps [10, 15]. A

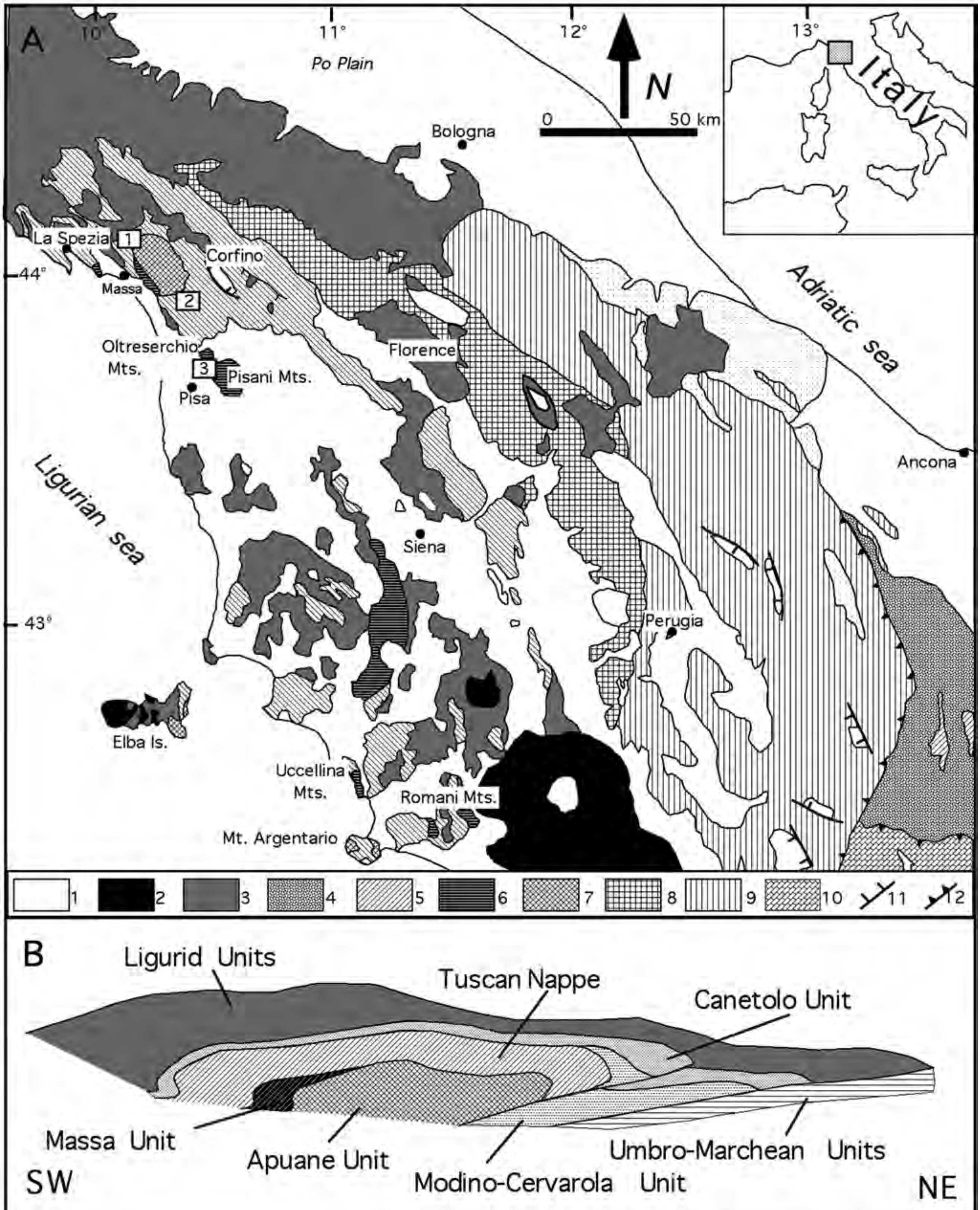

Fig. 1 Geological sketch map of the Northern Apennines and location of the study areas. In the squares are located detailed geological maps of Fig. 4, 7, 13 (1: Neogene-Quaternary sediments; 2: igneous rocks; 3: Ligurid Units; 4: Tortonian “Molasse”, Laga Formation and Pliocene external sediments; 5: Tuscan Nappe; 6: Massa Unit; 7: Metamorphic Tuscan Unit; 8: Cervarola-Falterona Unit; 9: Umbria-Marche Units; 10: Latium-Abruzzi sequences; 11: main normal faults; 12: main external thrusts); b: schematic geological cross-section (not in scale) through the Northern Apennines showing the main tectonic units.

general disagreement exists about the peak metamorphic conditions experienced by this tectonic unit: Franceschelli *et al.* [61] confined the peak conditions at 300-450°C and 0.6 GPa while Di Sabatino *et al.* [62] and Jolivet *et al.* [10] refer the temperature values in the range of 390-410°C at pressure of 0.6-0.8Gpa.

According to many authors [2, 18, 53, 63-64] after the stacking of the main tectonic units the belt was affected by a ductile extensional tectonic phase that ended at 8 Ma [31], during which the deepest metamorphic units were exhumed. The last stages of uplift have been constrained by apatite fission tracks analyses indicating ages between 8-5 Ma and 6-2 Ma for the Tuscan Nappe and the Apuane Unit respectively [65].

3. Structural evolution

Our study has been focused on the Tuscan Nappe outcropping on the western side of the belt (La Spezia area), on both the northwestern and southeastern side of the Apuane Alps massif and, more to the south, in the Monti D'Oltreserchio area (Fig.1a). Data have been also collected in the Corfino area located in the upper Serchio valley (Fig. 1a) as well as in some scattered outcrops in southern Tuscany.

The Massa Unit s.l. has been studied in the metamorphic dome of the Monti Pisani (Fig. 1a), located along the so-called "Mid Tuscan Ridge" extending from the Apuane Alps and Monti Pisani to the north, to the Monticiano-Rocca-Strada ridge, Monti dell'Uccellina, Monti Romani and Monte Argentario, to the south (Fig.1a).

The Apuane Unit has been investigated in the southeastern side of Apuane Alps, close to the tectonic boundary with the overlying Tuscan Nappe (Fig. 1a).

Geological mapping and meso to microstructural analyses pointed to the presence, in all the analized tectonic units, of a complex tectonic evolution. Different systems of superposed folds, deforming the main fabric (D_1) in the Tuscan Nappe and in the Monti Pisani Unit as well as the D_1 and D_2 fabrics of the Apuane Units, and late brittle and brittle-ductile shear zones have been recognized.

3.1. Earlier deformation phases

3.1.1. Tuscan Nappe (TN)

In the Tuscan Nappe the first tectonic phase (D_{1TN}) is associated to the development of mostly east-facing F_1 folds [3], developed at all scales, and to the overthrusting on the external units. Parallel to F_1 axial planes an S_{1TN} foliation developed under a very low-grade metamorphic environment [40-41] with maximum temperature values, estimated both through calcite-dolomite geothermometer [42] and fluid inclusion data [47], around 280/300° C.

During the first tectonic phase top-to the NE brittle-ductile shear zones and thrusts developed (Fig. 2) sometimes with the development of hectometric thrust slices [66].

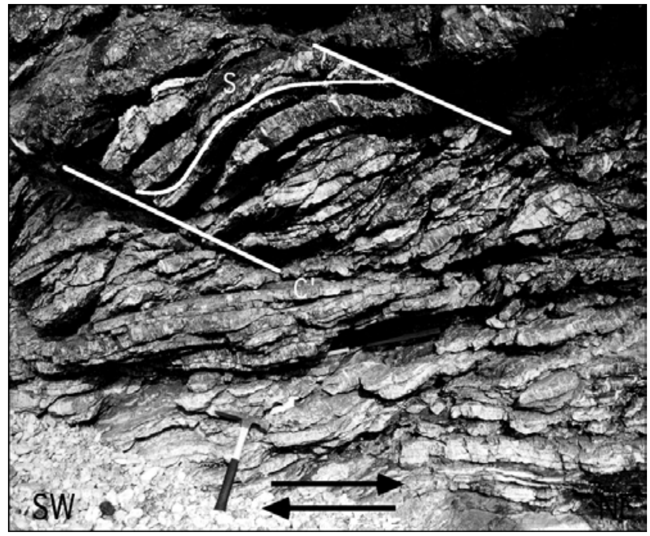

Fig. 2 Example of brittle-ductile shear zone developed in the Tuscan Nappe in the La Spezia area (Calcari ad Angulati formation, Rhaetian). Well developed S-C' fabric points out a top-to-the-NE sense of shear.

3.1.2. Monti Pisani Unit (MPU)

The $D_{1\ MPU}$ tectonic phase in the Monti Pisani Unit is related to tight to isoclinal F_1 folds often non cylindrical, associated with the development of a penetrative $S_{1\ MPU}$ foliation [67].

F_1 folds show quite steeply dipping axial planes and variable vergences, both toward the NE and the SW. Minor F_1 cleavage transected folds [68] or transpressed folds [69] have been detected in the southern portion of the massif [70].

During the $D_{1\ MPU}$ deformation phase, a prominent stretching lineation (L_1) developed on S_1 foliation and it is usually parallel or subparallel to axes of coeval F_1 fold [71].

S_1 axial plane foliation is associated to the syn-kinematic recristallization of quartz, muscovite, plagioclase, chlorite, pyrophyllite, paragonite and green biotite with minor amount of apatite, zircon, rutile, ilmenite, hematite, pyrite and tourmaline, confining the D_1 metamorphic event under the greenschist metamorphic condition (pyrophyllite zone, [54]).

3.1.3. Apuane Unit

In the study area the first deformation phase ($D_{1\ AU}$) produces a penetrative $S_{1\ AU}$ foliation that ranges from a continuous fine cleavage to a disjunctive spaced cleavage. According to Franceschelli *et al.* [54] $S_{1\ AU}$ foliation developed under greenschist metamorphic conditions. Porphyroblasts of chloritoid grew post $S_{1\ AU}$ and pre $S_{2\ AU}$ foliations. Isoclinal intrafolial folds are common and belong mostly to classes 1C and 2 [72]. F_1 fold axes trend NW-SE. The L_1 stretching lineation developed too, trending NE-SW.

