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D_2 asymmetric folds and their vergence meaning in the Montagnola Senese metamorphic rocks (inner northern Apennines, central Italy)

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Abstract

This study describes asymmetric folds whose vergence is derived from refolding of a pre-existing inclined foliation. The study area is in the Montagnola Senese area where Mesozoic rocks in the greenschist facies crop out. These rocks were affected by deformation during the collisional stage (late Oligocene–early Miocene) of the Northern Apennines (D_1 event), and during the post-collisional extensional tectonics (D_2 event) that affected the inner zone of the Northern Apennines since the early–middle Miocene. During the D_1 event, SW dipping axial plane schistosity and non-cylindrical folds indicative of a highly heterogeneous strain developed. During the second event westward verging folds developed. These folds are characterised by thick steep limbs. The S_2 foliation, which is well developed in narrow and localised zones, is mainly a pressure solution cleavage with NE plunging stylolitic teeth. Micro- and meso-structural observations are used to discuss the relation between cleavage distribution and strain during the D_2 event. The evolution of D_2 folds was mainly controlled by a dissolution process and by a component of partitioned shear-strain. In the relatively 'high' strain domains, deformation took place by the combined effects of volume loss and shear displacement. In low strain domains, deformation took place by a veining and flattening process. In this way, the pre-existing foliation can be deformed in folds with vergence opposite to the sense of shear. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Asymmetric folds; Vergence; Metamorphic rocks

1. Introduction

The vergence of folds describes the sense of asymmetry of asymmetric folds, without any direct relation to the kinematics that determined those folds (Bell A.M., 1981). However, there are geological examples where the sense of asymmetry is considered parallel to the sense of shear. Examples are minor folds whose rightward or leftward vergence are a useful tool for localising the hinge zone of major folds in simple deformed areas (i.e. Ramsay, 1967; Wilson, 1982): the vergence of these minor folds, which are commonly described as Z- and S-folds (Ramsay, 1967), is consistent with the sense of shear. In this case, the fold asymmetry can be used as a kinematic indicator. Furthermore, it is widely accepted that the axial plane of folds is almost normal to the maximum shortening direction and, therefore, the fold asymmetry can be used as a tool to define the sense of shear (Hudleston and Lan, 1993).

Asymmetric folds also characterise re-folded terranes where a pre-existing, generally inclined, foliation is deformed by a superimposed deformational event (Fig. 1). In these terranes, the vergence of the F_2 folds can be consistent or not consistent with the dominant shear sense. Examples of the first case are described in Carmignani and Kligfield (1990) and Carmignani et al. (1993, 1994). These authors demonstrated that the D_2 folds of western Alpi Apuane metamorphic core complex developed buckling in the original SW-dipping foliation by a superimposed rightward simple shear (Fig. 1a).

Examples of folds with a vergence opposite to the sense of shear (referred to as antivergent folds in this paper) are described by Ramsay et al. (1983) in the shear zone at the base of the Morcles nappe, in the Helvetic fold-and-thrust belt. Here, buckle folds with an original vergence consistent to the regional sense of shear were affected by high shear strains resulting in antivergent folds. The same was described by Froitzheim (1992) and Froitzheim et al. (1994), in the framework of Austroalpine units that had undergone syn-orogenic extension (Fig. 1b). Antivergent folds were also described by Krabbendam and Leslie (1996) who proposed that these can be developed by strongly partitioned rightward simple shear superimposing an original south-east inclined metamorphic foliation (Fig. 1c). This paper discusses antivergent folds that may develop

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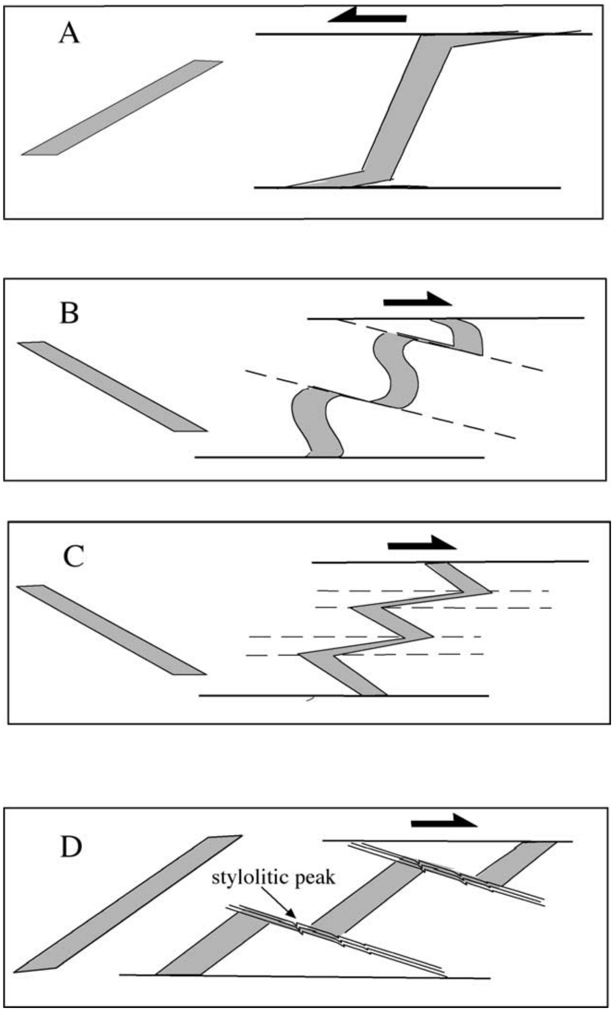

Fig. 1. Different strain paths may determine D_2 asymmetric folds characterised by a thick and steep limb. The vergence may be consistent or not consistent with the sense of shear: (A) after Carmignani et al. (1993, 1994); (B) after Ramsay et al. (1983), Froitzheim (1992) and Froitzheim et al. (1994); (C) after Krabbendam and Leslie (1996); (D) discussed in this paper.

from the deformation of pre-existing metamorphic foliations, dipping in the opposite sense of direction to the superimposed shear-strain (Fig. 1d). Strain partitioning and pressure solution processes (Bell and Johnson, 1992) can be seen to lead to antivergent folds during exhumation of metamorphic rocks. The study area is the Montagnola Senese area that is located in the inner Northern Appennines.

2. Geologic framework

The present structural setting of the Northern Apennines (Fig. 2) is the result of two deformation episodes (Fig. 3). The first one was associated with the convergence and subsequent collision (Treves, 1984; Carmignani et al., 1995 and references therein) between the European margin, represented by the Sardinia–Corsica massif, and the Adria plate (Cretaceous–late Oligocene, early Miocene). The second deformation episode was related to regional extension that has affected the whole Northern Apennines inner zone since the early–middle Miocene (Carmignani and Kligfield, 1990; Jolivet et al., 1991; Carmignani et al., 1994). Since the early–middle Miocene, extensional structures of the inner zone have been active simultaneously with compressional structures in the outer zone of the Northern Apennines (Lavecchia, 1988; Lavecchia et al., 1994).

During the collision process, different units belonging to the Northern Apennines palaeo-geographic domains were stacked (Fig. 3) while, during extension, at least two different deformation events affected the inner Northern Apennines. The older one (early–middle Miocene), caused a stretching of 120% or more and the exhumation of originally deeply buried rocks (Carmignani and Kligfield, 1990) now cropping out mainly along the Middle Tuscan Range (Fig. 2); the younger extensional event (late Miocene–Pliocene) caused a stretching value of not greater than 10% and determined the present horst and graben structure of the inner Northern Apennines (Carmignani et al., 1994).

