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Structural evolution of the Tuscan Nappe in the southeastern sector of the Apuan Alps metamorphic dome (Northern Apennines, Italy)

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Structural analysis carried out in the Tuscan Nappe (TN) in the southeastern sector of the Apuan Alps highlights a structural evolution much more complex than that proposed so far. The TN has been deformed by structures developed during four deformation phases. The three early phases resulted from a compressive tectonic regime linked to the construction of the Apenninic fold-and-thrust-belt. The fourth phase, instead, is connected with the extensional tectonics, probably related to the collapse of the belt and/or to the opening of the Tyrrhenian Sea.

Our structural and field data suggest the following. (1) The first phase is linked to the main crustal shortening and deformation of the Tuscan Nappe in the internal sectors of the belt. (2) The second deformation phase is responsible for the prominent NW–SE-trending folds recognized in the study area (Mt. Pescaglino and Pescaglia antiforms and Mt. Piglione and Mt. Prana synforms). (3) The direction of shortening related to the third phase is parallel to the main structural trend of the belt. (4) The interference between the third folding phase and the earlier two tectonic phases could be related to the development of the metamorphic domes. The two directions of horizontal shortening induced buckling and vertical growth of the metamorphic domes, enhancing the process of exhumation of the metamorphic rocks. (5) The exhumation of the Tuscan Nappe occurred mostly in a compressive tectonic setting.

A new model for the exhumation of the metamorphic dome of the Apuan Alps is proposed.

Its tectonic evolution does not fit with the previously suggested core complex model, but is due to compressive tectonics.

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1. INTRODUCTION

Collision mountain-belts are dominated by contractional structures, such as thrusts and folds, that collectively produce thickening of the continental lithosphere (Coward 1983, 1994). However, in their advanced stages of evolution, most belts are characterized by spreading and collapse, accommodated by normal faults and extensional shear zones that overprint pre-existing folds and thrusts (see e.g. Dewey 1988). This superposition may create structural complexities that are often very difficult to unravel. The local occurrence of palaeo-horizontal indicators, such as bedding surfaces, may help to discriminate the genuine character, extensional or contractional, of deformation structures. However, due to uplift and erosion, this information is often not available, and other criteria are required (see e.g. Wheeler and Butler 1993, 1994). The systematic study of overprinting relationships in terrains that have

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experienced multiple deformations may indeed provide critical information on the kinematic behaviour of investigated structures (Platt and Vissers 1989, and references therein). In this paper, we present the results of a structural analysis carried out in the inner part of the Northern Apennines of Italy, with the aim of discriminating the true kinematic character of superposed structures whose tectonic significance is controversial. Our structural investigations favour a new tectonic model for the Apuan Alps metamorphic dome, which has until now been regarded as a 'core complex' (Carmignani and Kligfield 1990).

In the context of the tectonic evolution of the Northern Apennines, the structural evolution of the Tuscan Nappe (TN) has been subjected to different interpretations, in relation to compressional or extensional tectonic interpretations of the belt. Moreover, in the last twenty years most of the tectonic studies focused mainly on the metamorphic rocks of the Apuan Alps Unit (AAU) and Massa Unit (MU), whereas the Tuscan Nappe received relatively little attention.

The presence of a polyphase structural evolution in the Tuscan Nappe has been recognized by Pertusati *et al.* (1977) and, until the 1990s, its tectonic history was entirely attributed to compressional tectonics. Nevertheless, Coli (1989), Carmignani and Kligfield (1990) and Carmignani *et al.* (1994) all interpreted the Apuan Alps as an extensional metamorphic core complex, attributing a large part of structures present in the area to extensional tectonics. Moreover, they were the first authors to recognize that large-scale recumbent folds in the Northern Apennines could be generated by extensional tectonics. According to them, the TN played the role of the non-metamorphic upper plate above the rising metamorphic tectonic units of the Apuan Alps in the lower plate. The D1 fabric in the TN was imprinted during the nappe stacking, whereas the following D2 structures were attributed entirely to extensional tectonics (Carmignani and Kligfield 1990; Giammarino and Giglia 1990; Carter 1992).

Recently, four deformation phases have been recognized in the TN (Carosi *et al.* 2002a, b), whose geometric and kinematic features cast doubts on the presence of an important extensional tectonics in the Tuscan Nappe. We believe that the study of post-D1 structures could contribute to a better understanding of the tectonic evolution of the Tuscan Nappe with implications on the evolution of the Northern Apennines.

To shed new light on this tectonic problem, we chose a field area located in the southeastern side of the Apuan Alps, where kilometre-size folds in the TN are well exposed (Figures 1 and 2). This is a key area for the extensional tectonics interpretation (Carmignani *et al.* 1991, 1995), being on the crest of the Apuan Alps dome. Here, according to this interpretation, we would expect to find folds and shear zones verging away from the crest line of the dome. It is therefore a very suitable place to unravel the tectonic evolution of the TN and to test the extensional hypothesis.

2. GEOLOGICAL SETTING

The Northern Apennines thrust-and-fold-belt originated during continental collision, from Late Oligocene, between the Corsica–Sardinia microplate and the Adria promontory (Boccaletti *et al.* 1971, 1980; Alvarez *et al.* 1974; Dallan Nardi and Nardi 1978; Boccaletti and Coli 1983; Kligfield *et al.* 1986). The belt comprises different tectonic units derived from both oceanic (Liguride sequences) and continental (Tuscan sequences) domains. The Tuscan sequences currently crop out within three tectonically stacked units: the Apuan Alps Unit (AAU), the Massa Unit (MU) and the Tuscan Nappe (TN). The Apuan Alps Unit is the lower unit and consists of Palaeozoic basement unconformably covered by a sequence ranging from Triassic to Oligocene, metamorphosed in greenschist facies. The Massa Unit, deformed under higher metamorphic conditions with respect to the underlying AAU, is characterized by a pre-Mesozoic basement and a Middle to Upper Triassic cover. The Tuscan Nappe crops out at upper structural levels and comprises Late Triassic to Lower Miocene age, very low-grade and non-metamorphic sedimentary rocks (Baldacci *et al.* 1967; Cerrina Feroni *et al.* 1983).