The second deformation phase ($D_{2\ AU}$) is the responsable of the main fabric ($S_{2\ AU}$) recognizable at the meso and at the microscopic scale [13]. It is associated to the development of F_2 folds (Fig. 3) with an S_2 axial plane crenulation cleavage. $S_{2\ AU}$ foliation usually shows a flat attitude all over the study area and is associated both to dynamic recristallization and to pressure-solution. F_2 fold axes and intersection lineations are scattered and range from SSE-NNW plunging few degrees toward SSE, in the northern part of the study area, to nearly ENE-WSW plunging toward ENE in the southern part.

Ductile/brittle shear zones developed during the $D_{2\ AU}$ deformation phase always showing a tectonic transport toward the NE.

Fig. 3 $D_{2\ AU}$ fold in the Oligocenic Pseudomacigno formation (Apuane Unit, southeastern portion of Apuane Alps).

3.2. Later folds and shear zones affecting the nappe pile

Two later systems of folds have been detected all over the study areas. The folds deform the main fabric in all the tectonic units represented by a S1 foliation both in the Tuscan Nappe and in the Monti Pisani Unit, while it is a penetrative S2 foliation in the Apuane Unit. According to this, the first system of folds has been appelled F2 in the Tuscan Nappe ($F_{2\ TN}$) and in the Monti Pisani Unit ($F_{2\ MPU}$), while in the Apuane Unit it has been named $F_{3\ AU.}$

Correlatively the superimposed second system of later folds has been named F_{3TN}, F_{3MPU} respectively in the Tuscan Nappe and in the Monti Pisani Unit, while in the Apuane Unit it is $F_{4AU.}$

3.2.1. First system of later folds (F$_1$ Later Folds, F$_{1LF}$ Carosi et al. *[14])*

This system of folds ($F_{2\ TN}$, $F_{2\ MPU}$, $F_{3\ AU}$ respectively in the Tuscan Nappe, Monti Pisani Unit and Apuane Unit) is widespread in the belt. Folds developed at all scales, varying from centimetric to kilometric in size (Fig. 4) and are characterized by upright or steeply dipping axial planes. They have wide interlimb angles, varying from 70° to 150°, and can be referred predominantly to classes 1B and C [72] in the Tuscan Nappe (Fig. 5) to classes 1B and 2 [72] in the Massa Unit of the Monti Pisani and to class 1B in the Apuane Unit, where they can reach interlimb angle values of 170°.

In the Tuscan Nappe fold axes vary from N130 to N160 and gently plunge (a few degrees) both towards the NW and the SE (Fig. 6a). In the Monti Pisani Unit fold axes show orientation ranging from NNW-SSE to NNE-SSW and slightly plunge towards the N and the S (Fig. 6b). In the Apuane Unit fold axes trend predominantly NNW-SSE and plunge a few degrees toward SSE (Fig. 6c).

A foliation developed parallel to their axial planes. In the less competent layers it is a zonal spaced crenulation cleavage while in the more competent levels it is a disjunctive spaced cleavage [73]. The predominant deformation mechanism associated with the foliation is pressure solution.

In the Monti Pisani Unit this system of fold is better developed in the calcareous sequence and one of the most striking structure is located in the western sector of the Monti Pisani massif (Fig. 7). $F_{2\ MPU}$ folds deform previous F1 synclines and anticlines. The complex interference pattern is highlighted by the boundary between the Calcare selcifero and the Calcare ceroide formations. An hectometric $F_{2\ MPU}$ antiform folds a F_1 syncline (Fig. 7). The fold axis steeply plunges northwestward because the fold affects steeply dipping limbs of the previous $F_{1\ MPU}$ syncline [14, 74].

In the underlying triassic siliciclastic sequence the presence of a kilometric upright $F_{2\ MPU}$ fold could be the responsible for the continuous variation in trend of D_1 structural elements that, proceeding from the southern to the northwestern sector of the massif, vary from NW-SE to NE-SW [67].

In the Tuscan Nappe outcropping on the northwestern side of Apuane Alps $F_{2\ TN}$ folds are deformed by later collapse folds associated with a sub-horizontal axial plane crenulation cleavage (Fig. 8).

3.2.2. Second system of later folds (F$_2$ Later Folds, F$_{2LF}$ Carosi et al. *[14])*

This system of folds ($F_{\ 3TN}$, $F_{3\ MPU}$, $F_{4\ AU}$ respectively in the Tuscan Nappe, Monti Pisani Unit and Apuane Unit) developed in all the study tectonic units, even if they have not been recognized in all the study areas where the Tuscan Nappe outcrops.

They develop from metre to kilometre scale and are mostly referable to class 1B of Ramsay [72]. Interlimb angles vary from 70 to 110 degrees. In the calcareous cover of the Monti Pisani Unit lower interlimb angle values have been sometimes detected and folds assume a kink shape geometry (Fig. 9). $F_{3\ MPU}$ axes trend E-W varying from N080 to N110 plunging at most 30° both towards the E and the W (Fig. 10). Also this system of folds is characterized by steeply dipping to vertical axial planes.

This system of folds is not usually associated with the development of an axial plane foliation even if sometimes a spaced disjunctive, in some cases stylolitic-cleavage, has been observed.

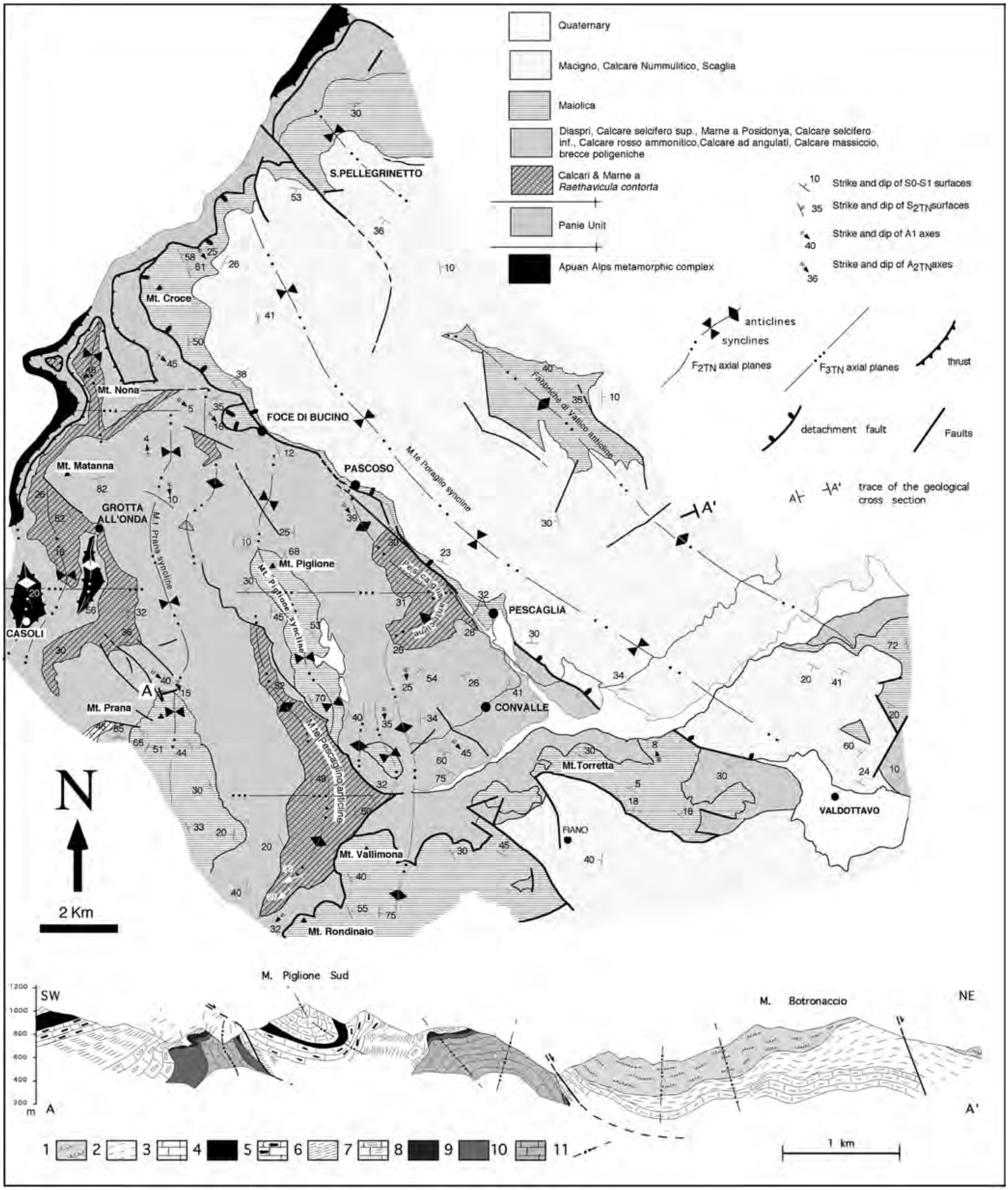

Fig. 4 Geological sketch map of the Tuscan Nappe in the SE termination of the Apuan Alps (square 2 in Fig. 1a); M. Matanna – Valdottavo area. The traces of F_{2TN} axial planes are clearly deformed by $F_{3\,TN}$ folds. The M. Croce-Pescaglia low-angle normal fault crosscuts the F_{2A} and F_{2B} fold systems. Cross section: 1: Macigno; 2: Scaglia; 3: Maiolica; 4: Diaspri; 5: Calcare selcifero superiore; 6: Marne a Posidonia; 7: Calcare selcifero inferiore; 8: Calcare rosso ammonitico; 9: Calcare ad angulati; 10: Calcari e marne a Rhaetavicula Contorta: 11: F_{2A} axial planes traces; 12: faults.