The Montagnola Senese area is located in the central sector of the Middle Tuscan Range, where Triassic–Cretaceous rocks of the greenschist facies are exposed (Giannini and Lazzarotto, 1970). The Montagnola Senese area is considered part of the Monticiano–Roccastrada Unit (Costantini et al., 1988), which consists of metamorphic rocks from Palaeozoic to Cretaceous in age (Fig. 4). The Monticiano–Roccastrada Unit is divided in two different sub-units (Costantini et al., 1988): (a) the inner Montepescali–Monte Quoio Sub-unit, which experienced a pressure of about 6–8 kbar and a temperature of ~350 °C (Giorgetti et al., 1998); and (b) the outer Monte Leoni–Montagnola Senese Sub-unit, which experienced a pressure of about 9–10 kbar and a temperature of ~400 °C (Giorgetti et al., 1998). The tectonic juxtaposition of these two sub-units is dated from late Oligocene to early Miocene (Bertini et al., 1991) when the stacking of the tectonic units belonging to the inner Northern Apennines occurred (Fig. 3).

3. The Montagnola Senese stratigraphic and structural setting

In the study area, rocks from the external Tuscan domain (Fig. 3) crop out. The structural and stratigraphic relationship among the different litothypes and formations are shown in Figs. 4 and 5.

3.1. Lithology

The deepest tectonic unit is represented by the Monte Leoni Montagnola Senese Sub-unit, which consists of metamorphic rocks (Fig. 5). From bottom to top, it is made up of

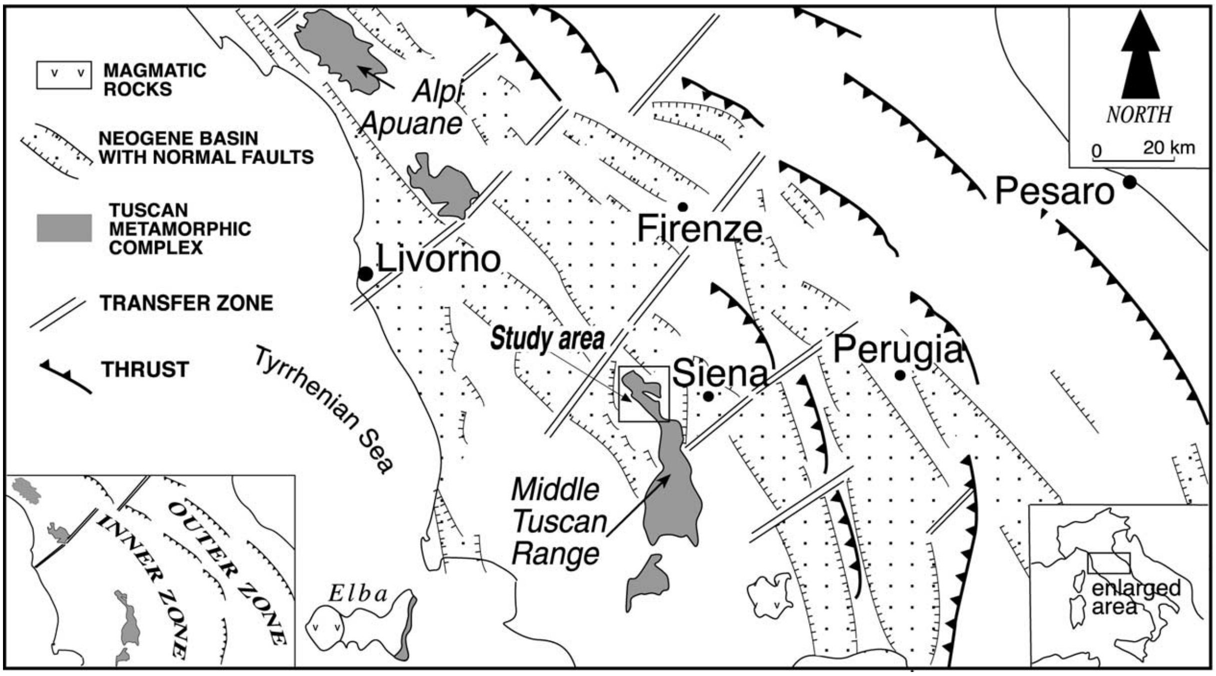

Fig. 2. Sketch map of the Northern Apennines showing the main structural features and the location of the study area.

the following units. Ladinian–Carnian violet metasiltite, metarenite and interlayered reddish quartz-conglomerate (Verrucano Group; Costantini et al., 1988). Rhetian dolostones rest on the Verrucano Group; these carbonate rocks are poorly layered and characterised by light grey and whitish dolostone with dolomitic marble levels and grey metamarl beds (Grezzoni Formation; Giannini and Lazzarotto, 1970). This formation passes upwards to early Liassic white and/or yellow massive marble. This marble is characterised by strongly oriented minerals and a common fine-grained fabric. The mineralogic association is made up of calcite + dolomite ± phyllosicates (mainly biotite) ±

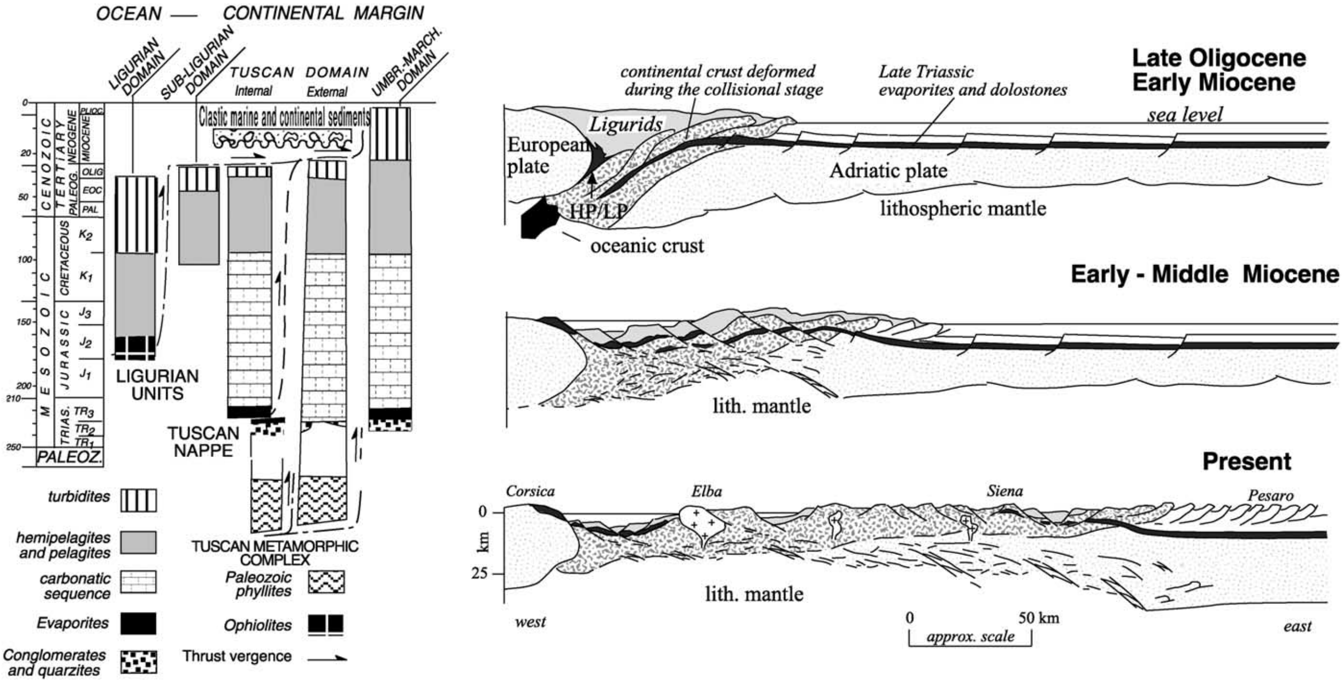

Fig. 3. Left: relationship between the different tectonic units of the Northern Apennines and related paleogeographic domains. Right: schematic crustal geologic cross-sections showing the collisional and post-collisional evolution through the inner zone of the Northern Apennines (after Carmignani et al., 1994 and Decandia et al., 1998, modified).