In the study area the sedimentary sequence of the TN is not complete. It consists of an Upper Triassic carbonate basal formation ('Calcare e Marne a *Rhaetavicula contorta*' Formation) overlain by Hettangian shallow-water limestones ('Calcare Massiccio' Formation). The sequence continues upwards with pelagic limestones and marls ('Calcare Rosso Ammonitico', 'Calcare selcifero inferiore', 'Marne a Posidonia' and 'Calcare selcifero superiore' formations) and Dogger radiolarites ('Diaspri' Formation). The upper part of this sequence is characterized by the

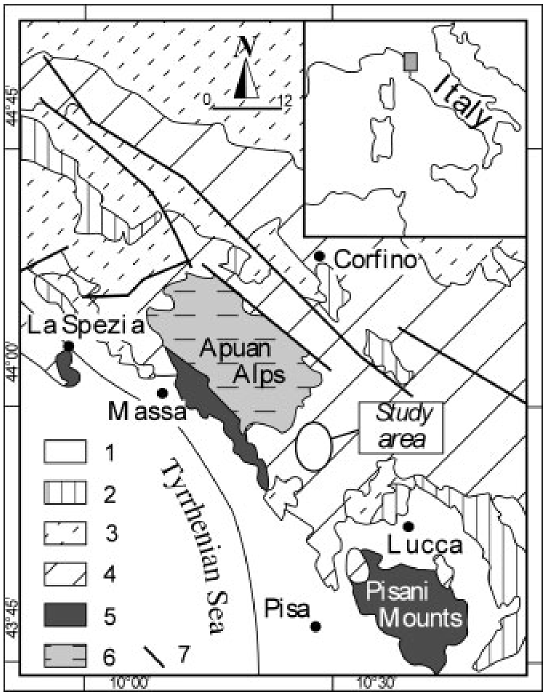


Figure 1. Geological sketch of the Northern Apennines around the Apuan Alps metamorphic dome and location of the study area. 1, Quaternary cover; 2, Mio-Pliocene deposits; 3, Ligurian units; 4, Tuscan Nappe; 5, Massa Unit s.l.; 6, Apuan Alps Metamorphic Complex; 7, faults.

presence of thick Cretaceous calcilutites ('Maiolica' Formation) (Nardi 1961; Baldacci *et al.* 1967; Dallan Nardi and Nardi 1974).

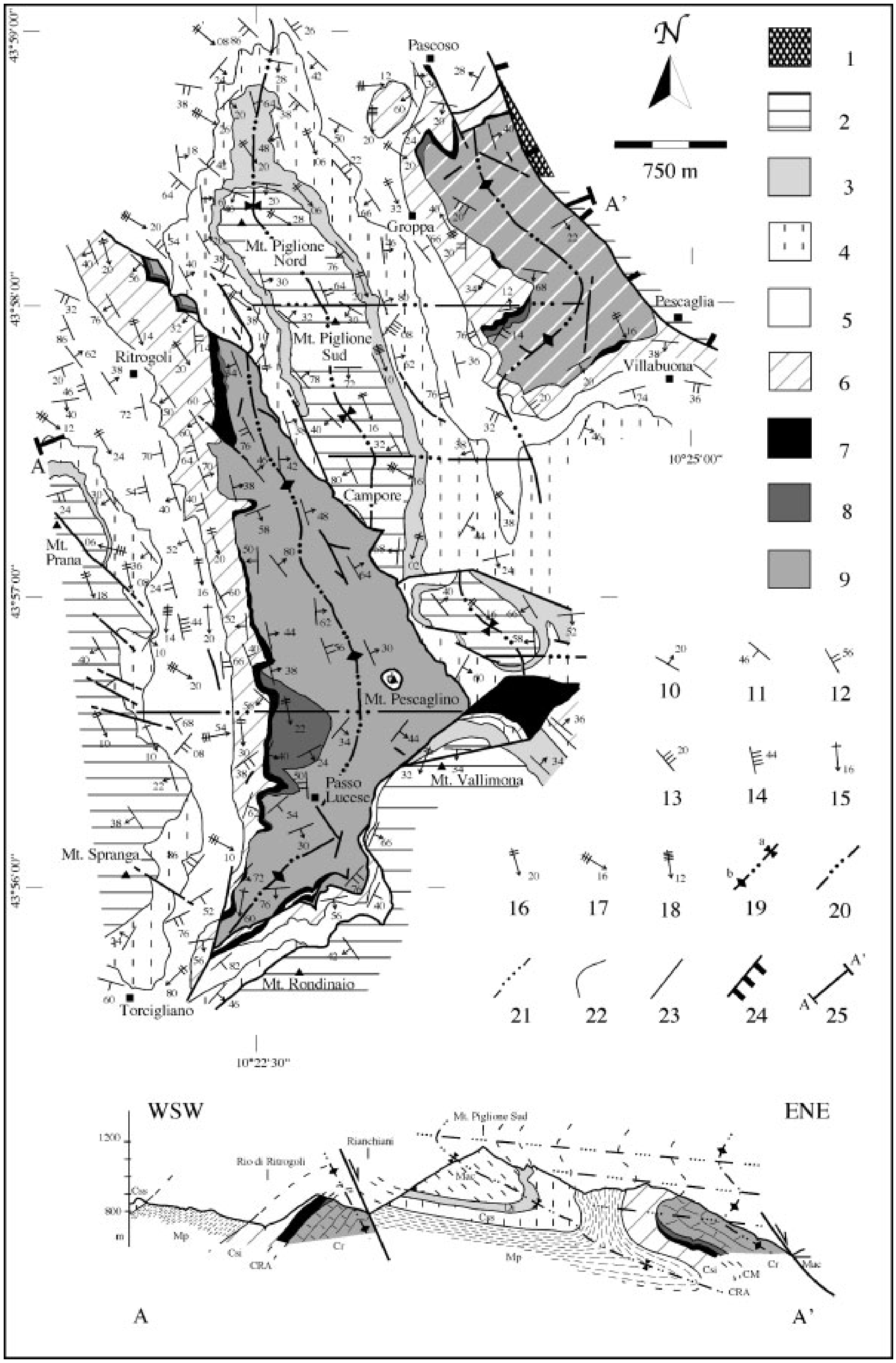
During Late Oligocene–Early Miocene times, the nappes were transported eastwards (Abbate *et al.* 1970), with the development of hinterland-to-foreland propagating thrusts, overturned folds and reverse faults (Bortolotti *et al.* 1970). The Ligurian Units and the Tuscan Nappe were stacked onto the external MU and AAU.

According to some authors (Carmignani and Kligfield 1990; Giammarino and Giglia 1990; Carmignani *et al.* 1991, 1992b, 1995; Carter 1992; Del Tredici *et al.* 1997), the Tuscan Nappe and the underlying Massa and Apuan Alps Units have been affected by an extensional deformation phase, which they refer to as D2, connected to the collapse of the Northern Apennines thrust wedge ('Apuan Alps Metamorphic Core Complex' model by Carmignani and Kligfield 1990). In this model, detachment faults were responsible for progressive exhumation of the metamorphic units toward higher structural levels, whereas collapse folds (F2) develop with opposite vergence on both sides of the Apuan Alps Metamorphic Complex.

K/Ar and $^{40}Ar/^{39}Ar$ determinations from the AAU show an age of 27 Ma for the D1 phase of initial crustal shortening (Kligfield *et al.* 1986), while a radiometric age of 8 Ma marks the end of the D2 extensional deformation phase (Giglia and Radicati di Brozolo 1970; Kligfield *et al.* 1986). Ages between 8 and 5 Ma for the TN and 6 and 2 Ma for the AAU, obtained from apatite fission track analyses, constrained the last stage of uplift (Abbate *et al.* 1994). The features, role and tectonic significance of D2 and younger structures are the focus of a detailed analysis that we present in the forthcoming sections.