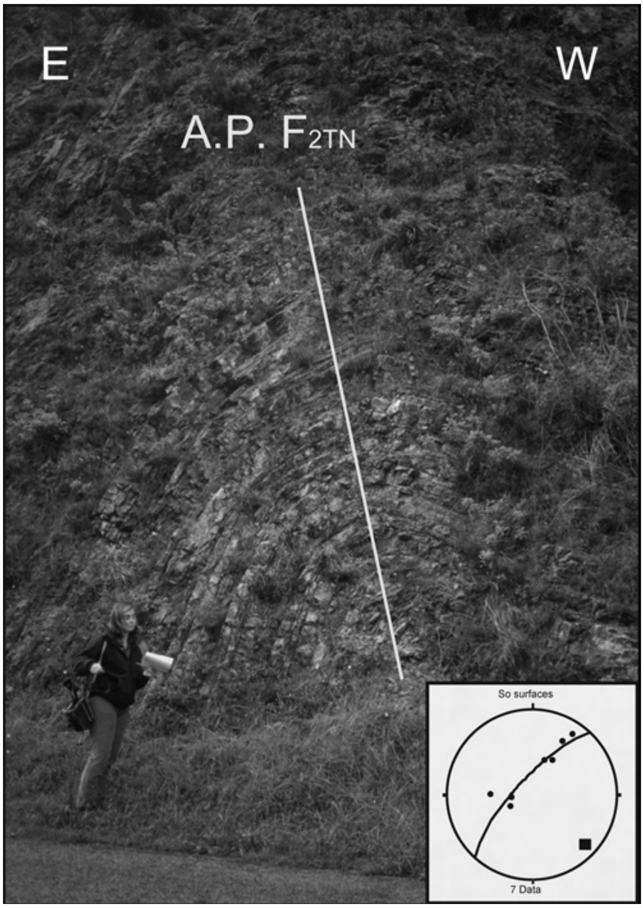

Fig. 5 $F_{2\ TN}$ fold developed in the Tuscan Nappe (Calcare selcifero formation outcropping in the Monti D'Oltreserchio area) characterized by a steeply dipping axial plane. In the stereonet poles to folded $S_{1\ TN}$ surfaces have been plotted, the square corresponds to the calculated fold axes.

They deform the axial planes of F_{2TN}, $F_{2\ MPU}$ and $F_{3\ AU}$ folds both in the metamorphic and in the non-metamorphic units (Fig. 4) so that they postdate this system of folds.

The two systems of later folds are characterized by axial planes and axes almost perpendicular, so their interference pattern is referable to type 1 of Ramsay [72]. Such an interference pattern is recognizable both at the outcrop and at the map scale causing large scale domes and basins structures.

For example in the Corfino area the older Rhaetian limestone, at the bottom of the Tuscan Nappe, outcrops in the core of a kilometre-scale dome (Fig. 11).

3.2.3. Brittle-ductile reverse shear zones and reverse faults

Low-angle brittle-ductile shear zones are associated with both generations of later folds. The occurrence of conjungate systems allow us to better assess the SW-NE direction of shortening.

In the Tuscan Nappe low-angle brittle-ductile shear zones have been recognized in the Calcare selcifero and in the Calcari & Marne a *Rhaetavicula contorta* formations outcropping in the Monti D'Oltreserchio area (Fig. 1a). The shear zones strike vary between N100 and N160 and dip from 20° to 40° toward the SW. Calcite fibres measured on C planes trend from N30 to N90 and plunge about 30° toward the W-SW. Kinematic indicators, mainly S-C fabric, indicate a prevailing top-to-the-EastNorthEast sense of shear. Some minor conjugate shear zones with a top-to-the-SouthWest sense of shear are also present. (Fig. 12).

Shear zones deform the steeply dipping limbs of F_{2TN} upright folds so that they post-date the folding event.

In the Monti Pisani Unit similar shear zones have been recognized both in the Triassic sequence and in the carbonatic cover on the northern side of the Monti Pisani massif. In the first case, they develop in fine quartzites ("Quarziti di Monte Serra" formation). The shear planes show variable attitude but they mostly trend E-W and dip from 20° to 40° toward the South. Striae on the shear planes trend from NS to N015 and dip toward the South. The shear planes clearly deform S1 foliation that is dragged along shear planes with a sense of tectonic transport toward the N-NE. In the carbonatic cover of the Monti Pisani Unit conjugate brittle reverse shear zones are related to conjugate F_{3MPU} upright kink folds. In this case shear zones developed after fold amplification during the latest stages of the folding event

Geometric relations between shear zones and later systems of folds point out that shear zone developed after F_{2TN} and from syn to later $F_{3\ MPU.}$

3.2.4. Strike-slip brittle shear zone

The most striking brittle shear zone has been recognized in the area located on the northwestern side of Apuane Alps. It is a dextral strike-slip fault developed near the boundary between the Tuscan Nappe and the underlying Apuane Unit. The fault trends WSW-ENE and it extends for several kilometres (Fig. 13a). A complex array of fault surfaces has been highlighted by geological mapping and structural analysis. Two mainly E-W trending fault planes have been recognized connected by a SW-NE left bend. The fault has a steeply dipping attitude and only sometimes it shows lower dipping values, around 50° toward the South.

Slickenside striae and calcite fibres have been measured on the fault surface. These features trend nearly E-W and plunge 10-25° eastward indicating a prevailing strike-slip movement of the fault as proposed by Decandia *et al.* [75].

A variety of shear fractures have been recognized associated with the strike-slip fault. En-echelon array of Riedel shear fractures developed both at small and high-angles with respect to the main fault plane. The orientation of both types of shear fractures confirm the dextral sense of displacement of the fault. Low-angle synthetic Riedel fractures (R) are oriented N140 and dip 55SW; they have slickenside striae trending N130, 20NW. High-angle Riedel fractures (R') show an average orientation of nearly N180 (dip 80W) and have an antithetic sense of movement with respect to the main fault. Also on these faults striae trend N170 dipping 50N. Foliated cataclasites with S-C fabric [76], have been also observed in more pelitic levels confirming the dextral sense of displacement.

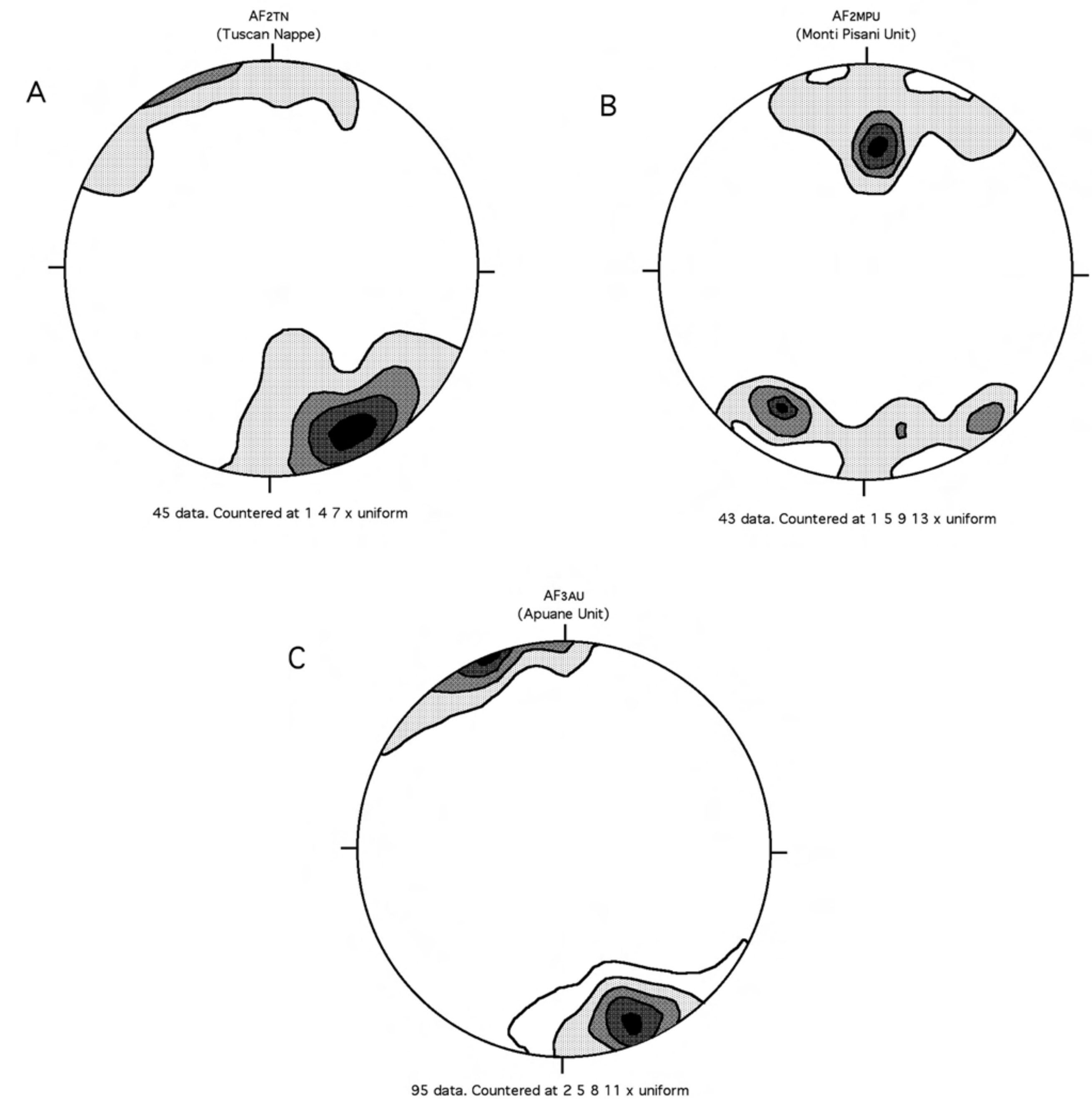

Fig. 6 Stereographic projections (equal area projection, lower hemisphere) of: a) $F_{2\,TN}$ fold axes, b) $F_{2\,MPU}$ fold axes and c) $F_{3\,AU}$ fold axes.

The fault surface shows a curved attitude that is responsible for a complex deformational pattern [77]. In particular, the left bend located in the Tenerano area allows the development of a localized zone of transpressive deformation. The fault displaces with a dextral displacement a west-verging kilometric fold (Castelpoggio fold [75]) interpreted as a collapse fold related to extensional tectonics [19].

3.2.5. Low angle normal faults and collapse folds

In the Tuscan Nappe $F_{2\,TN}$ and $F_{3\,TN}$ folds are affected by low- and high-angle normal faults [2, 19]. One of the most striking low-angle normal fault is located in the southeastern side of the Apuane Alps. It extends for a dozen kilometers from Mt. Croce to south of the village of Pescaglia [9, 14] (Fig. 4). A well-developed foliated cataclasites develops in the pelitic levels interbedded with calcilutites of the Maiolica formation. S-C fabric indicates a top-down-to-the-North East sense of shear (Fig. 14). Microscopic observations indicate that the main deformation mechanisms are cataclasis and pressure solution.