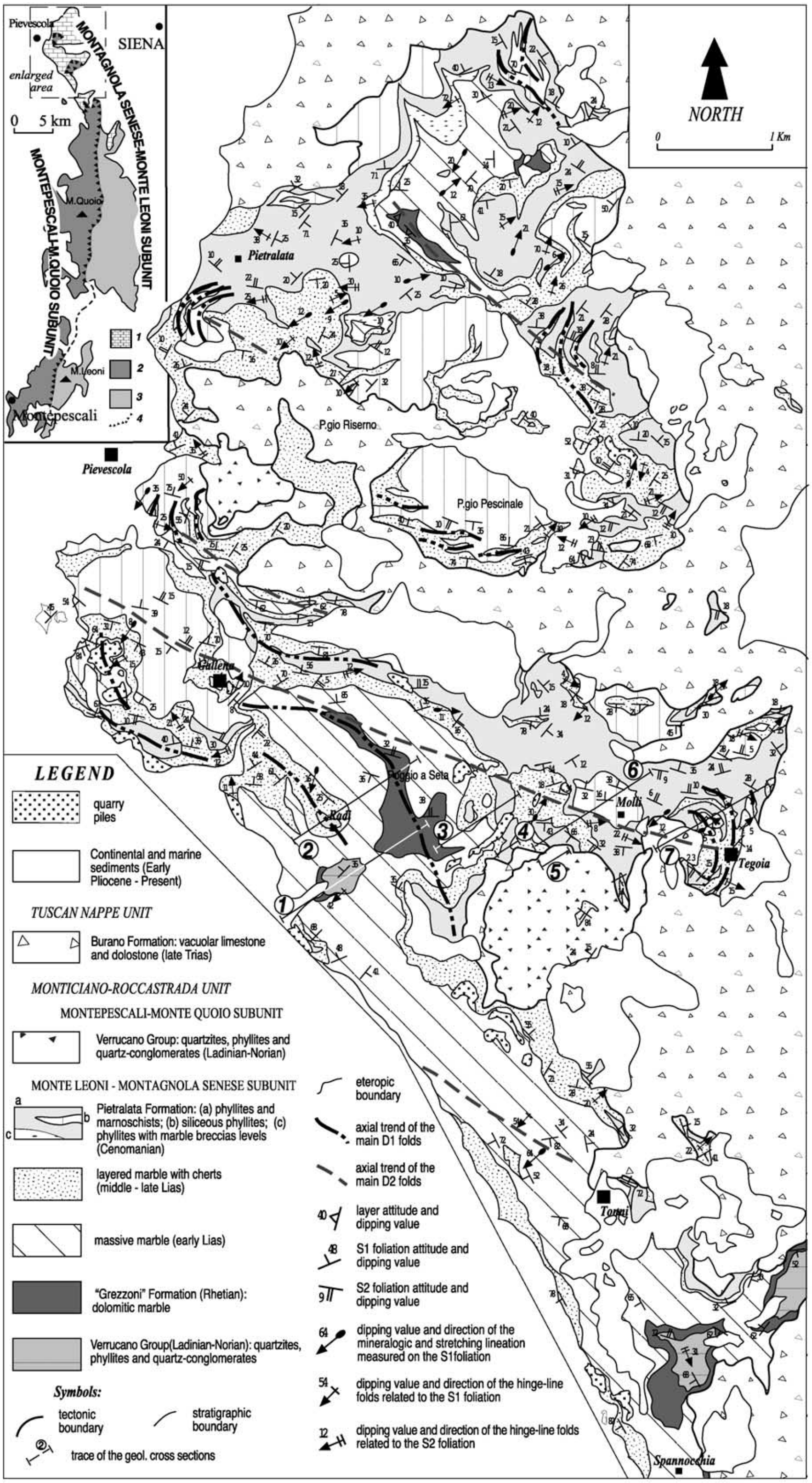

Fig. 4. At the top left: sktech map of the Monticiano–Roccastrada Unit (after Costantini et al., 1988) outcropping in the middle Tuscan Range (see also Fig. 1); symbols: 1—Triassic–Paleozoic Formations belonging to the Montepescali–Monte Quoio Sub-unit; 2—Triassic–Paleozoic Formations belonging to the Montagnola Senese–Monte Leoni Sub-unit; 3—Mesozoic Formations belonging to the Montagnola Senese–Monte Leoni Sub-unit; 4—thrust. Enlarged area: Geologic and structural sketch map of the study area.

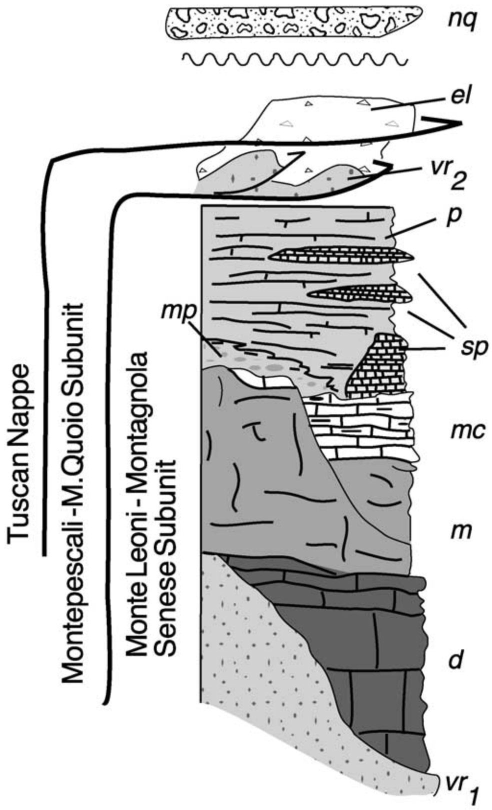

Fig. 5. Relationship of the stratigraphic and tectonic units of the Montagnola Senese area. Symbols: Montagnola Senese–Monte Leoni Sub-unit: vr$_1$—Verrucano Group: (Ladinian–Carnian); d—“Grezzoni” Formation (Rhetian–Norian); m—massive marble (Early Lias); mc—layered marble with cherts (middle–late Lias); p—Pietralata Formation with marble breccias at the base and siliceous phyllites (sp) interlayered (Cenomanian); Montepescali–Monte Quoio Sub-unit: vr$_2$—Verrucano Group (Ladinian–Carnian); Tuscan Nappe: el—Burano Formation (late Trias); nq—Neogene and Quaternary sediments.