3. STRUCTURAL ANALYSIS

Structural analysis highlights a complex tectonic evolution, characterized by three compressive folding phases and the later development of collapse folds and low- to high-angle normal faults.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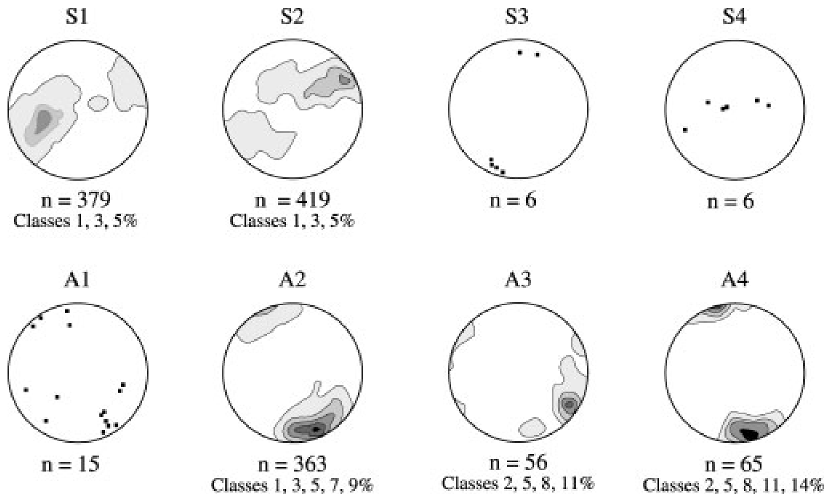

Figure 3. Stereographic projections of the main structural elements recognized in the area: poles to S1, S2, S3 and S4 foliations and A1, A2, A3 and A4 fold axes (Schmidt equal projection, lower hemisphere).

3.1. D1 deformation phase

The first deformation phase did not produce major folds. The most prominent structural element is represented by the S1 foliation, which is well developed in the less competent beds (pelites and siltstones).

F1 folds

F1 folds are rare and generally developed at metric to millimetric scales in the less competent beds. These folds, with shallowly SE plunging (10–35°) axes, are characterized by rounded fold hinges, tight interlimb angles and axial planes steeply dipping (about 50–60°) toward the NE (Figure 3). F1 folds display often an isoclinal geometry, with attenuated limbs and thickened hinges. They conform to class 1C of Ramsay (1967).

S1 foliation

S1 foliation is the most important structural element associated with the first deformation phase. It ranges from a penetrative foliation (slaty cleavage) in the pelites, to a spaced, disjunctive cleavage in the more competent lithologies. The best outcrops are offered by the upper part of the 'Calcare selcifero inferiore' and the 'Marne a Posidonia' formations, where the S0/S1 angle is generally smaller than 30–35° (Figure 4). Nevertheless, in the less competent layers, the S1 foliation can transpose the bedding surfaces.

In the analysed thin sections, the S1 foliation is generally defined as a continuous fine foliation (slaty cleavage). It is characterized by a lepidoblastic structure with lenticular domains separated by oxides and hydroxides and by

Figure 2. Geological and structural schematic map and geological cross-section (A–A′) of the study area. This map is based on original unpublished data from Giorgi R, Rossi L, Storti O and Pertusati PC, 1989–1992 (scale 1:10,000) and Carosi R, Frassi C and Montomoli C, 1989–2002 (scale 1:5000). 1, 'Nummulitico' Fm. (Nm); 2, 'Maiolica' Fm. (Mac); 3, 'Diaspri' Fm. (Di); 4, 'Calcare selcifero superiore' Fm. (Css); 5, 'Marne a Posidonia' Fm. (Mp); 6, 'Calcare selcifero inferiore' Fm. (Csi); 7, 'Calcare Rosso Ammonitico' Fm. (CRA); 8, 'Calcare Massiccio' Fm. (CM); 9, 'Calcari e Marne a *Rhaetavicula contorta*' Fm. (Cr); 10, strike and dip of S0 bedding surface; 11, strike and dip of S1 foliation; 12, strike and dip of S2 foliation; 13, strike and dip of S3 foliation; 14, strike and dip of S4 foliation; 15, trend and plunge of A1 axis; 16, trend and plunge of A2 axis; 17, trend and plunge of A3 axis; 18, trend and plunge of A4 axis; 19, F2 axial plane; a, synforms; b, antiforms; 20, trace of F3 axial plane; 21, trace of F4 axial plane; 22, stratigraphic boundaries; 23, faults; 24, detachment faults; 25, trace of geological cross-section A–A′.

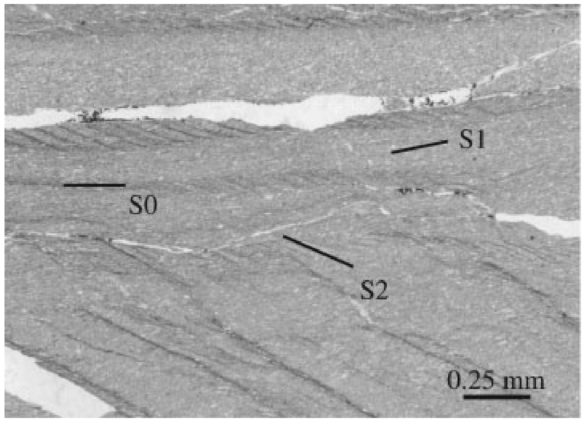

Figure 4. Microscopic relationships between the main planar structural elements: spaced zonal S2 crenulation cleavage, S1 fine continuous foliation and S0 bedding surface in the 'Marne a Posidonia' Formation near Mt. Pescaglino. Plane-polarized light; the scale bar is 0.25 mm.

thin phyllosilicate films. The domains are defined by calcite, quartz, detrital micas (chlorite), albite and oxides, with a strong shape-preferred orientation.

S1 foliation is often deflected around porphyroclasts of calcite and quartz, with recrystallization of calcite and quartz in the blocky pressure shadows. Clasts of quartz often present a grain-shape-preferred orientation, with undulatory extinction and deformation bands, parallel to the S1 foliation. Calcite crystals sometimes show mechanical deformation by lamellar twinning referable to classes 1, 2 and 3 of Burkhard (1992), suggesting a temperature of deformation between 150 and 300°C.

The main deformation mechanisms developed during the D1 phase are represented by pressure solution and solution transfer. Intracrystalline deformation and recovery are often present, whereas dynamic recrystallization probably represents a less important mechanism.

Generally, the S1 foliation shows a NW–SE trend (N140E to N170E) with a variable dip both towards the east and towards the west. Nevertheless, near the village of Villabuona and in the Torcigliano-Passo Lucese area the foliation varies from N030E to N080E (Figure 2).

Linear elements

In the study area, F1 fold axes (A1) show an overall change in strike from N140E to N160E and plunge from 10 to 35° towards the SE (Figure 3). The trend of the S0/S1 intersection lineation (LS0–S1) shows a wider scatter, from N110E to N180E, and in general dips moderately towards the SE. Nevertheless, in the southern termination of the Monte Pescaglino Antiform, near the village of Torcigliano, the lineations trend nearly NNE–SSW (N008E–N010E) and plunge 60–70° towards the SW (Figures 2 and 5).