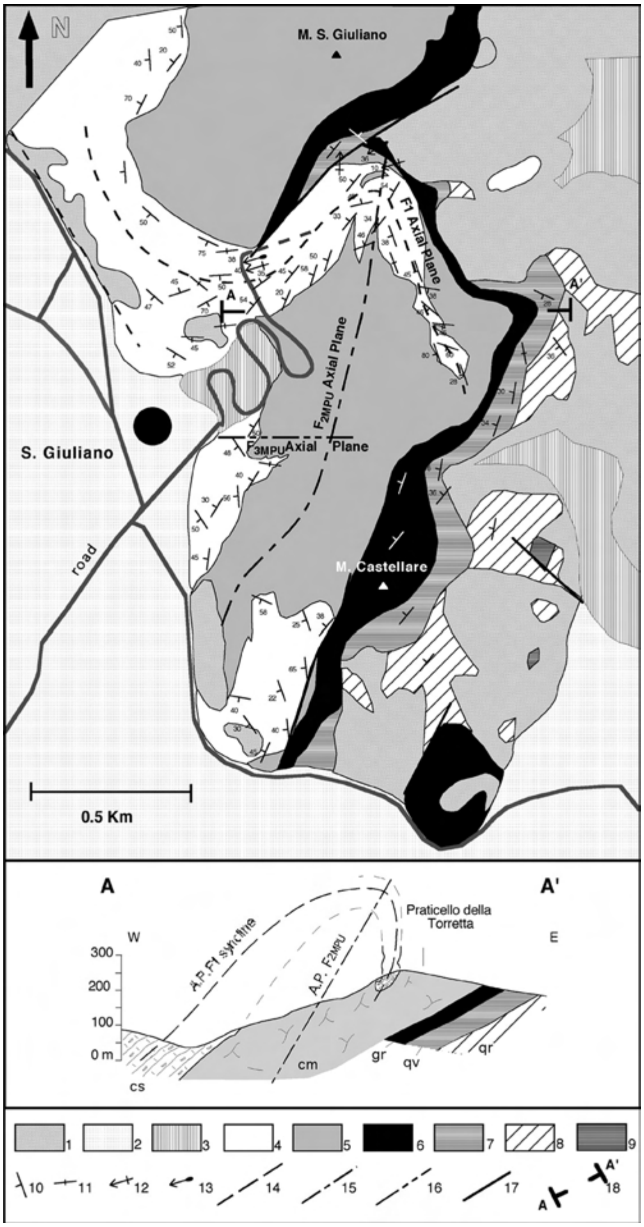

Fig. 7 Geological sketch map of the S. Maria del Giudice Unit in the western sector of the Monti Pisani Unit (square 3 in Fig. 1a). The complex outcropping pattern is due to an interference pattern between a $F_{1\ MPU}$ syncline and a $F_{2\ MPU}$fold. In the geological cross-section both $F_{1\ MPU}$ and $F_{2\ MPU}$ axial planes have been reported.

(1: Quaternary covers; 2; alluvial deposits; 3: terraced alluvial deposits; 4: Calcare selcifero Formation (cs); 5: Calcare ceroide Formation, metabreccias and thin levels of Calcare rosso ammonitico (cm); 6: Grezzoni Formation (gr); 7: purple-banded quartzites (qv); 8: light-pinkish quartzites (qr); 9: greenish quartzites; 10: S_1 foliation; 11: vertical S_1 foliation; 12: $F_{1\ MPU}$ fold axes; 13: L_1 stretching lineation; 14: axial plane of $F_{1\ MPU}$ fold; 15: axial plane of $F_{2\ MPU}$ fold; 16: axial planes of $F_{3\ MPU}$ fold; 17: fault; 18: trace of the geological cross-section).

4. Discussion

4.1. *Compressional* vs *extensional post-collisional tectonic evolution*

One of the most current idea concerning the tectonic history of the Northern Apennines is that after the main stacking of the tectonic units (D1 phase, sensu Carmignani & Kligfield [2]) the belt has been affected by extensional tectonics (D2 phase, sensu Carmignani & Kligfield [2]) causing collapse folds with opposite vergences with respect to the axial culmination of the different metamorphic domes [2, 18-20, 63, 78].

On the contrary, a contractional tectonic setting for the D_2 phase has been proposed by Pertusati *et al.* [3] for the Tuscan Nappe, and by Boccaletti and Gosso [57], Boccaletti *et al.* [58], Capitani and Sani [79], Moratti *et al.* [80], Coli and Pandeli [81] and Storti [82] for the D_2 phase in the metamorphic complex.

It is worth noting that the tectonic regime linked to post-D_1 deformations in the Tuscan units is not yet fully understood and remains an open question, but we believe that the study of later systems of folds could contribute to a better understanding of the tectonic evolution of the Northern Apennines and of the processes of exhumation of the metamorphic units.

Two generations of later folds and brittle and brittle-ductile shear zones developed at upper crustal levels have been recognized to affect the main fabric represented by a S_1 foliation in the Tuscan Nappe and Monti Pisani Unit and by a penetrative S_2 foliation in the Apuane Unit.

Some later folds described in this work have been regarded by previous Authors as linked to extensional tectonics, affecting both the Apuane Unit and the overlying Tuscan Nappe (D_2 folds sensu Carmignani and Kligfield, [2]; Carmignani *et al.*, [19]). They have been interpreted as collapse folds, facing away from the crest of the metamorphic complex antiform in the upper plate (Tuscan Nappe), and developed during the movement of low-angle normal faults. Some examples are represented by later folds outcropping in the Pescaglia area, such as the Mt. Nona antiform (referred to as $F_{2\ TN}$ in this work; Fig. 4). This fold has been interpreted as a roll-over anticline related to the movement along a low-angle extensional fault [9, 19, 83]. However, the Mt. Nona F_{2TN} fold is closed, the limbs are moderately to steeply dipping (nearly 40° northward and 50° southward), shows moderately to high-dipping axial planes and metric-size upright parasitic folds are present on the limbs. This geometry is in agreement with a sub-horizontal direction of shortening causing mechanically active folds and their amplification.

Also in the northern termination of the Apuane Alps, some F_{2TN} folds described in this work (such as the Campedello antiform, [14]) have been previously interpreted as west-verging extensional structures with an east dipping low-angle axial plane related to the presence of a top-to-the-

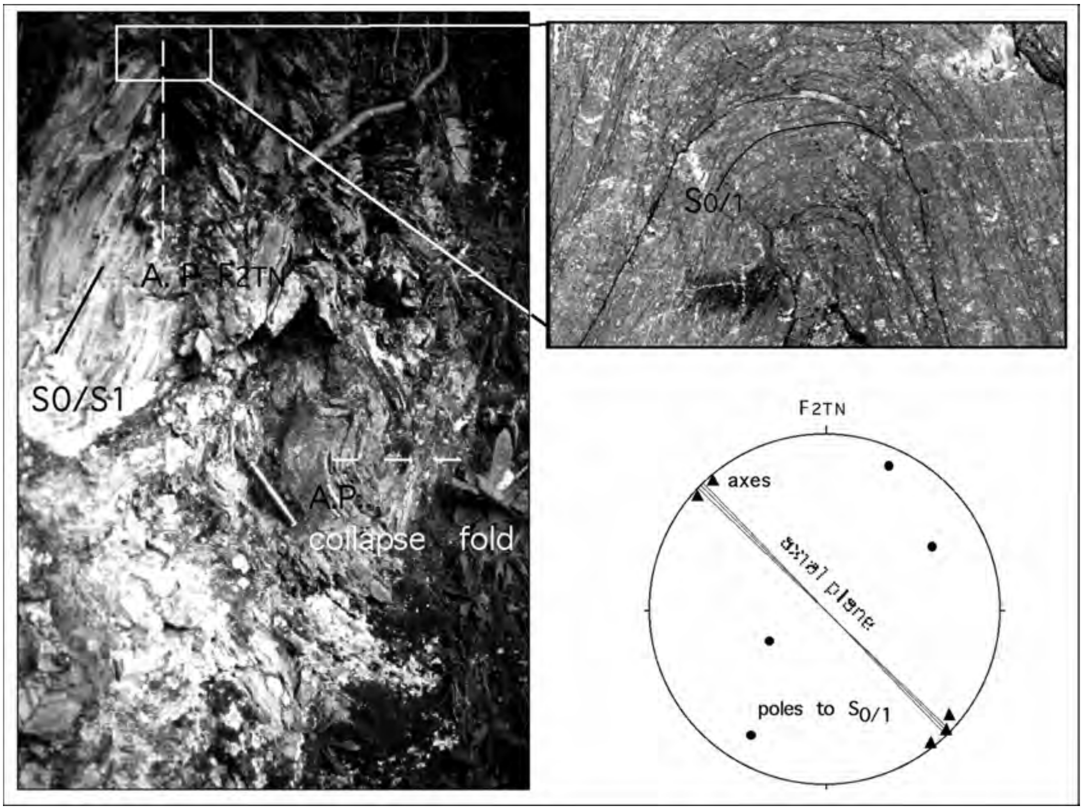

Fig. 8 Outcrop and microscopic aspect of a tight upright $F_{2\ TN}$ fold in the Marne a Posidonia formation (Tuscan Nappe, NW termination of Apuane Alps). The fold is affected by later collapse folds with sub-horizontal axial planes. In the stereonet (equal area projection, lower hemisphere) the structural elements of $F_{2\ TN}$ folds in the same outcrop in A are shown.

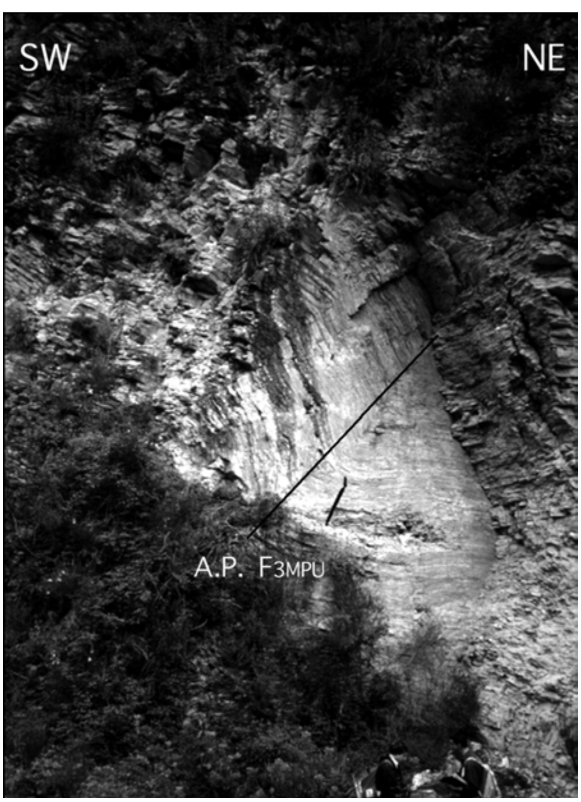

Fig. 9 Example of $F_{3\ MPU}$ fold in the calcareous sequence of the Monti Pisani Unit showing a kink like geometry.

west detachment fault at the boundary between the Tuscan Nappe and underlying metamorphic unit [78, 84]. However, no kinematic analysis of the detachment fault has been reported and our structural data highlight a quite different fold geometry. The eastern limb is not horizontal nor shallowly dips westwards [84] but instead it dips eastwards. As a consequence the fold has a steeply dipping axial plane inclined toward the west that does not fit with a top-to-the-west sense of movement; rather the geometry of the fold is more compatible with sub-horizontal shortening (Fig. 13b).