K-feldspar. Sphene and/or rutile are commonly distributed over the other minerals. This massive marble is related to the early Liassic ‘calcare massiccio’ Formation (Giannini and Lazzarotto, 1970) belonging to the non-metamorphic sequence of the internal Tuscan domain. The massive marble gradually passes to a layered marble with cherts. No fossils were recognised in these marbles, but the stratigraphic features seem to indicate a relationship to the ‘Calcare Selcifero’ Formation (middle Lias) of the internal Tuscan domain sequence. Strongly oriented minerals characterise the fine-grained fabric of this marble. The mineralogic association is: calcite + quartz + muscovite ± biotite ± dolomite ± K-feldspar. Quartz occurs in thin beds or it is spread through the sample. Sphene and/or rutile are distributed over the other minerals.

The Pietralata Formation rests unconformably on the massive and layered marbles (Giannini and Lazzarotto, 1970). This formation is made up of violet phyllite, marno-schist and grey or green calc-schists; siliceous phyllite beds characterise the lower–middle part (Fig. 5). Marble breccias are interlayered at the base of the Pietralata Formation when this rests on the early Lias massive marbles. The mineralogic association that typifies the Pietralata Formation is: phyllosilicates (muscovite, mainly) + quartz + calcite ± dolomite. The siliceous phyllite beds are instead characterised by: quartz + biotite ± muscovite ± calcite. Homogeneously distributed sphene contribute to the colour of the rock. The Pietralata Formation can be attributed to the Cenomanian, on the basis of its fossil contents (Giannini and Lazzarotto, 1970) and it can be related to the ‘Scaglia Toscana’ Formation of the internal Tuscan domain.

Moreover, the Rhetian–Cenomanian sequence cropping out in the Montagnola Senese area is quite similar to the one that characterises the eastern side of the Alpi Apuane core complex (Carmignani et al., 1987).

The Monte-Pescali–Monte Quoio Sub-unit and the Tuscan Nappe rests tectonically on the above mentioned Mesozoic rocks. The Monte-Pescali–Monte Quoio Sub-unit is made up of the Verrucano Group lithologies while the Tuscan Nappe is defined by the evaporites belonging to the Burano Formation (late Trias; Giannini et al., 1971). In the study area, the Burano Formation is represented by a thick cataclasite made up of vacuolar dolomitic limestone, locally re-worked during the Late Miocene–Pliocene periods (Giannini and Lazzarotto, 1970). Marine early Pliocene sediments and continental Quaternary colluvial deposits conclude the stratigraphic sequence of the study area.

3.2. Deformation

Three different foliations were recognised in the Montagnola Senese area. The first foliation (S$_0$) is the sedimentary bedding. The other two foliations are tectonic foliations (S$_1$ and S$_2$). S$_1$ developed during a first deformation phase (D$_1$). It is a planar, pervasive schistosity, mainly defined by sub-parallel orientation of micas and carbonate minerals (Fig. 6a) as well as some biotite, indicating that S$_1$ developed under greenschist metamorphic conditions. S$_1$ is an axial planar foliation associated with isoclinal folds with fold axes trending NE (Figs. 6b and 7d) on average. The general trend of S$_1$ in the central part of the study area is shown in Fig. 7a. S$_1$ is folded in SSW-verging folds during a second deformation event (D$_2$). A prevalent southwest dipping attitude of the S$_1$ foliation is widely recognised (Fig. 7c). S$_1$ is mostly oriented parallel to the bedding (S$_0$) except in the hinge zones of the D$_1$ folds where it is oriented perpedicularly to S$_0$ (Fig. 6b). The fold axes (F$_1$) of which S$_1$ is the axial plane foliation, are roughly parallel to the stretching lineation (L$_1$) present on S$_1$ (Fig. 7d and e).

L$_1$ consists of elongated quartz grains in the cherts of the layered marbles, elongated biotite grains in the marbles, and elongated marble pebbles (Fig. 6c) at the base of the Pietralata Formation. Asymmetric cherts nodules or boudins in layered marble are the most common D$_1$ kinematic

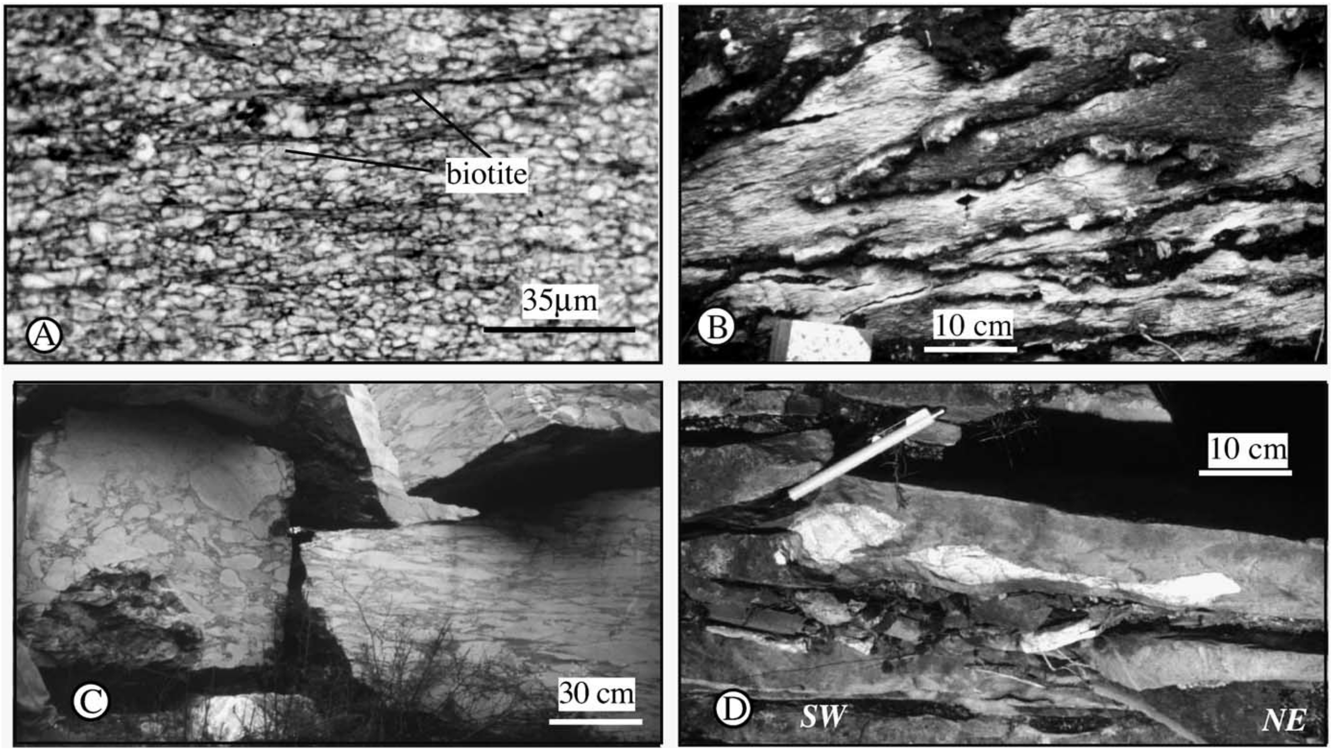

Fig. 6. (A) Thin section of a massive marble sample: the layers of biotite and the orientation of the carbonate minerals point out the metamorphic foliation S_1 (parallel nicols, 10X); (B) isoclinal folds in the layered marble with cherts; (C) pebbles of Liassic massive marble interlayered at the base of the Pietralata Formation (Cenomanian): these pebbles are commonly N60-elongated; (D) kinematic indicators are usually given by the asymmetry of cherts in the layered marble: they indicate always a tectonic transport toward the North East.

indicators in the study area. They unvariably show a transport direction toward the NE (Fig. 6d).