The stretching lineations (L1) are commonly developed on the S1 foliation surfaces in the intraformational breccias. L1 is mainly defined by the long axes of grains, pebbles and quartz fibres in the extension veins and quartz fibres around pyrite crystals. Their orientations vary from parallel to sub-parallel to F1 fold axes.

3.2. D2 deformation phase

D2 develops the most prominent folding phase recognized in the Tuscan Nappe.

F2 folds

The F2 folds vary from kilometric (see e.g. Mt. Piglione Synform; Figure 2) to metric and centimetric scales. Outcrop-scale F2 folds are very common in the well-layered formations such as the 'Marne a Posidonia', 'Calcare

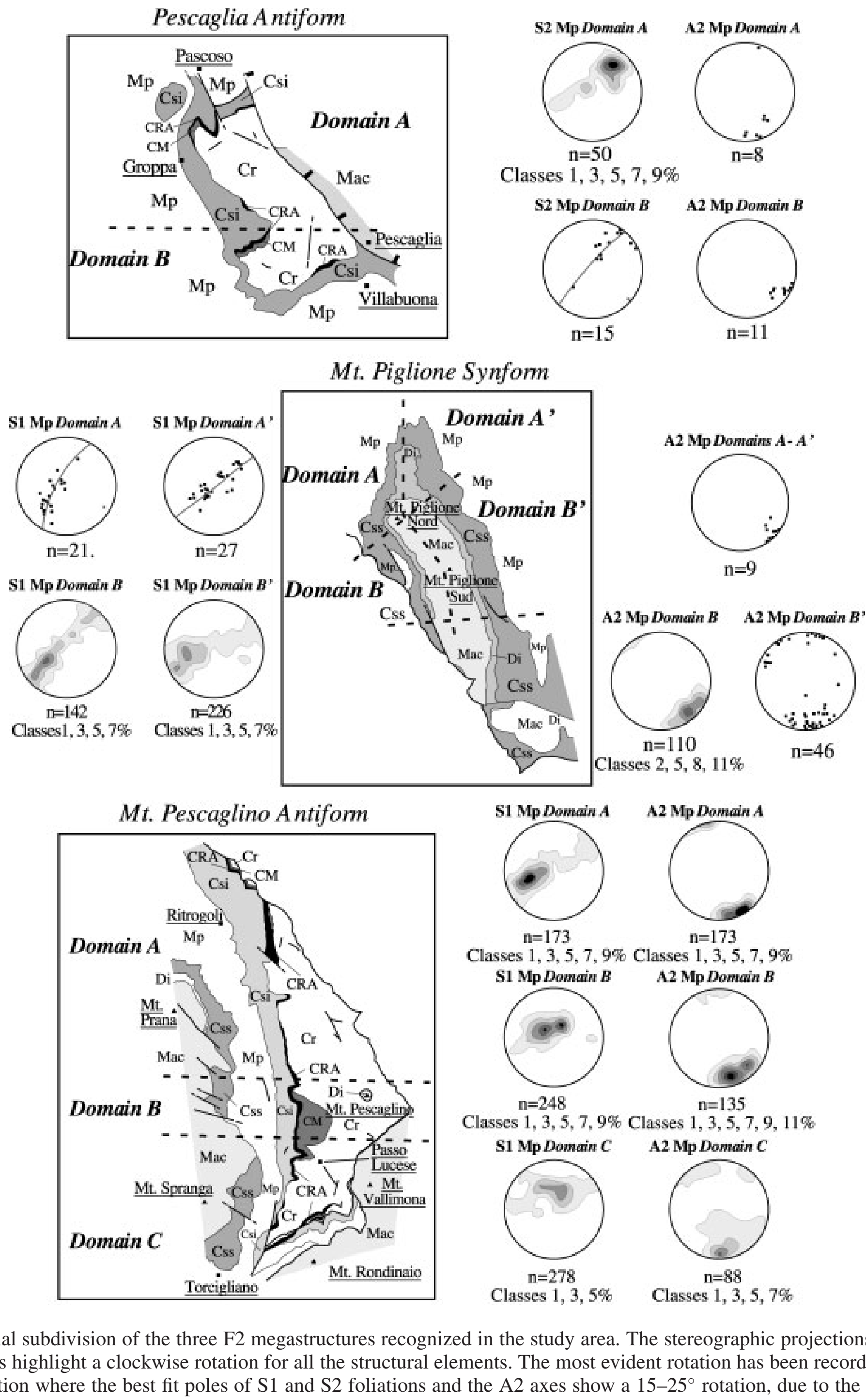

Figure 5. Domainal subdivision of the three F2 megastructures recognized in the study area. The stereographic projections of the D1 and D2 structural elements highlight a clockwise rotation for all the structural elements. The most evident rotation has been recorded by the 'Marne a Posidonia' Formation where the best fit poles of S1 and S2 foliations and the A2 axes show a 15–25° rotation, due to the presence of the D3 deformation phase. Mac, 'Maiolica' Fm.; Di, 'Diaspri' Fm.; Css, 'Calcare selcifero superiore' Fm.; Mp, 'Marne a Posidonia' Fm.; Csi, 'Calcare selcifero inferiore' Fm.; CRA, 'Calcare Rosso Ammonitico' Fm.; CM, 'Calcare Massiccio' Fm.; Cr, 'Calcare e Marne a *Rhaetavicula contorta*' Fm.; S1, first phase foliation; S2, second phase foliation; A2, F2 fold axis. For the map symbols see Figure 2.

selcifero' and 'Diaspri' formations, where they develop predominantly from decametric to centimetric scale. In the 'Calcare Massiccio' and the 'Calcare e Marne a *Rhaetavicula contorta*' formations, F2 folds are rare and they have been recognized only on a decametric scale.

The geometry of F2 folds is strictly controlled by the deformed lithotypes. In the carbonate lithotypes, the folds have rounded hinges, interlimb angles varying from 25 to 85° and a moderately dipping axial plane toward the west and the east. Rarely they present asymmetric profiles. The 'Calcare selcifero' and the 'Diaspri' formations often show metric-size chevron folds with a convergent spaced S2 foliation axial plane. In less competent beds the F2 folds are generally characterized by an asymmetric profile, moderately dipping axial plane and frequently slightly thickened hinges. They have an interlimb angle lower than 60° and rounded hinges. In the more incompetent layers, such as those in the 'Marne a Posidonia' Formation, the D2 deformation phase produced centimetric and millimetric kink folds, often developed in symmetric conjugate systems.

Flexural flow mechanisms could have probably been active during the D2 folding phase, as indicated by the development of striae and slickenlines on slickenside surfaces in some fold limbs. F2 folds often show almost similar geometry. They can be referred to classes 2 and 3 of Ramsay (1967). F2 axial planes dip steeply toward the east, indicating a westerly vergence for this fold system.

S2 foliation

During the D2 phase, an S2 foliation developed parallel to the F2 axial surfaces. In the less competent layers, it is represented by a penetrative crenulation cleavage, developed at the expense of the pre-existing S1 foliation. In the competent beds it is often developed as spaced cleavage defined by dissolution surfaces.