The consideration that later fold geometries are compatible with an overall sub-horizontal direction of shortening and that these folds are widespread, as well as the overprinting criteria between low-angle normal faults and folds and the lack of genetic relations between later folds and low-angle normal faults, all cast doubts on their link to an extensional tectonic regime. The overall sub-horizontal shortening direction does not fit with the sub-vertical direction of shortening associated with an extensional tectonic regime, rather it suggests a compressive tectonic setting responsible for the two later system of folds described.

Late brittle-ductile reverse shear zones have been described for the first time in this work. Their attitudes combined with well developed kinematic indicators showing a top-to-the-N-NE sense of movement, constrained their development to a compressive tectonic setting. Clear conju-

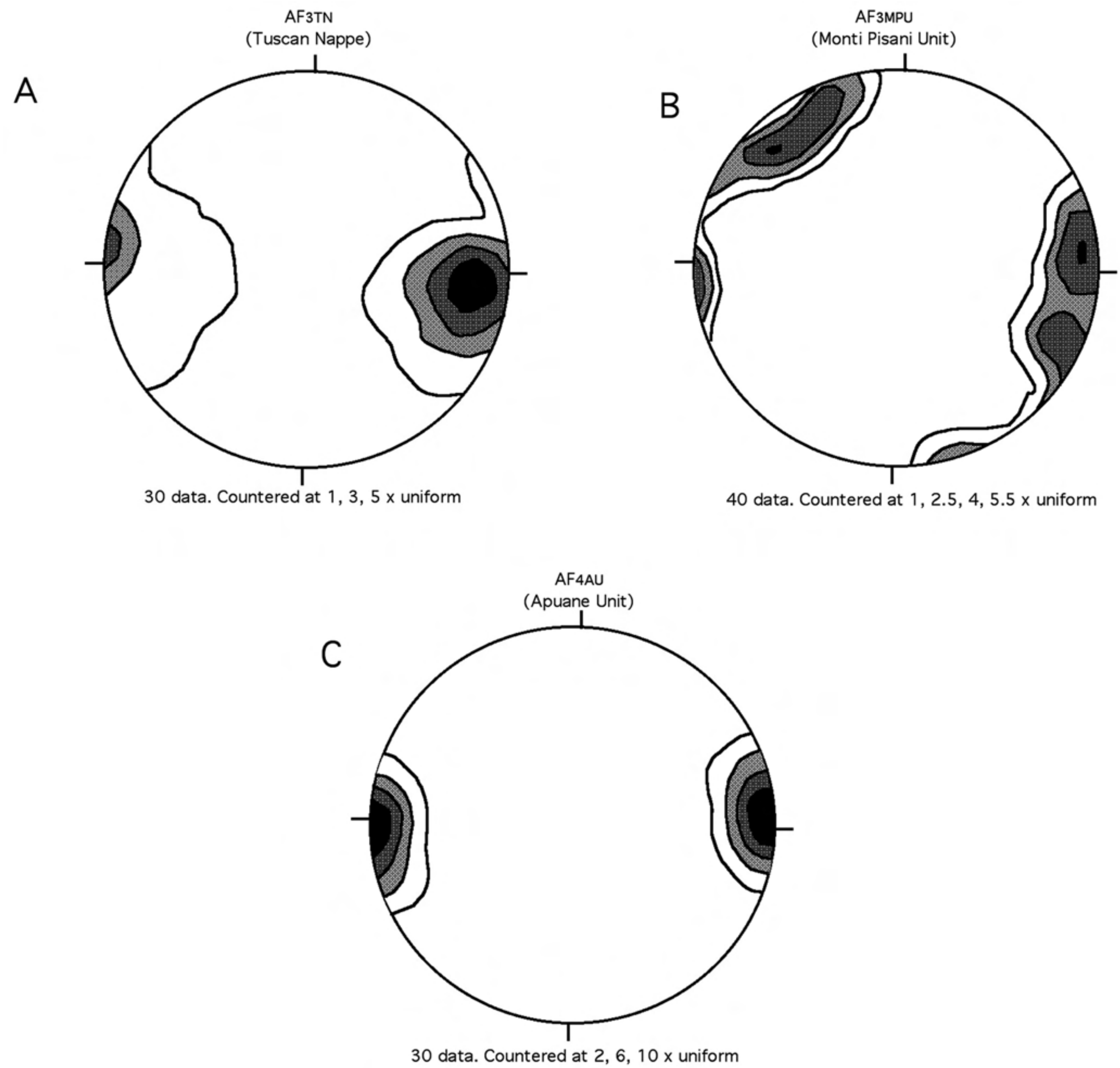

Fig. 10 Stereographic projections (equal area projection, lower hemisphere) of: a) $F_{3\ TN}$ fold axes, b) $F_{3\ MPU}$ fold axes and c) $F_{4\ AU}$ fold axes.

gate systems of later reverse faults linked to $F_{2\ TN}$ folds allow to constrain the NE-SW direction of maximum shortening. It is worth to note that brittle-ductile shear zones affect also different tectonic units. For example in southern Tuscany (Niccioleta area) the Calcare Cavernoso, at the bottom of the Tuscan Nappe, thrusts over a flysch of the Liguride Units with a top-to-the-North West sense of shear (Fig. 15).

However, the systems of later folds here described are also recognizable at a larger scale. In the Monti dell'Uccellina area (Southern Tuscany) (Fig. 1a) an analogous structural frame has been documented [85]. In this area all the nappe pile is folded by a kilometric N-S trending upright antiform with an axis plunging toward the North. The antiform deformes all the tectonic units from the lower, here represented by the Massa Unit s.l. to the upper one correlated with the Tuscan Nappe [85].

Considering a large sector of the Northern Apennines some problems of correlation between structures outcropping in different sectors of the belt may arise in the absence of available radiometric ages. However, it is worth to stress out that both systems of later folds affect both the main fabric (D_1 for the Tuscan Nappe and Monti Pisani Unit and D_2 for the Apuane Unit, Fig. 16) and the tectonic boundary between the tectonic units. These fold generations are subsequently cross-cut by low-angle extensional faults. Therefore, their development is bracketed between contraction and (brittle) extension implying that their interpretation is crucial for understanding the evolution of the belt.

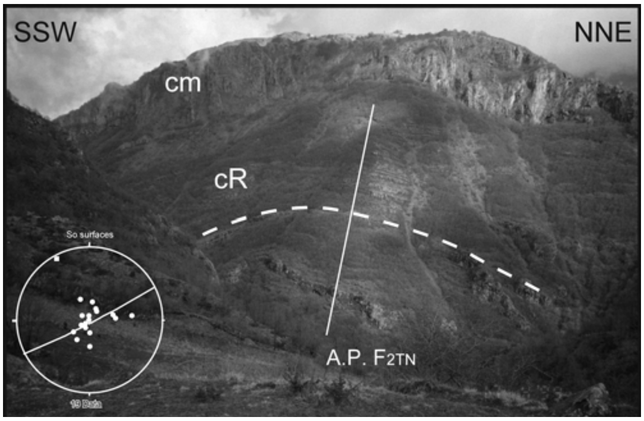

Fig. 11 Panoramic view of the kilometric $F_{2\,TN}$ fold in the Corfino area involving the Tuscan Nappe (cm: "Calcare massiccio" formation; cR: "Calcari & Marne a *Rhaetavicula contorta"* formation). In the stereonet poles of S_o surfaces measured along the $F_{2\,TN}$ fold have been plotted. The white square represents the calculated axes of the $F_{2\,TN}$ fold.

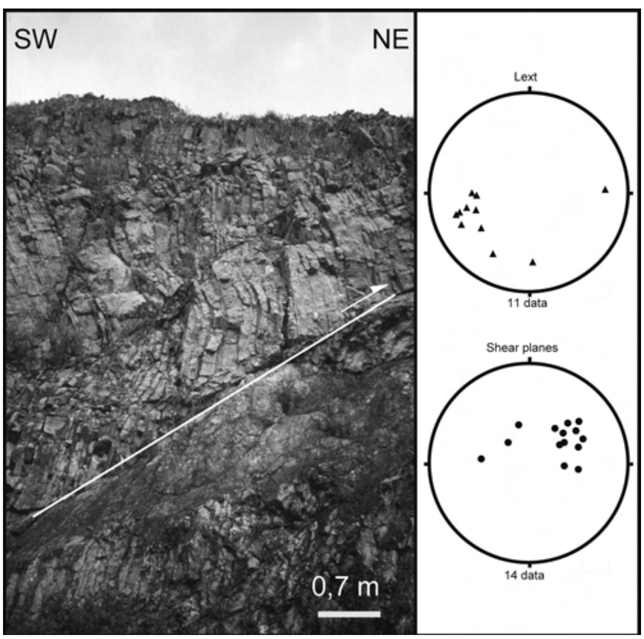

Fig. 12 Late brittle-ductile shear zones in the "Calcare selcifero" formation (Tuscan Nappe, Monti D'Oltreserchio area). In the stereonets the orientation of clacite fibres (upper), measured on the shear planes, and the orientation of shear planes (lower) are represented.

Recent structural data pointed out that also in the southern sector of Apuane Alps and in the Monti Pisani later system of folds (F_{2MPU}, $F_{3\,MPU}$ and F_{3AU} and F_{4AU} respectively for the Monti Pisani and Apuane Unit) affect the tectonic boundary among the units in the nappe pile [13], with paired tectonic units characterized by different metamorphic imprints (i.e. very-low grade metamorphic sequence of the Tuscan Nappe over the more metamorphic Massa Unit s.l. and Apuane Unit "Autoctono Auctt."). F_{3AU} and F_{4AU} folds have been recognized also in the underlying metamorphic Apuane Unit, where they show a sub-vertical axial plane foliation too. So, whatever is the tectonic regime in which they developed, the later folds postdate the emplacement of the Tuscan Nappe over the underlying metamorphic units.