D_1-structures were deformed and re-oriented during D_2, when S_2 developed. S_2 is particularly well expressed in the north-eastern side of the study area (Fig. 7a). The main concentration of S_2 poles indicates a plane with a mean strike of N120° and a mean dip of 10–15° to the NE (Fig. 7f). Few data suggest an opposite orientation, which might be derived from a minor late folding event. Stylolitic teeth (Fig. 7h), whose main concentration is a N40 plunge of 34° to the NE, were recognised (Fig. 8a and b) on the S_2 planes of the Liassic layered marbles. Here S_2 is marked by fine, optiqually opaque grains. Newly grown calcite veins are often coupled to the S_2 foliation (Fig. 8c and d), especially in the carbonate lithotypes. Calcite twins such as observed in these veins suggest a deformation temperature in the range of 150–300 °C (Burkhard, 1993). Therefore metamorphic grade must have been very low to low during D_2.

D_2-folds are open, SSW-verging (Fig. 7a and b), structures with their fold axes mainly oriented N120-18° (Fig. 7g). These folds are always characterised by inclined, thick and generally short limbs and less inclined, thin and generally long limbs. This is recognisable on the geological sections scale (Fig. 7a and b) on a meso-scale (Fig. 9) and on a micro-scale (Fig. 10). S_2 is more closely spaced in the less inclined limbs of the D_2 folds (Fig. 11). In the more inclined limb and hinge zone, S_2 is roughly orthogonal to S_1 (Fig. 11).

Depending on structural location, S_2 displays different morphologies in the Pietralata Formation. Microscopic analysis emphasized that in less inclined limbs of D_2-folds S_2 displays a high intensity, resulting in a zone of smooth and anastomosing cleavage, while the microlithons are generally characterised by asymmetric micro-folds (Fig. 10a and b). Dark material is generally concentrated along less inclined limbs of these micro-folds, whereas new crystallisation characterises the hinge zones. Transition from cleavage to micro-lithons is normally gradational. In contrast, thin sections from more inclined limbs of D_2-folds show that S_2 is commonly represented by a parallel spaced wriggly foliation, dividing up micro-domains where S_1 is well preserved (Fig. 10c and d). Optically opaque grains always characterise S_2 and new crystallisation is still significant.

4. Discussion

D_1-fold axes are mainly concentrated in a SW–NE direction, parallel to L_1. This geometrical relation suggests the existence of highly non-cylindrical folds (Ramsay, 1967) produced by the rotation of the hinge line toward

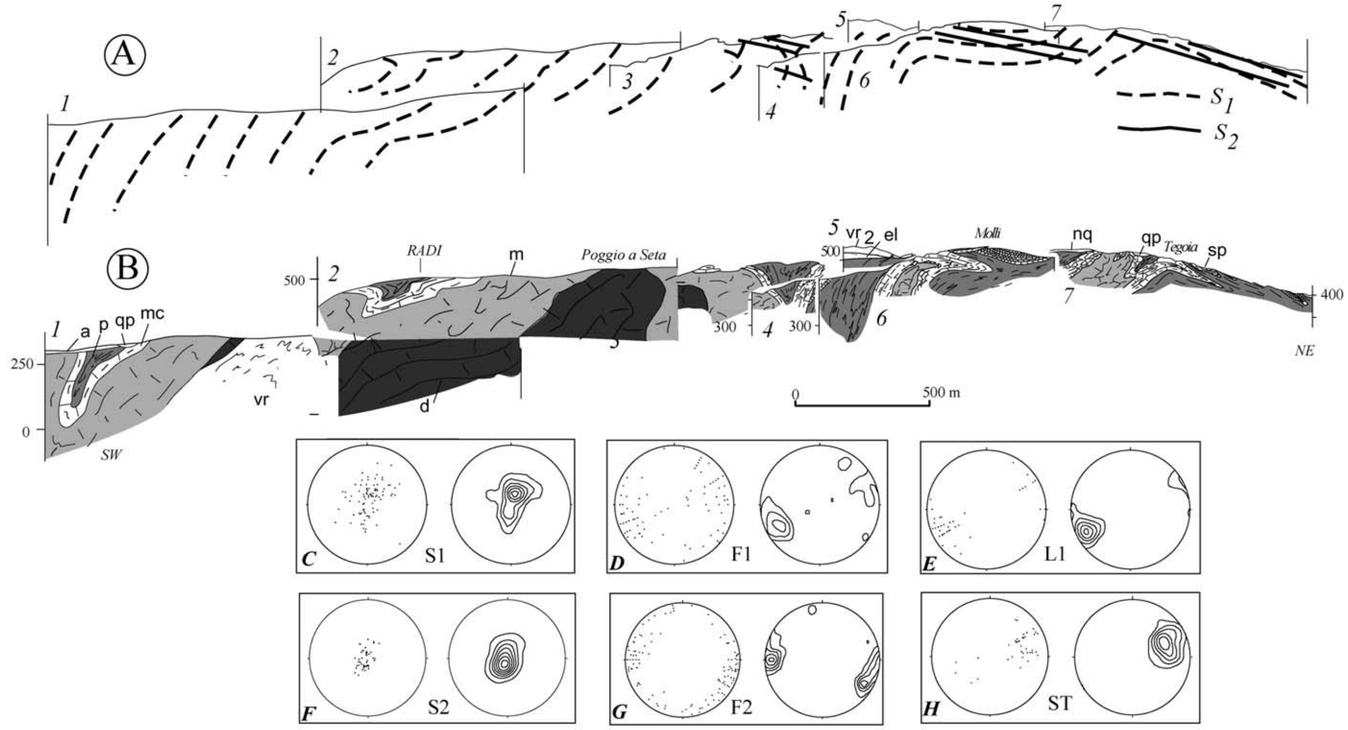

Fig. 7. Geological cross-sections through the central part of the study area. (A) Sections showing the pattern of the S_1 and S_2 foliations. The numbers refer to the traces given in Fig. 4. (B) Sections showing the pattern of bedding. See Fig. 4 for the traces. Stereonets (lower emisphere, equiangular net) of the structures related to the first (D_1) and second (D_2) deformational events, respectively. (C) Left: poles of the S_1 foliations (93 data); right: contouring at <2, 3–4, 5–6, 7–8, 9–10, 11–12, >12%. (D) Left: hinge lines of meso-folds developed during the D_1 event (A_1, 92 data); right: contouring at: <2, 3–4, 5–6, 7–8, >9%. (E) Left: stretching lineations (L_1, 55 data) measured on the S_1 foliations; right: contouring at: <3, 4–6, 7–9, 10–12, 13–15, >15%. (F) Left: poles of the S_2 foliations (48 data); right: contouring at <2, 3–8, 9–14, 15–20, 21–27, 28–33, >34%. (G) Left: hinge lines of meso-folds developed during the D_2 event (A_2,148 data); right: contouring at <2, 3–4, 5–6, 7–8, 9–10, 11–12, 13–14, >14%. (H) Left: direction of the stylolitic teeth (ST) measured on the S_2 foliations (42 data); right: contouring at <2, 3–4, 5–6, 7–8, 9–10, > 11%.

the tectonic transport direction (X). The X–Y plane of the strain ellipsoid is thus considered parallel to axial plane schistosity S_1. These non-cylindrical folds are indicative of the occurrence of a highly heterogeneous strain (Alsop and Holdsworth, 1999) during D_1. This event is related to the collisional stage of the Northern Apennines (Late Oligocene–early Miocene) on the basis of structural and geochronological data from the Alpi Apuane core complex (Kligfield et al., 1986).