In the pelitic and semi-pelitic layers, the S2 foliation surfaces generally intersect the S0–S1 surfaces with an angle greater than 40° (Figure 4). Pencil cleavage is developed in the more pelitic levels of the 'Marne a Posidonia' Formation.

In the analysed thin sections, the S2 foliation is highlighted by the folding of the previous S1 foliation. The S2 foliation can be classified as both zonal and discrete crenulation cleavage (Twiss and Moores 1992). The S2 cleavage domains are mainly made up of oxides and clay minerals: elongated calcite and quartz crystals are less frequent, whereas synkinematic white micas are occasionally present.

Rotation of D1 micas and pressure solution are the main deformation mechanisms developed during the D2 phase. S2 foliation shows an overall change in strike from N120E to N160E in the study area (Figure 3). The plunge varies from 20 to 80° mainly towards the east.

Linear elements

A2 fold axes and the intersections between S2 foliation and folded S0–S1 surfaces (LS0–S2 and LS1–S2) range from NW to SE, and plunge a few degrees towards SSE. Striae and slickenlines on slickenside surfaces in fold limbs present a WSW–ENE trend, nearly perpendicular to A2 fold axes.

F2 megastructures

The major F2 folds in the study area are represented from west to east by the Mt. Pescaglino Antiform, the Mt. Piglione Synform and the Pescaglia Antiform. The adjacent Mt. Pescaglino Antiform and Mt. Piglione Synform are separated by a NW–SE-striking normal fault, as well as the eastern limb of the Pescaglia Antiform.

The cores of the antiforms are made by the 'Calcare e Marne a *Rhaetavicula contorta*' Formation, while the core of the synform is made by the 'Maiolica' Formation. The folds' axial planes dip moderately to steeply towards the E, NE and SE, with F2 fold interlimb angles ranging from 60 to 80°. Minor folds have been recognized along the limbs and in the hinge zones. It is worth noting that the F2 axial planes change in strike from NNW–SSE to NNE–SSW (Figure 2).

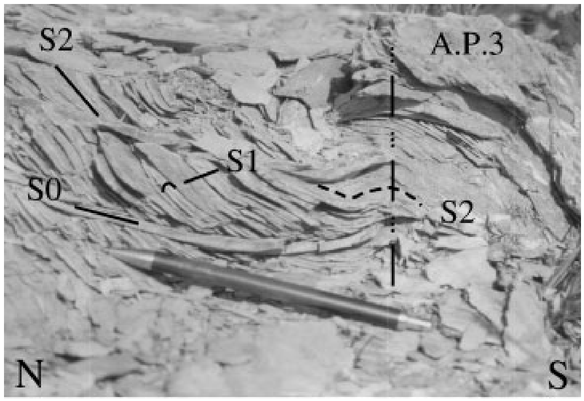

Figure 6. Centimetric, upright F3 fold in the 'Marne a Posidonia' Formation on the northern slopes of Mt. Prana. Pen (13 cm) for scale. S0, bedding surface; S1, first phase foliation; S2, second phase foliation; A.P.3, F3 fold axial plane surface.

To make this structural pattern clearer, the major F2 folds have been subdivided into structural domains (Figure 5). Stereographic projections highlight a clockwise rotation for all the structural elements of the D1 and D2 deformation phases. The best fit pole of S0 bedding, S1 and S2 foliations, the A1 and A2 axes and the intersection lineations are all affected by a 15–25° rotation, which is particularly well developed in the 'Marne a Posidonia' Formation (Figure 5).

3.3. D3 deformation phase

A D3 deformation phase has been recognized during fieldwork. It is a phase of weak folding, better recorded in the less competent layers, at the expense of the previous S2 foliation.

F3 folds

The D3 deformation phase produces nearly parallel F3 folds that can be assigned to class 1B of Ramsay (1967). F3 folds are centimetric size and show an upright attitude, with rounded hinges and interlimb angles greater than 70° (Figure 6). They are rare and mainly developed in the less competent layers (e.g. 'Marne a Posidonia' Formation). Their axial planes trend WNW–ESE, and dip steeply 70–90° toward either southwest or northeast.

S3 foliation

An S3 axial plane foliation is rarely seen at outcrop scale. It is a spaced crenulation cleavage only developed in the less competent layers. In the analysed thin sections, S3 foliation is well developed especially on the S2 cleavage domains (Figure 7). Its development is localized in small areas, such as the fold hinge zones and in pelitic layers. The S3 foliation displays a WNW–ESE to E–W strike, and a sub-vertical attitude.

Linear elements

The A3 fold axes and the S2/S3 intersection lineation trends WNW–ESE (N110E–N130E), plunging a few degrees towards the ESE (Figures 2 and 3).

3.4. Fold interference patterns

F2 folds are overprinted by F3 folds with sub-vertical axial surfaces. This interference pattern is rarely developed at the mesoscopic scale, but can be classified using the average attitude of the fold axes and the axial plane surfaces

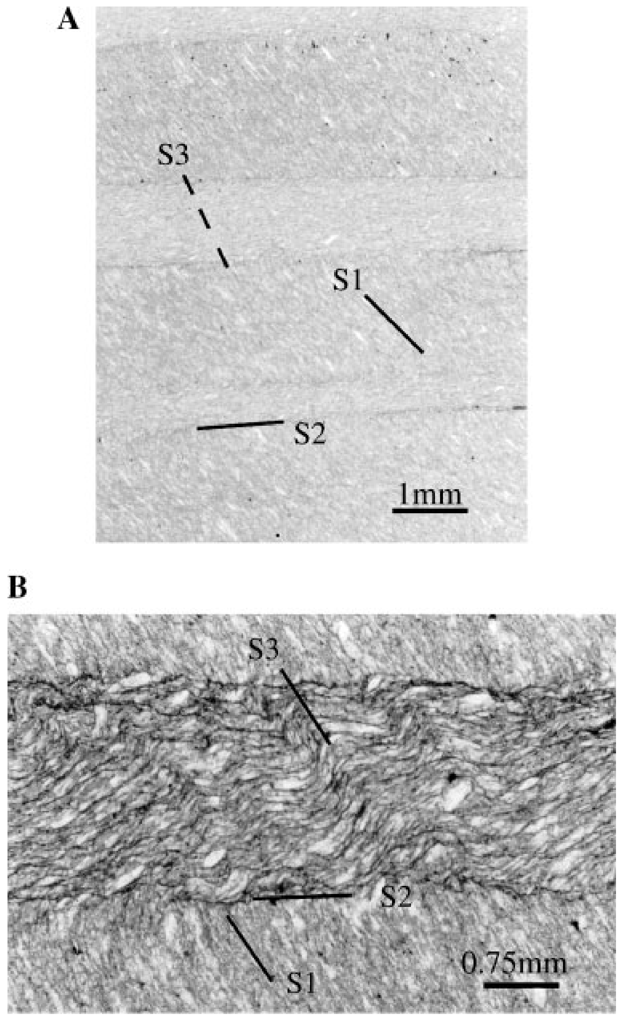

Figure 7. (A) Selective development of S3 crenulation cleavage localized in S2 cleavage domains, which are oriented nearly parallel to the direction of shortening. The S1 fine continuous foliation is stretched during D3 (and not crenulated) because it is oriented in the direction of flattening, perpendicular to the direction of shortening (Mt. Prana, 'Maiolica' Formation). Plane-polarized light; the scale bar is 1 mm. (B) Enlargement of an S2 cleavage domain in A, showing F3 folds. Plane-polarized light; the scale bar is 0.75 mm. S1, first phase foliation; S2, second phase foliation; S3, third phase foliation.

of F2 and F3 folding phases. The interference pattern can be classified between types 1 and 2, according to Ramsay (1967).