The main consequence of this evolution is that a large part of the exhumation of the metamorphic units had already occurred before the onset of later folding events.

The dextral East-West striking strike-slip fault located at the northern termination of the Apuane Alps massif has previously been described by Valduga [86] as a reverse fault and by Decandia *et al.* [75] as a strike-slip fault on the basis of the general displacement of the structures, later reactivated as a normal fault accommodating the uplift of the Apuane Alps. The same fault has been interpreted also as a detachment fault by Del Tredici *et al.* [78] not on the basis of geometric and kinematic analyses but only correlating the F_2 folds (sensu Carmignani & Kligfield [2]) in the Tuscan Nappe with the F_2 folds (sensu Carmignani & Kligfield [2])observed in the underlying metamorphic unit. The geometry and kinematics of the fault here described point to a complex strike-slip movement with a compressive component. At places, superimposed slickenside striae and calcite fibers suggest a normal reactivation in accordance with Decandia *et al.* [75].

The not so clear overprinting relations between the transversal strike-slip fault, in the NW sector of the Apuane Alps, and the extensional Castelpoggio fold [19] could be interpreted in two different ways:

– the fault post-dates the recumbent fold implying a renewed phase of shortening parallel to the belt after the onset of extensional tectonics, suggesting that a complex interplay between contraction and extension is to be expected in the later tectonic evolution of the Northern Apennines [82];
– extensional tectonics post-dates the strike-slip fault that is reactivated as a normal fault accompanied by the development of collapse folds.

4.2. *Breccias along the boundary between the Tuscan Nappe and the metamorphic units*

Detailed geological mapping and structural analysis on the tectonic boundary between the Tuscan Nappe and the underlying metamorphic sequences performed in the southern sector of the Apuane Alps (Fig. 1a) and in the Monti Pisani revealed a structural evolution much more complex than that outlined so far [13]. The comparison between the structural evolution of the two tectonic units provided new constraints on the tectonic evolution of the Northern Apennines. The two tectonic units recorded a different structural evolution during the first stages of compression, while they shared the same deformation history after both the Apuane Alps and Monti Pisani Units were overthrust by the Tuscan Nappe. The Apuane Unit shows the presence of D_1-D_2 (D_{1AU} and D_{2AU}, Fig. 16) penetrative fabric whereas the Tuscan Nappe shows a D_1 penetrative fabric only ($D_{1\,TN}$, Fig. 16). Both tectonic units have been then deformed by two systems of later folds (F_{2TN} and F_{3TN} for the Tuscan Nappe and $F_{3\,AU}$

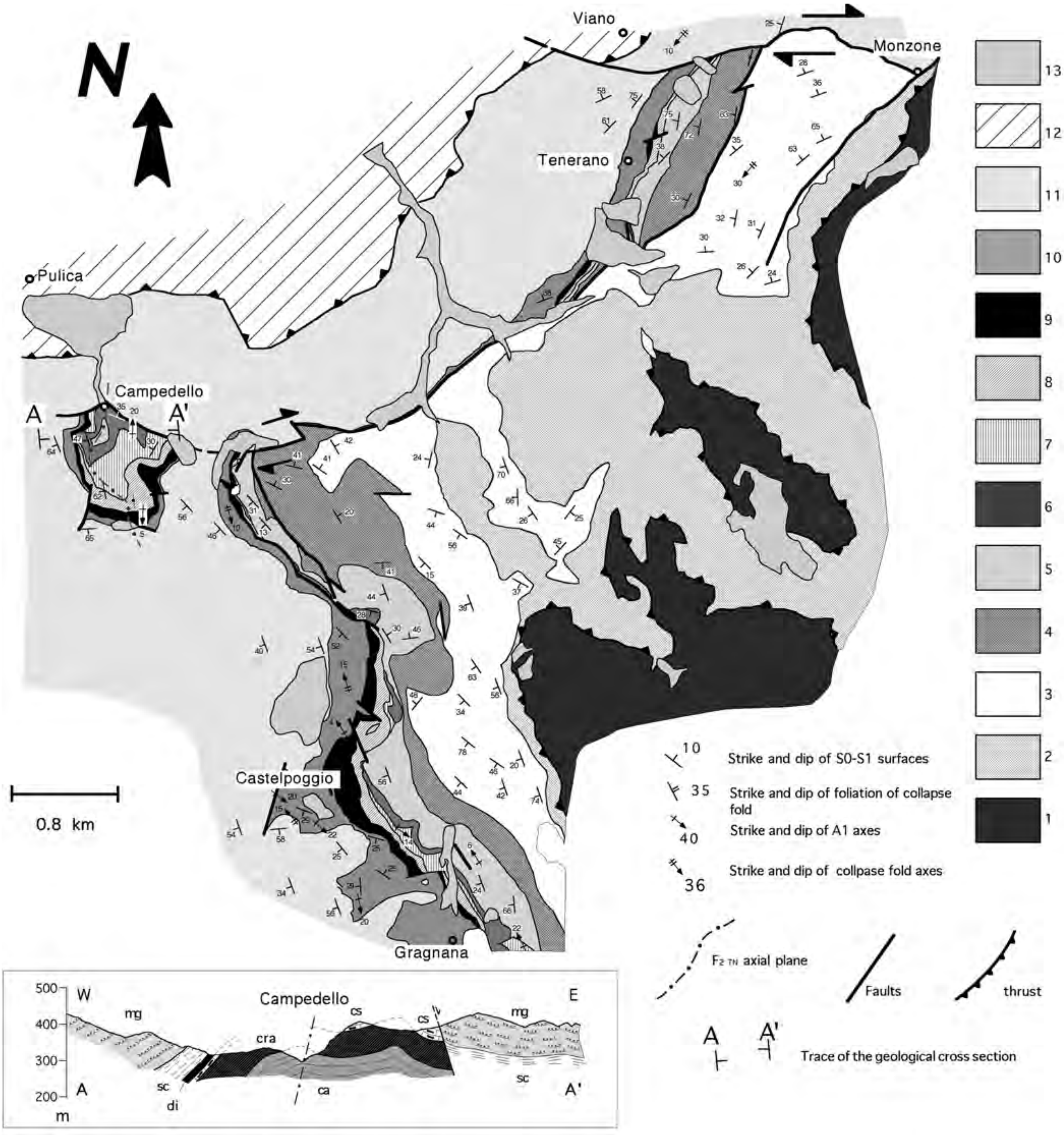

Fig. 13 Geological sketch map of the Tuscan Nappe NW of Apuane Alps (square 1 in Fig. 1a) and geological cross section through the $F_{2\ TN}$ Campedello antiform (1: Undifferentiated Apuane Unit; 2: Calcare cavernoso; 3: Calcari & Marne a *Raethavicula contorta*; 4: Calcare massiccio; 5: Calcare ad Angulati (ca); 6: Calcare Rosso ammonitico (cra); 7: calcare selcifero (cs); 8: Marne a Posidonia; 9: Diaspri (di); 10: Scaglia (sc); 11: Macigno (mg); 12: undifferentiated Ligurid Units; 13: quaternary cover).

and $F_{4\ AU}$ for the Apuane Unit, Fig. 16) in a compressive tectonic regime [13].

A key role in the structural evolution of the Northern Apennines tectonic units is also represented by the “breccias” whose origin in sedimentary or tectonic significance have been debated since the seventies [2, 87-94].

Nevertheless, these breccias are characterised by a complex evolution and by some different types of breccias, including both sedimentary (quite common) and tectonic breccias. In the Monti Pisani we have recognized at least two generations of karst breccias, related to high-angle joints and faults, the last one showing recent Pleistocenic continental

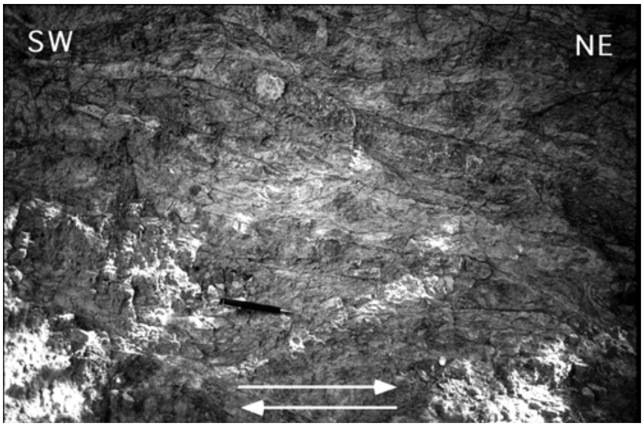

Fig. 14 Aspects of the foliated cataclasite developed in correspondence of the Mt. Croce-Pescaglia low-angle normal fault near Foce di Bucino (Fig. 4) (Maiolica formation, Tuscan Nappe). Shear planes shallowly dip towards the NE with a top down to the NE sense of shear.

Fig. 15 Overthrusting of the Calcare cavernoso Formation, belonging to the Tuscan Nappe (right in the photo), over a calcareous flysch of the Ligurid Unit (left in the photo) cropping out in Southern Tuscany.