At the scale of geological sections, the S_1 pattern defines a monocline on the western side of the study area while on the eastern side, where S_2 is particularly well expressed, S_1 describes asymmetric folds (Fig. 7a and b) with a thick and steep limb implying the vergence meaning (Fig. 1).

Differences in cleavage morphology depend on lithology and chemical composition, other factors being equal (Engelder and Marshak, 1985 and references therein). Both in the marble and in the Pietralata Formation, S_2 is characterised by a concentration of optically opaque grains and related veins: this close association leads to the explanation that the opaque grains are residuals of the more soluble calcite, which reprecipited in the veins, as a result of the concomitant transfer and deposition of the dissolved phases (Engelder and Marshak, 1985; Worley et al., 1997; Davidson et al., 1998 and references therein). S_2 is therefore explained as a pressure solution cleavage (Cosgrove, 1976). Transfer of material from the limbs of asymmetric micro-folds to their hinge zones (Cosgrove, 1976; Gray and Durney, 1979) particularly characterises the samples from the Pietralata Formation (Fig. 10). Solution–deposition processes were significant deformational processes during D_2, as expected at very low metamorphic grade (Bell and Cuff, 1989; Worley et al., 1997).

With regard to the relation between S_2 and strain, spacing of cleavage domains depends on strain, if the initial content of clay minerals is equally dispersed (Engelder and Marshak, 1985). Following this and considering the Pietralata Formation (Fig. 10), the more inclined and thick limbs of the D_2-folds should be located in low strain domains, whereas the less inclined, generally thin, limbs should be located in high strain domains. Here the anastomosing geometry of the cleavage suggests a component of shear-strain (Bell T.H., 1981). In the marble, however, the closer spacing of S_2 determined the thin long limbs of the D_2 folds (Fig. 9). These features are also recognisable at the geological section scale in the Molli and Tegoia areas (Fig. 7a and b). The stylolitic teeth on the S_2 foliation in the marble indicate the contractional strain direction during

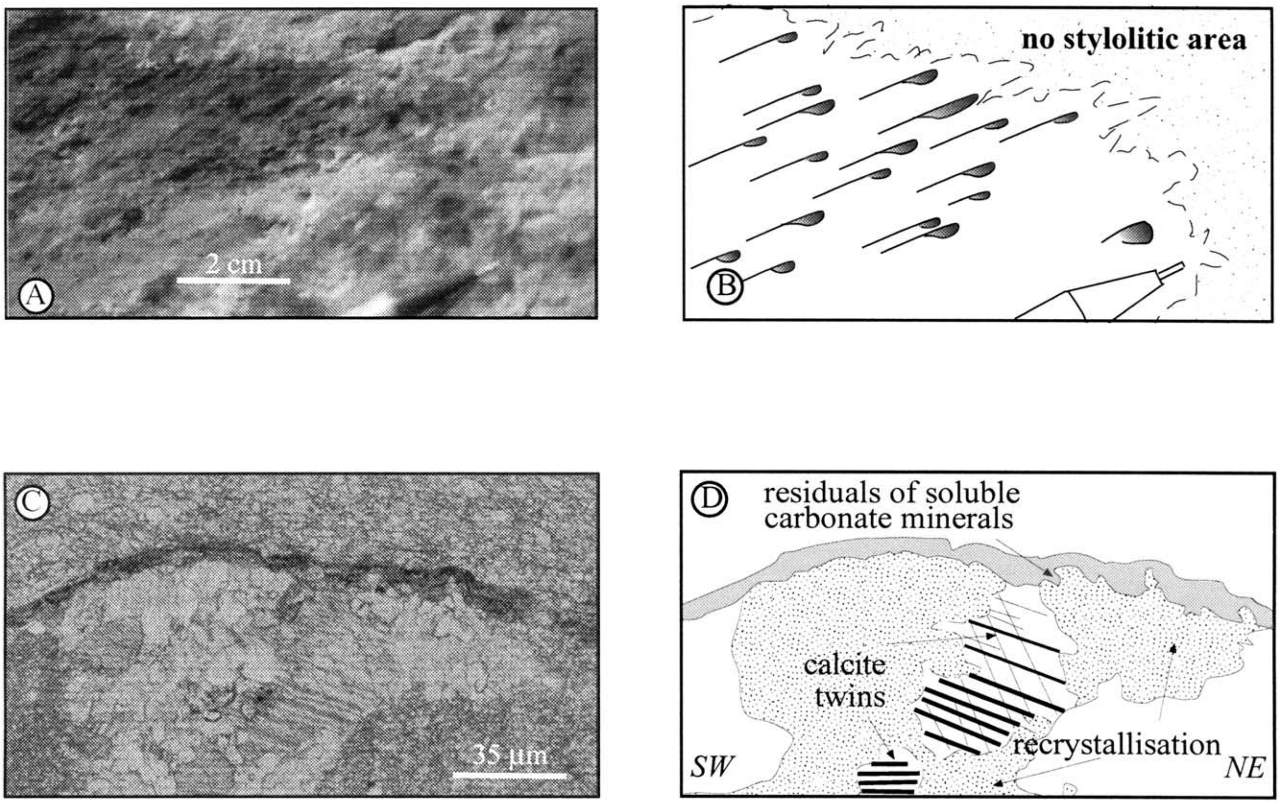

Fig. 8. (A) and (B) Example of stylolitic teeth on the S_2 foliation from the layered marble and its line drawing. (C) and (D) SW–NE-oriented thin section (parallel nicols, length of view: 1.0 mm) of the sample shown in (B) and its line drawing; note the inclined orientation of the peaks.