3.5. Later deformation structures

The three fold systems are later affected by another system of folds (F4) and by low- to high-angle normal faults related to extensional tectonics.

D4 deformation phase

D4 deformation phase produces nearly parallel folds (class 1B of Ramsay 1967) with axial planes dipping gently toward either the east or the west (Figure 8). F4 folds show an open recumbent attitude (with interlimb angles

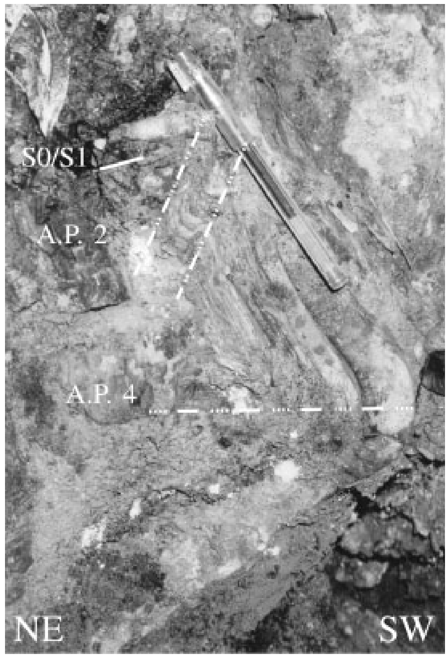

Figure 8. Centimetric F2 folds in the 'Marne a Posidonia' Formation near the village of Pascoso, showing limbs affected by collapse F4 folds with sub-horizontal axial plane. Pen (13 cm) for scale. S0/S1, bedding/S1 foliation; A.P.2, F2 axial plane; A.P.4, F4 axial plane.

greater than 70°) and either rounded or angular hinges. They are mainly developed in the short, sub-vertical limbs of the Mt. Piglione and Mt. Pescaglino folds, where they range from centimetric to decametric size. A4 fold axes trend NNW–SSE and plunge gently toward the southeast. S4 axial plane foliation is rare (Figures 2 and 3).

Normal faults

Low- and high-angle normal faults cross-cut all the previously described fold systems (Carmignani and Kligfield 1990; Carmignani *et al.* 1991, 1995). They mainly strike from N130E to N150E, also if there are secondary fault systems trending SW–NE.

Low-angle normal faults are also developed at the kilometric scale. Two main faults have been recognized, both trending NW–SE and dipping towards the northeast. The westernmost fault, developed along 'Rio delle Campore', cuts the Mt. Pescaglino Antiform and puts it in contact with the 'Calcare selcifero superiore', 'Diaspri' and 'Maiolica' formations of the Mt. Piglione Synform (Figure 2). It is a low-angle normal fault in its southern branch whereas northward it is cross-cut by a later high-angle fault as shown in the cross-section of Figure 2.

Kinematic indicators are preserved in metric-scale NW–SE-trending shear zones, mainly developed in the northern part of the study area near Rianchiano and Campo Faina (Figure 2). S-C fabrics point to a normal, top down-to-the-NE sense of shear. The Pescaglia–Mt. Croce low-angle normal fault, developed for *c.* twelve kilometres, from Mt. Croce to south of the village of Pescaglia, represents the eastern boundary of the study area. This fault presents a listric geometry (Carmignani *et al.* 1992a) and dips shallowly toward the east, in the Mt. Croce area, whereas it dips moderately in the study area. A foliated cataclasite is developed along the fault in the 'Maiolica' Formation. Microscopic observations indicate that the main deformation mechanisms are cataclasis and pressure solution. Kinematic indicators, such as well developed S-C fabrics, point to a normal, top down-to-the-NE sense of shear.

The southern termination of the Mt. Pescaglino antiform is cut by a normal fault, developed along the Rio Lucese, which shows a SW–NE trend and dips toward the SE. No fault surfaces have been clearly observed, so it is impossible to determine its kinematics. Nevertheless, along the Passo Lucese–Casa Pedogna road there are minor shear zones that show a normal, top down-to-the-SE sense of shear.

4. DISCUSSION

In the Tuscan Nappe, the D1 syn-metamorphic tectonic phase generated a pervasive low-grade foliation oriented at a very low angle to bedding, with development of minor intrafolial isoclinal folds. The D2 tectonic phase is associated with the development of centimetric to kilometric scale; west-verging folds with an axial plane foliation classified both as zonal and spaced crenulation cleavage. The D3 deformation phase is responsible for the development of upright folds, with a nearly E–W direction. The D4 tectonic phase, associated with recumbent folds and low- to high-angle normal faults, developed during later extensional tectonics.

Several authors (Carmignani *et al.* 1991, 1992a, b, 1993, 1994, 1995) interpreted the west-verging F2 folds as the result of extensional tectonics responsible for the exhumation of the Apuan Alps metamorphic dome and the overlying TN. However, the original vergence of the steeply dipping F2 folds cannot be assessed precisely, because these structures are overprinted by recumbent F4 folds, resulting in a type 3 interference pattern (Figure 9).

Carmignani and Kligfield (1990) and Carmignani *et al.* (1991, 1992b, 1995) suggested that during the exhumation of the metamorphic dome the study area was affected by folds verging away from its crest and by conjugate extensional detachments. These authors interpreted the western vergence of the F2 folds as being linked to the displacement of a supposed west-dipping low-angle normal fault located in the lower slope of Mt. Prana, which should represent the upper boundary of a shear zone bracketed between the 'Calcare Cavernoso' and 'Marne a Posidonia' formations. The east-dipping Pescaglia–Mt. Croce detachment fault should represent an analogous structure associated with east-verging F2 folds.

Our field investigations and structural analysis do not confirm the presence of a major low-angle fault within the 'Marne a Posidonia' Formation in the lower slope of Mt. Prana, or east-verging F2 folds associated with the Mt. Croce–Pescaglia low-angle normal fault. The characteristics of the F2 folds, their geometry, the dip of their axial planes, the direction of shortening, the cross-cutting relations with the extensional faults and the lack of direct relationship with extensional detachments suggest that these structures cannot be interpreted as developed during an extensional tectonic regime. Moreover, our structural data point out that F2 folds are close, and show steeply dipping axial planes (50–60° NE) and metric to centimetric scale, well-developed parasitic folds on the limbs. This is in agreement with a sub-horizontal direction of shortening in a compressional regime.