TUSCAN NAPPE	MONTI PISANI UNIT	APUANE UNIT
D1TN East-facing F1 folds with penetrative axial plane S1 foliation. Top-to-the-NE brittle/ductile shear zones. Very low grade metamorphism.	D1MPU Tight to isoclinal F1 folds, often non cylindrical with penetrative axial plane S1 foliation. Low grade metamorphism	D1AU Isoclinal F1 folds with NW-SE trending axes. Penetrative S1 foliation ranging from a continuos fine cleavage to a disjunctive spaced cleavage. NE-SW stretching lineation Low grade metamorphism D2AU Tight F2 folds with axial plane penetrative S2 foliation which represents the main fabric. SSE-NNW to ENE-WSW trending axes. Top-to-the- NE ductile to brittle shear zones Low grade metamorphism.
TECTONIC BOUNDARY Top-to-the-NE brittle-ductile shear zones with foliated cataclasites		
D2TN F2 folds from centimetric to kilometric in size. Classes 1B and C. Steeply dipping axial planes and axes trending NNW-SSE and gently plunging. S2 is a disjunctive spaced cleavage.	D2MPU F2 folds belonging to classes 1B and 2. Steeply dipping axial planes and axes varying from NNW-SSE to NNE-SSW. Sa varies from a zonal spaced crenulation cleavage to a disjunctive spaced cleavage.	D3AU Open F3 folds belonging to class 1B. Steeply dipping axial planes and axes trending NNW-SSE. S3 is a zonal spaced crenulation cleavage.
D3TN Open upright folds, nearly E-W trending axes. Poorly developed S3 spaced crenulation cleavage. Top-to-the-NE brittle-ductile shear zones .	D3MPU Open upright folds, nearly E-W trending axes. Poorly developed S3 spaced crenulation cleavage. Top-to-the-NE brittle-ductile shear zones.	D4AU Gentle to open upright folds, nearly E-W trending axes. Poorly developed S4 spaced crenulation cleavage.
EXTENSIONAL TECTONIC PHASE Low-to-high-angle normal faults and collapse folds		

Fig. 16 Synoptic table of the deformation phases with their main structural feautures in the Tucan Nappe, Monti Pisani Unit and Apuane Unit.

fossils (Carosi *et al.* in prep.) overprinting breccias with clearly preserved sedimentary features and cataclasites linked to low- to high-angle normal and strike-slip faults and older cataclasites. The most significative for the tectonic evolution of the units are the older ones, preserved at few places; characterised by the presence of metamorphosed and deformed clasts deriving from the underlying metamorphic units. They have been recognized in the Monti Pisani (Rupe Cava outcrop) and in the southern side of the Apuane Alps [13]. Along the tectonic boundary between the underlying Monti Pisani Unit and the upper Tuscan Nappe, when kinematic indicators can be observed they always show a top-to the NE sense of shear. The clasts from the metamorphic units are affected by two ductile penetrative foliations suggesting that the breccias developed after the metamorphic units have been affected by at least two deformation events and have suffered the main metamorphic imprint (Fig. 17).

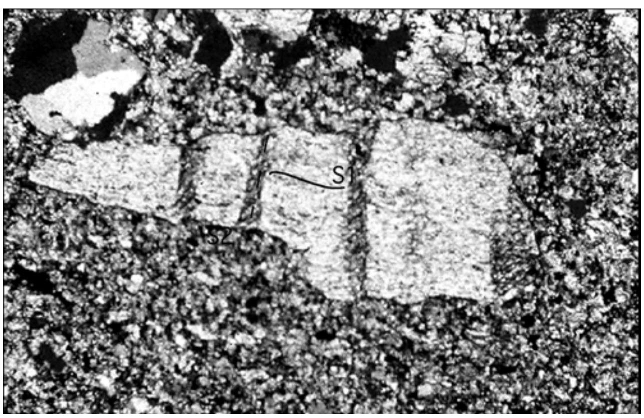

Fig. 17 Thin section of the polygenic breccia located near the boundary between the Tuscan Nappe and the underlying Apuane Unit (SE termination of Apuan Alps). The clast in the centre, made up by phyllites, is deformed by two deformation phases (Nicol X, 30x).

The compared structural and metamorphic evolution of the Tuscan Nappe and the metamorphic units and the characteristics of the breccias fit well together and shed new light on the tectonic evolution of the belt indicating a later tectonic superposition of the Tuscan Nappe over the metamorphic units.

4.3. *Relations between the Tuscan Nappe and the metamorphic units*

The nature of the contact between the Tuscan Nappe and the underlying Massa s.l. and Apuane Units is still an argument of debate. The boundary was originally regarded as a thrust contact [1], or as a thrust reactivated by extensional tectonics [2] and as an extensional detachment [10].

The superposition of the very low-grade metamorphic Tuscan Nappe over the more metamorphic units of the Apuane Alps metamorphic complex is often taken as a proof of there being an extensional fault between them. However, we stress out that the maximum pressure and temperature reached by the Tuscan Nappe are lower with respect to the underlying units that are underthrust more deeply [10]. This means that whatever the contractional or extensional setting of the tectonic contact, the difference in the metamorphic grade between the tectonic units cannot be used without other structural and kinematic evidence as indicative for the tectonic setting.

A syncollisional exhumation of the more metamorphic units in a contractional tectonic setting is testified by the overthrusting of the Massa Unit s.l. over the Apuane Unit as proposed by Carmignani *et al.* [1], Jolivet *et al.* [10] and Molli *et al.* [15], so inducing an inverted metamorphic gradient in the underlying unit [45, 54]. In addition, a partly contractional setting for the exhumation of the metamorphic units has been also proposed by Storti [82] in the Punta Bianca area hypothesising the activity of an out-of-sequence thrust.

The timing of tectonic superposition of the Tuscan Nappe onto the metamorphic complexes still represents a problem. The difference in the tectonic and metamorphic evolution of the stacked tectonic units implies that the Tuscan Nappe and the metamorphic units didn't share the same evolution [13] and that the D_1 fabric in the Tuscan Nappe cannot be easily correlated with the D_1 fabric in the metamorphic units as proposed by Carmignani & Kligfield [2] and Del Tredici *et al.* [78, 84]. Giglia [48], Boccaletti & Gosso [57] and Carosi *et al.* [13] suggested that the overthrust of the Tuscan Nappe took place after the main metamorphic imprint in the Apuane and Massa s.l. Units. At the present state of knowledge we can constrain the overthrust of the Tuscan Nappe onto the metamorphic units from syn-D_2 up to post-D_2 deformation phase in the metamorphic units and before the onset of F_{2TN} and F_{3TN} later folds.

4.4. *Pressure – Temperature constraints of F_{2TN} folds in the Tuscan Nappe*

Pressure-temperature constraints for later folds are available only for F_{2TN} folds developed in the Tuscan Nappe. Fluid inclusion analyses have been performed on suitable quartz crystals in syn-F_{2TN} veins in the Macigno Formation in the La Spezia area. These analyses pointed out a retrograde metamorphic pattern, with pressure values ranging from 250 to 100 MPa and temperature ranging from 280° to 160°C from the initial stage up to the final stages of D_{2TN} deformation [16, 47]. The presence of a strong isothermal pressure fluctuation from 250 to 100 MPa, or lower, detected in the metamorphic system by the coexistence of fluid inclusions, representing two end-members of immiscible fluids, could have been related to the opening of the vein system during exhumation [47].

Even in the presence of possible uncertainties in the correlation between later folds developed in different areas of the chain, these results suggest, at least, that the Tuscan Nappe underwent a post-$D_{1\ TN}$ retrograde pattern. Since the $D_{2\ TN}$ phase is contractional-related deformation and from the $D_{1\ TN}$ to $D_{2\ TN}$ deformational phases the Tuscan Nappe moved from nearly 250 MPa and 280°C to at least about 100 MPa and almost 200°C, we propose that most of the exhumation of the unit was driven by contractional tectonics.

4.5. Metamorphic domes and later folds

The Apenninic metamorphic domes are characterised by the presence of large-scale NW-SE antiforms folding the main fabric of the stacked units.

As shown by Carmignani *et al.* [1-2, 95] the culmination of the metamorphic dome is located in correspondence of Mt. Croce [1, 95]. This is a large-scale (wavelenght >> 5 km) antiform with a steeply dipping axial plane. Some other similar minor antiforms and synforms are present in the metamorphic complex with the development of a sub-vertical axial planes [9, 58, 79]. The NW-SE trending upright crenulation cleavage pre-dates the extensional F_2 folds sensu Carmignani & Kligfield [2]. Also in the Monti Pisani the overall attitude of S1 foliation in the massif describes a large upright dome [67] accompanied by smaller-scale steeply dipping antiforms and synforms [96].

However, the flat lying S_2 foliation (sensu Carmignani & Kligfield [2]) related to the development of collapse folds recognised in the Apuane Alps and Monti Pisani is not parallel to the axial planes of the steeply dipping antiforms and synforms in the domes.

The moderate to steeply dipping attitude of S_o and S_1 (and $S_{2\ AU}$ for the Apuane Unit) could have originated by kilometric wavelength upright folds over gently dipping $D_{1\ TN,}$ $D_{1\ MPU,}$ $D_{1\ AU}$ and $D_{2\ AU,}$ structures. Kilometric wavelength upright folds could be also responsible for the dome structure of the S1 foliation recognized in the Monti Pisani, subsequently inherited by the collapse-related deformation phase. During the stage of collapse of the overthickened nappe pile the steeply dipping attitude of S_0 and S_1 ($S_{2\ AU}$ for the Apuane Unit) enhanced the development of recumbent, nearly symmetric collapse folds.

A similar mechanism of extensional collapse of upright antiforms and synforms in other collisional belt [97] has been described in the Austroalpine nappes of Switzerland [98], in the Higher Himalayan Crystallines of the Nepalese Himalayas [26] and in the Variscan belt of Sardinia [7].

It is worth noting that the presence of later structures perpendicular to the trend of the Northern Apennines has been detected over a large sector of the inner part of the belt. The structures investigated could have played an important role in the development of the metamorphic domes. $F_{3\ TN}$ and $F_{3\ MPU}$ folds ($F_{4\ AU}$) and faults are compatible with a direction of shortening parallel to the main trend of the belt. Overprinting criteria show that the orogen-parallel shortening related structures developed during the final stages of the orogenesis as they deform the later $F_{2TN,}$ $F_{2\ MPU}$ and $F_{3\ AU}$ synforms and antiforms. The interference between the two described later fold systems, characterized by almost perpendicular fold axes and steeply dipping axial planes (compare Fig. 6 with Fig. 10), contributed to the dome shape of the metamorphic complexes in the Northern Apennines such as the Apuane Alps, the Monti Pisani and the Monti dell'Uccellina located in southern Tuscany.

In our tectonic reconstruction, the dome shape of the metamorphic complexes is not related to extensional tectonics causing the development of metamorphic core complexes [2], but instead it was originated initially by the antiformal nappe stacking [2] that was subsequently enhanced by the interference pattern between the two high-angle systems of folds. In essence, the domes are caused by the continuing contraction from D_1 deformation phase up to the late $F_{2TN,}$ $F_{2\ MPU}$, $F_{3\ AU}$ and $F_{3\ TN}$, $F_{3\ MPU}$, $F_{4\ AU}$ folds.

The presence of NE-verging brittle-ductile shear zones both in the Tuscan Nappe and in the Monti Pisani Unit cross-cutting the main fabric and the later systems of folds testifies that contractional tectonics was still acting in the belt during $D_{3\ TN}$ and $D_{3\ MPU}$.