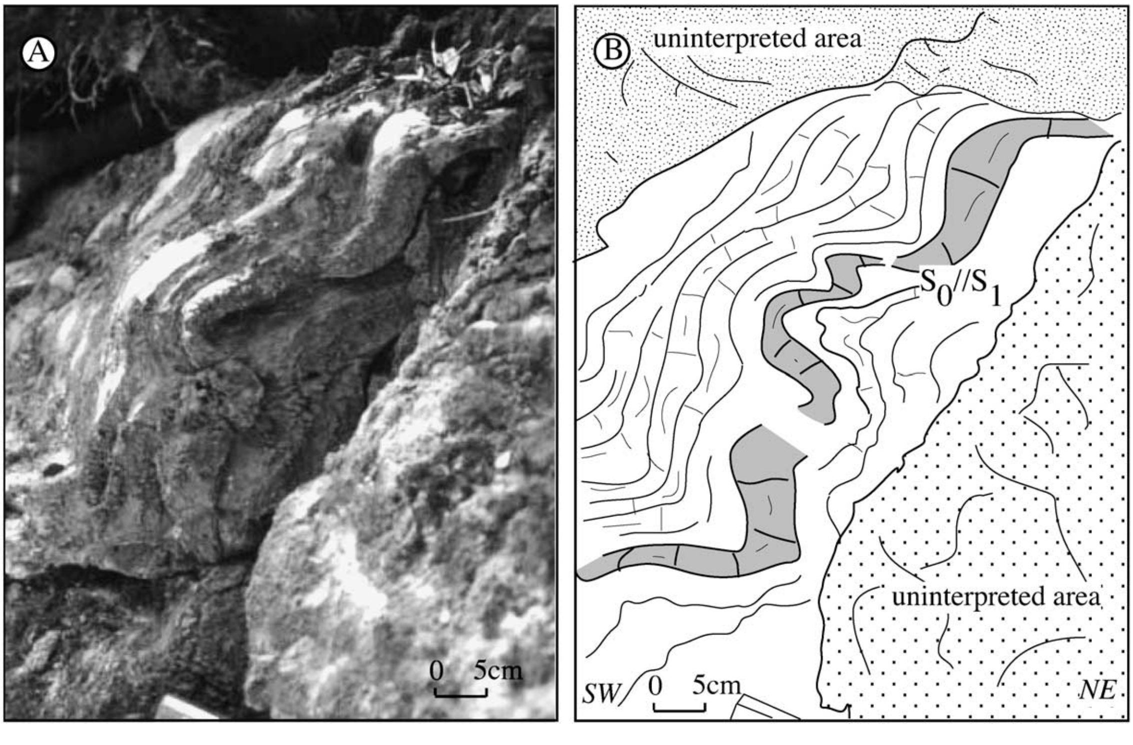

Fig. 9. (A) Mesoscopic examples of folds related to the second deformational event from the layered marble with cherts. (B) Line drawing of the examples given in (A): the differences in thickness between the more inclined and the less inclined are highlighted.

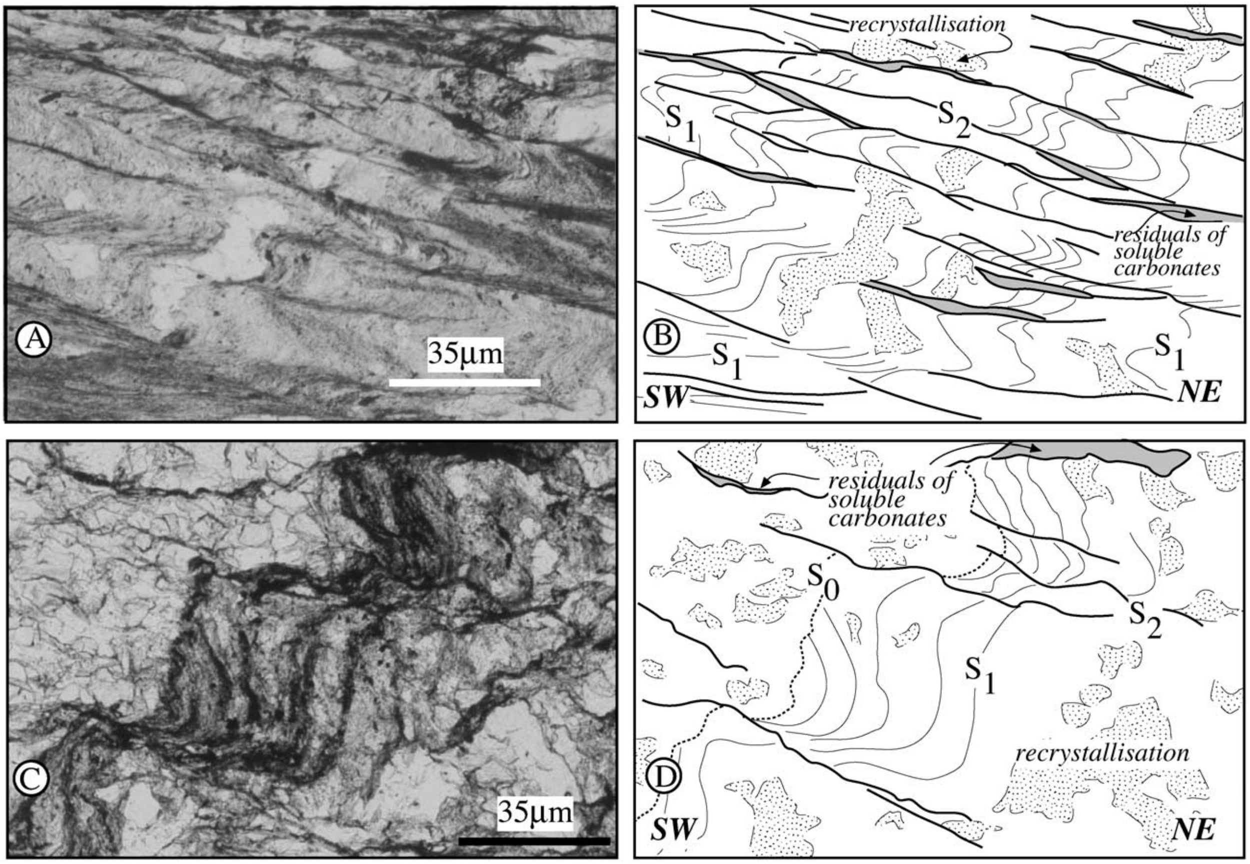

Fig. 10. SW–NE-oriented thin sections from the same rock sample belonging to the Pietralata Formation (parallel nicols; 10×). (A) and (B) Microscopic example from the less inclined limb of the D_2 meso-fold and its line drawing: the anastomosing S_2 foliation and the recrystallisation in the hinge zones are highlighted. (C) and (D) Microscopic example from the more inclined limb of the D_2 meso-fold and its line drawing: the S_2 foliation results spaced and wriggly: in the microdomains the S_1 is highlighted by opaque minerals that overprint allignaments of the micas.

their formation (Alvarez et al., 1978). Because this shortening direction is oblique with respect to S_2, this foliation does not represent the X–Y plane of the D_2 strain ellipsoid. Two different hypotheses can be proposed in order to explain this point. (a) The compressional direction suggested by the stylolitic peaks reflects a late stage of compression on S_2 planes. If this is the case, the D_2 folds vergence is without kinematic constrains, since contrasting strain-paths can

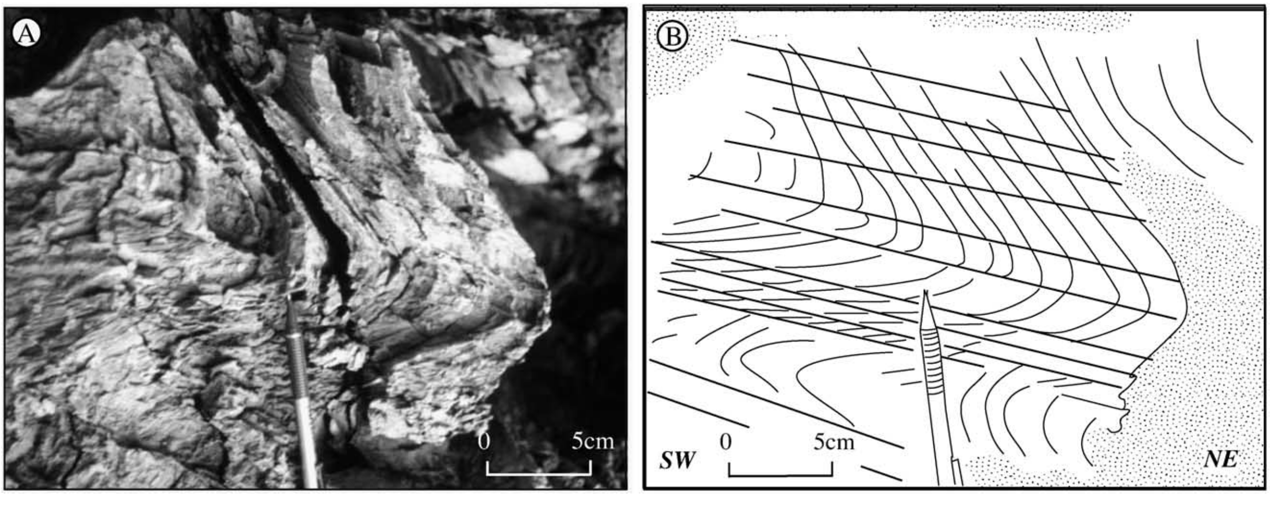

Fig. 11. (A) D_2 mesofold from the Pietralata Formation (phyllite) and (B) its line drawing: the S_2 foliation results more closely spaced in the less inclined limb.