The Mt. Pescaglino Antiform, the Mt. Piglione Synform and the Pescaglia Antiform show a large-scale bending (Figure 2), highlighted also by stereographic analysis of the D1 and D2 structural elements (Figure 5). The documented system of F3 open folds in a nearly WNW–ESE direction is responsible for refolding of the F2 folds.

An alternative interpretation for the clockwise bending of the southern portion of the Mt. Pescaglino Antiform has been suggested by Carmignani *et al.* (1995). These authors link the rotation of the antiform to drag during a dextral strike-slip movement along a NE–SW-trending fault running from the northwestern slopes of Mt. Rondinaio and Mt. Vallimona (Figure 2). However, no kinematic data are reported by Carmignani *et al.* (1995), and our field investigations do not confirm the presence of an important strike-slip fault. The strike-slip fault, if present, could only partly contribute to the kilometre-scale bending of the antiform because horizontal separation at a map scale is too small in relation to the large bend of the F2 fold. This bending also affects the Pescaglia and Piglione folds, which are not cross-cut by any SW–NE-striking strike-slip faults. This suggests that the bend of the Mt. Pescaglino Antiform is due not to a local structure, but rather to the development of F3 folds. This interference is responsible for the large-scale folding of the axial planes of the kilometric-scale west-facing F2 folds present in the area.

The recognition of four folding phases in the TN clarifies and better constrains the role of extensional structures in the structural evolution of the belt. The geometric features of the F2 and F3 folds are consistent with a sub-horizontal direction of shortening in a protracted compressive regime of deformation after the construction of the nappe pile.

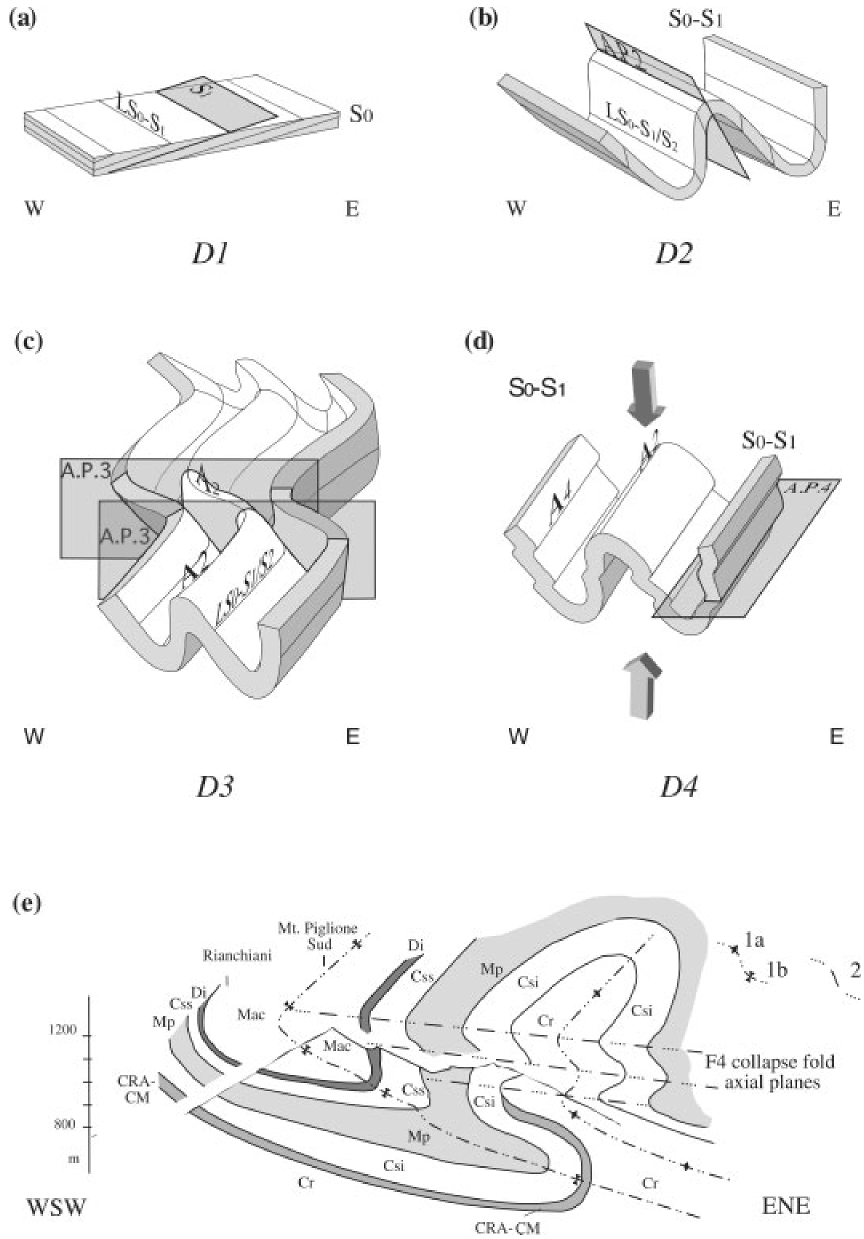

Figure 9. Sketch of the structural evolution of the Tuscan Nappe in the study area. After the D1 deformation phase responsible for west-dipping slaty cleavage S1 (a), the Tuscan Nappe was affected by a second folding phase that caused kilometric-size west-facing folds with axial planes moderately dipping to the east (b). The last compressive deformation phase (D3), that produced nearly E–W-trending folds with steeply dipping axial plane surface (c), overprinted the previous structural elements and the F2 axial plane surfaces. Stage (d) shows the last folding phase that affected the area. During extensional tectonics, collapse folds with a sub-horizontal axial plane developed mainly on the sub-vertical fold limbs, slightly modifying the previous structures. In (e), tectonic interpretation of the F2 Mt. Piglione Synform and the F2 Mt. Pescaglino Antiform modified by the D4 deformation phase. 1, F2 axial plane. a, antiform; b, synform; 2, F4 collapse fold axial plane. Mac, 'Maiolica' Fm.; Di, 'Diaspri' Fm.; Css, 'Calcare selcifero superiore' Fm.; Mp, 'Marne a Posidonia' Fm.; Csi, 'Calcare selcifero inferiore' Fm.; CRA, 'Calcare Rosso Ammonitico' Fm.; CM, 'Calcare Massiccio' Fm.; Cr, 'Calcare e Marne a *Rhaetavicula contorta*' Fm.; S0, bedding; S1 first phase foliation; LS_0–S_1, intersection lineation between S0 and S1 foliation; LS_0–S_1/S_2, intersection lineation between S0–S1 and S2 foliation; A_2, F2 fold axes; A.P.2, F2 fold axial plane; A.P.3, F3 fold axial plane; A4, F4 fold axes; A.P.4, F4 fold axial plane.