In this scenario, most of the exhumation is syncollisional and compression-related, whereas only the final part of the exhumation history was accommodated by collapse folds and low- to high angle normal faults related to extensional tectonics at higher structural levels. Folding is likely to be an important mechanism contributing to the exhumation of some parts of orogens and the ability of large-scale antiformal folds to exhume lower metamorphic units for dozens of kilometers has been documented by Burg *et al.* [24-25] for the Namche Barwa syntaxis in the eastern Himalayas.

The vertical growth of the large-scale domes accelerated the instability of the already thickened crust in the Northern Apennines (up to this stage affected only by "tangential" tectonics) enhancing the development of collapse folds and low-angle extensional shear zones. This happened especially in the more "amplified" areas such as the crest of the domes.

No radiometric data are available for these late tectonic events. Only the last stages of exhumation in the Northern Apennines have been constrained by apatite fission track analyses, which indicate ages ranging from 6 to 2 Ma in the Apuane Alps [65] and Monti Pisani (Balestrieri *et al.*, in prep.), and 8-5 Ma in the Tuscan Nappe Apuane [65], attributed to extensional tectonics [2].

The transversal structures described above (represented by $F_{3\ TN,}$ $F_{3\ MPU}$ and $F_{4\ AU}$ folds and later faults) are likely to have been separated by a period in which extensional tectonics prevailed. In this framework, the above described relations in the northwestern side of Apuane Alps could confirm the presence of contractional tectonics after the late Miocene, as proposed by some Authors ([11] with references therein).

The cause of shortening parallel to the belt causing $F_{3\ TN,}$ $F_{3\ MPU}$ and $F_{4\ AU}$ folds can be tentatively explained considering the large-scale plate motion in western Mediterranean from collision at nearly 27-25 Ma onward. According to the microplate reconstructions in western Mediterranean both Corsica-Sardinia Block and northern Apennines uderwent counterclockwise rotation. This means that during Oligocene the trend of the Apenninc belt was mainly NE-SW reaching a nearly N-S trend after the rotation of the Corsica-Sardinia Block at Lower Miocene [99-100] that ended at nearly 16 Ma [101]. The relative direction of motion of Africa with respect to Europe has been changed from NW-SE to nearly N-S in this period, as the velocity of convergence is slow since 25-20 Ma. Even if E-W shortening and extension predominates in the system ([99], with references therein; [102-103]) the north-south motion of Africa starts to induce a minor component of orogen-parallel shortening in the rotated belt that could be responsible of the orogen-parallel shortening related system of late folds.

4.6. Stages of the structural evolution

The collected data allow us to identify the subsequent structural evolution for the tuscan continental units of the Northern Apennines (Fig. 18):

–westward underthrusting of the tectonic units; during this stage the tectonic units received their main deformative imprint [1-3, 36, 43] and progressively reached their metamorphic climax and the Massa Unit s.l. experienced the higher pressure and temperature conditions [10, 15, 54, 61];

–syncollisional exhumation of the deepest buried (Massa Unit s.l.) units in a compressive tectonic setting; the Massa Unit was superposed onto the Apuane Unit [10, 15, 48];

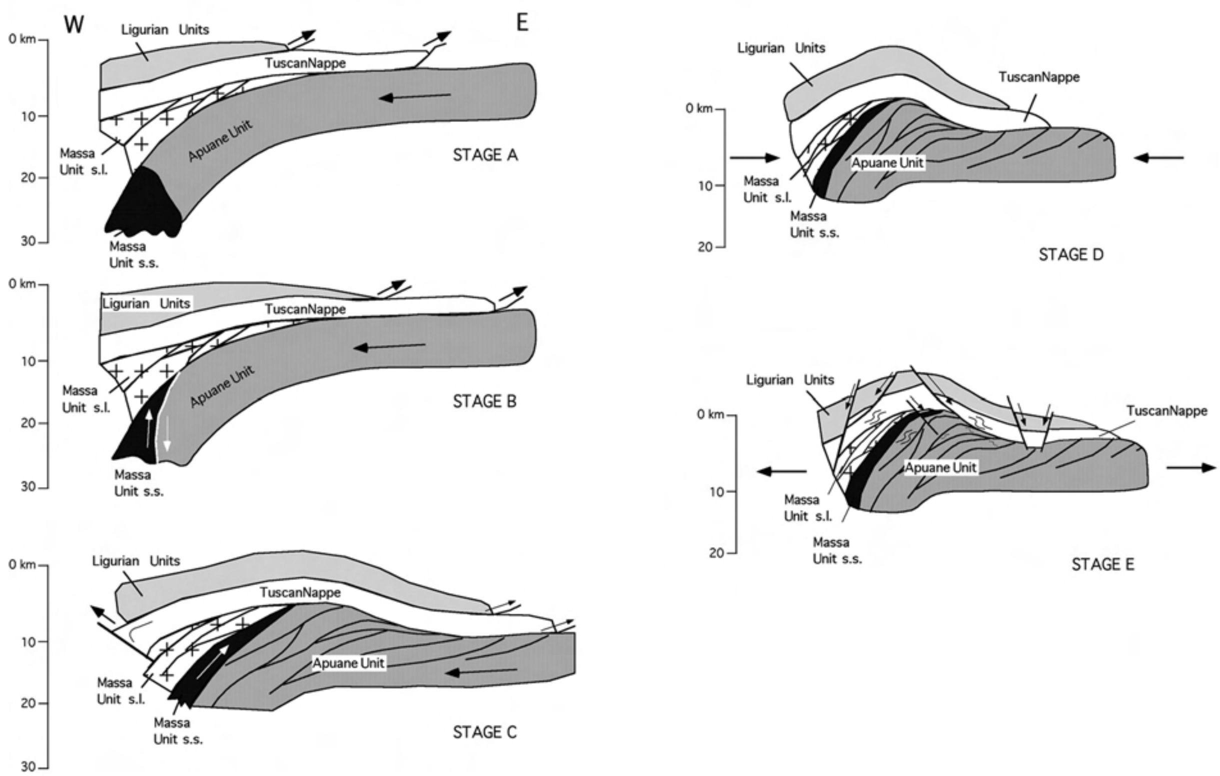

Fig. 18 Simplified tectonic sketch of the evolution of the Northern Apennines around the studied sectors (modified after Carmignani & Kligfield [2] and Molli *et al.* [15]).

Stage A: Collision and underthrusting of metamorphic tuscan units that reached their metamorphic climax. The lacking of evaporites at the base of the Exterrnal Domain sequence made the sequence coupled with its basement that is underthrusted up to 0.8-1 GPa in the Massa Unit s.s. The Massa Unit s.l. is splitted in different slices reaching different depths and recording different T and P conditions. The metamorphic units underwent the D1 deformation phase and developed the penetrative S1 fabric (e.g. at nearly 27 Ma in the Apuane Unit [31]).

Stage B: Continuing underthrusting of the Tuscan Domain and syncollisional exhumation of the Massa Unit s.s. Deformation and metamorphism in the Tuscan Nappe is due to the eastward translation and to the load of the overlying Ligurian Units.

Stage C: Continuing contraction and exhumation of the Massa Unit s.l. and formation of the stack of metamorphic units during the D2 deformation phase after the main stages of prograde metamorphism. In this stage it is likely that the Tuscan Nappe overthrust the exhumed metamorphic units. During this stage of contraction and continuing collision no more underthrusting happened in the inner part of the belt and it is likely that backthrusts and backfolds developed in the western side of the belt. The Ligurian Units have completely overthrust the Tuscan Nappe at this stage causing very-low grade metamorphism and complete development of the D1 fabric in the Tuscan Nappe.

Stage D: Development of later systems of folds. Orogen-perpendicular contraction caused the development of NW-SE trending antiforms and synforms onto the stacked tectonic units. The main antiformal stack, at the level of the Alpi Apuane, is amplified constituting one of the biggest dome in the Northern Apennines. Orogen-parallel contraction caused the development of dome-and-basin like structures interferring with the previous folds. Uplift of the nappe pile.

Stage E: Extensional tectonics affected the thickened and uplifted nappe pile by collapse folds and low- to high-angle normal faults (at nearly 6-2 Ma in the Apuane Unit and 8-5 in the Tuscan Nappe [65]).

– stacking of the tectonic units at higher structural levels and overthrusting of the Tuscan Nappe onto the Massa s.l. and Apuane Units after the $D_{1\ AU}$ and syn- to post-$D_{2\ AU}$ deformation phase in the Apuane Unit [13];
– further shortening gave rise to large antiforms and synforms in Apenninic direction ($F_{2\ TN}$, $F_{2\ MPU}$ and $F_{3\ AU}$ folds);
– orogen-parallel contraction ($F_{3\ TN}$, $F_{3\ MPU}$ and $F_{4\ AU}$ folds) causes interference pattern of dome and basin type with the previous folds; the largest domes are due to further fold amplification of the antiformal stack. This deformation affects the units at higher structural levels, i.e. after a large part of exhumation had already occurred, as testified by brittle shear zones and the lacking of recrystallization along the axial planar foliation;
– development of extensional tectonic setting by collapse folds and low- to high-angle faults and shear zones when shortening migrated eastwards.

5. Conclusions

New structural data carried out in the three main Tuscan tectonic units of the Northern Apennines allow to propose a different interpretation for the tectonic evolution of a large sector of the belt after the main collisional stage. Such a deformation picture is more complex than that up to now accepted by most of the Authors working in the Northern Apennines. Moreover, the comparison of deformation history in the different superposed tectonic units allow to constrain the relative timing of their tectonic superposition. The Tuscan Nappe was thrusted over the metamorphic sequences after the D_1 and syn- to post-D_2 deformation phases that affected the Apuane Unit. This point sheds new light on the significance of polygenic breccias interposed between the Tuscan Nappe and the underlying metamorphic units. The breccias are of different types but the older cataclasites contain already deformed (at least by two deformation phases) and metamorphosed clasts thus supporting the above interpretation. The tectonic boundaries among the main tectonic units are affected by at least two generations of later folds and brittle shear zones, indicating two nearly orthogonal directions of shortening, producing a dome and basin structuration in the Northern Apennines. However, the largest domes are located in correspondence of the main antiformal stack of tectonic units. It is likely that further horizontal shortening in the nappe pile caused further instabilities of the overthickened crust and enhanced the collapse of the stacked units gradually passing into an extensional tectonic setting at higher structural levels when the driving forces of mountain building ceased or migrated eastward. In this picture, extensional tectonics is mostly confined to the final stages of the evolution of the thickened crust.

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