A part of the extensional structures highlighted by Carmignani *et al.* (1991, 1992b, 1995) can be identified with the F4 collapse folds recognized in the study area. For the development of F4 folds we identify a mechanism similar to that proposed by Froitzheim (1992), in the Austroalpine Nappes of the Alps, and Harris *et al.* (2002), where sub-vertical layers easily form recumbent folds during a phase of vertical shortening in an extensional tectonic regime. Froitzheim (1992) indicates transpression as a possible mechanism for the presence of steeply dipping foliation in orogenic belts. In this study, we recognize the presence of kilometric-size F2 and F3 folds with steeply dipping axial planes resulting in steeply dipping sedimentary and tectonic layering. A result of this upright folding was to thicken the crust, thus enhancing the later development of recumbent F4 folds by collapse of the steep layers in thickened crust ('collapse folds'). This pattern of folds rotating an early main collisional fabric into a steep orientation is common in many orogens (see e.g. the Northern Apennines, Carosi *et al.* 2002b; the Variscan belt in Sardinia, Carosi *et al.* 1998; Conti *et al.* 1999; the Himalayas, Carosi *et al.* 1999). As such, it could represent a useful mechanism for steepening early sub-horizontal layers and enhancing the development of later collapse folds.

In our reconstruction, the first three folding phases affecting the TN developed during a compressive tectonic regime, whereas the fourth is connected to the collapse of the over-thickened orogenic wedge in an extensional tectonic regime with a sub-vertical direction of shortening. The D1 and D2 phases show NW–SE-trending axes and moderately to steeply dipping axial planes, confirming a NE–SW sub-horizontal shortening at a high angle with respect to the main trend of the belt. The third deformation phase instead is characterized by a nearly NNE–SSW direction of shortening.

The structural data and inferred tectonic history presented for the TN assume a particular relevance for the tectonic evolution of the belt, especially when compared with the structural evolution of the metamorphic units. Carosi *et al.* (2002a) completed a structural analysis of both the AAU and the overlying TN a few kilometres west of the study area. Their most relevant conclusion was that the two units had a different early tectonic and metamorphic evolution during D1 and D2 in the AAU and D1 in the TN. After this early history, the TN was tectonically superposed on the AAU and the two units then shared a common deformation history (i.e. D2 and D3 in the TN are equivalent to D3 and D4 respectively, in the AAU).

The tectonic boundary between the TN and the AAU is folded by F2, F3 folds in the TN, corresponding respectively to F3 and F4 folds in the AAU. The observed kinematic indicators on the basal contact of the nappe always point to a top-to-NE and E sense of shear, both in the SW and in the NE and E sides of the metamorphic complex. Consequently, the top-down-to-the-NE displacement on the NE side cannot be unequivocally attributed to extensional tectonics, but rather, might result from late folding of a pre-existing thrust surface. In addition to this, the kinematic indicators on the basal contact of the nappe on the SW side again show a top-to-NE sense of shear. This does not fit with the centrifuge extensional D2 kinematic model proposed by Carmignani and Kligfield (1990), mainly based on the asymmetry of F2 folds. In this way, extensional tectonics did not produce a classical metamorphic core complex in the AAU, but only affected a folded antiformal stack of tectonic units after some compressional events during underthrusting and large part of exhumation (Carosi *et al.* 2002a, b).

A deformation history similar to that proposed in this study was recognized in several places in the belt: in the Tuscan Nappe in the Castelpoggio-Tenerano area and in the southern sector of the Apuan Alps (Metato-Casoli area; Carosi *et al.* 2002a), in the La Spezia area (Montomoli *et al.* 2001; Montomoli 2002), Corfino (Carosi *et al.* 2002b) and Monti dell'Uccellina areas (southern Tuscany, Campetti *et al.* 1999). One main difference is that the angle between F2 and F3 fold axes here is generally lower than 90°. The recognition and description of these deformation phases in many outcrops of the Tuscan Nappe suggest that the proposed evolutionary model could be valid at the regional scale, too.

We observed that the interference between the F2 and F3 fold systems generated dome and basin-like structures affecting the TN and the underlying metamorphic units, and their tectonic boundary (Carosi *et al.* 2002a, b). This contributed to the development of the dome shape of the metamorphic complexes in the Northern Apennines (Apuan Alps, Monti Pisani) and Monti dell'Uccellina (southern Tuscany).

In this reconstruction, the dome shape of the metamorphic complexes may be formed from the development of initial antiformal stacks (Carmignani *et al.* 1978; Carmignani and Kligfield 1990) during the superposition of tectonic units in the Internal Tuscan Domain of the Apenninic chain. The interference between F2 and F3 fold systems amplified the former antiformal stack contributing to the exhumation of metamorphic rocks (see also Cello and Mazzoli 1996).

The vertical growth of these large-scale domes affecting the already thickened crust in the Northern Apennines enhanced the development of instabilities in the over-thickened nappe pile inhibiting the formation of collapse folds and low- to high-angle normal faults and contributed to the exhumation of Apuan Alps, Monti Pisani and Monti dell'Uccellina metamorphic domes. An important time constraint is represented by the results recently obtained by Balestrieri *et al.* (2003). They report that higher exhumation/erosion rates between 6 and 4 Ma (Messinian) probably related to local tectonic (normal faults) structures, and played an important role during the final phases of Apuan Alps exhumation. According to these authors, exhumation rates of 1.3–1.8 mm/y obtained for the Apuan Alps can be explained only through the development of normal faults, because such a high exhumation rate does not agree with the sedimentary record of adjacent continental basins of Sarzana, Aulla-Olivola and Serchio.

The normal fault that separates the Mt. Piglione and the Mt. Pescaglino folds can be tentatively assigned to this extensional tectonics, and hence its major movement may be dated between 6 and 4 Ma. In this scenario the exhumation of the Apuan Alps metamorphic complex is mainly syn-collisional and compression related, whereas extensional tectonics, e.g. collapse folds and normal faults, developed only in the late stage after the tectonic units were repeatedly folded and brought to higher structural levels. Moreover, extensional tectonics affected the TN only after its overthrusting onto the AAU (Carosi *et al.* 2002a) and it is not responsible for the F2 folds in TN.

5. CONCLUSIONS

The data presented in this study reveal that the Tuscan Nappe is characterized by a tectonic evolution much more complex than that proposed so far. Four deformation phases (D1, D2, D3, D4) have been documented. The first three developed during a compressive tectonic regime responsible for the building of the Apenninic chain, while the latter (D4) is related to later extensional tectonics.

In this tectonic reconstruction, compressional tectonics plays a very important role from the nappe stacking D1 phase to the development of dome and basin-like structures (interference between D2 and D3 phases), creating the domal (or antiformal) shape of the metamorphic complexes in the Northern Apennines. These observations, coupled with the lack of evidence for centrifugal detachment faults or collapse (F2) folds in the crest areas of the dome, clarify the real role played by extensional tectonics in the structural history of Northern Apennines. Previous interpretations have invoked a crucial role for extensional tectonics in the entire exhumation of the metamorphic rocks in the inner part of the belt. However, according to our tectonic reconstruction the only structures that can be attributed to extensional tectonics are represented by F4 collapse folds and low- to high-angle normal faults overprinting a large set of compression-related fabrics and folds. In this picture, extensional tectonics seems to have been restricted just to the final stages of the evolution.

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