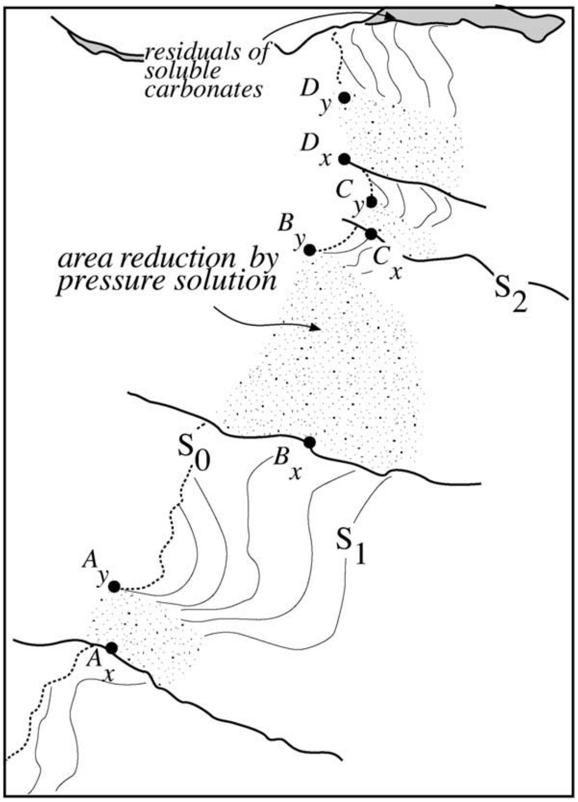

Fig. 12. Qualitative estimation of the area reduction caused by pressure solution processes during S_2 development considering the thin section shown in Fig. 10c and d. S_0 is the reference marker. Ax, Bx, Cx and Dx indicate the points where S_0 lies on S_2 (compare with Fig. 10c and d); Ay, By, Cy and Dy indicate their restored location before D_2.

produce asymmetric folds (Fig. 1) such as those described here. However, no foliation normal to these stylolitic peaks was recognised in the Montagnola Senese study area nor were any regional structures consistent with this compressional direction ever described. (b) A top-to-the-NE shear-component is associated with S_2. The anastomosing geometry in the long limbs of the D_2 folds (Fig. 10a and b) and the different distribution of cleavage may support this explanation. Nevertheless, the relation between maximum principal shortening direction and cleavage orientation is not maintained if deformation is thought to be progressive (Groshong, 1975; Engelder and Marshak, 1985 and references therein). Possibly, the bulk of the deformation might be induced by dissolution, whereas little deformation is by shear-strain. A qualitative estimation of the dissolution ($\approx 70\%$ of area reduction) during D_2 is geometrically derived from Fig. 10c and d assuming the S_0 offset along S_2 as caused by pressure solution processes (Fig. 12).

The distribution of cleavage suggests that a partitioned shear regime (Platt and Vissers, 1980; Bell and Johnson, 1992) could develop during D_2. It is therefore supposed that in the 'high' shear-strain domains, the original spacing of the S_1 foliations was partially reduced also by a dextral shear-strain. By contrast, in the low-strain domains, due to

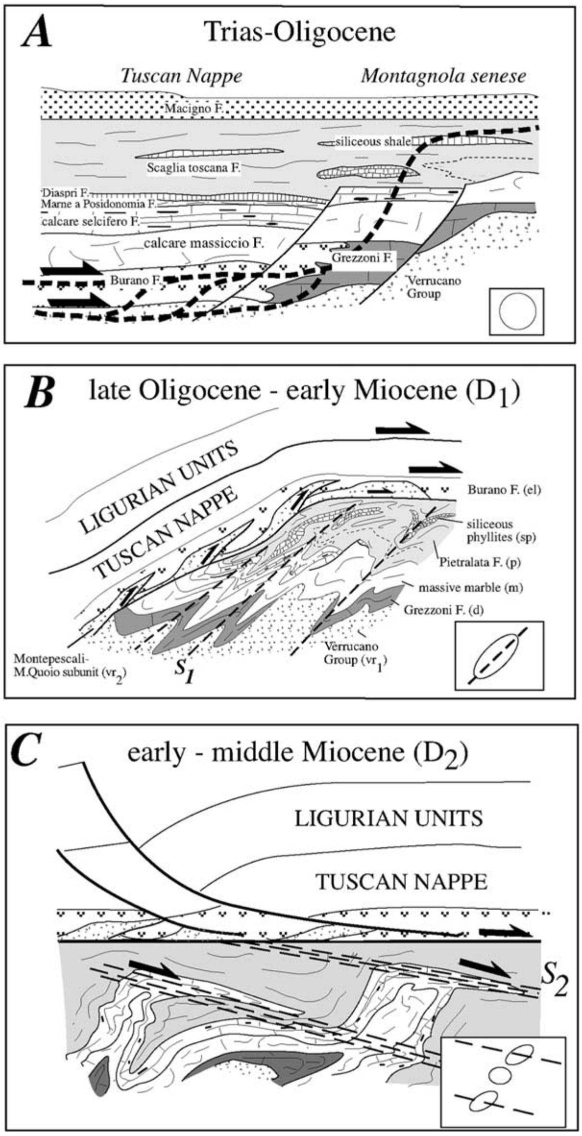

Fig. 13. Schematic geological evolution of the Montagnola Senese area from Trias to middle Miocene (not to scale). (A) In the Tuscan Domain, the Montagnola Senese represented a structural relief, during the Trias–Oligocene time period: thus, the sedimentary sequence is originally reduced in this sector, as resulted from the peculiar relationship between the Pietralata Formation and the marbles; dashed lines indicate possible traces of future contractional shear planes. Square—undeformed marker circle. (B) During the collisional stage of the Northern Apennines the late Triassic evaporitic formation constituted the main detachment level (e.g. Baldacci et al., 1967; Bally et al., 1988; Carmignani et al., 1994). Rhetian dolostones are located at the same structural level of the evaporites, in the study area. A contractional shear zone across bedding could have developed where Rhetian dolostones existed during D_1. As a consequence, strongly non-homogeneous strain occurred during the D_1 event. S_1 foliations and isoclinal folds developed; the Montepescali–Montequoio Sub-unit, the Tuscan Nappe and the Ligurian units were stacked over the Montagnola Senese zone. Contemporaneously, the stacking of the more internal units contributed to the greenschist facies metamorphism of the rocks now cropping out in the Montagnola Senese zone. Square—strain ellipse with respect to the previous stage. (C) The post-collisional extensional tectonics resulted in semi-brittle structures just below the Triassic evaporites. Square—strain is partitioned and the zone, which is between two sets of cleavages is represented as a relatively unstrained domain.

the contractional component acting on S_2, buckling and deposition accomodated the developement of the more inclined (thick and generally short) limb of the D_2-folds. If this is the case, the D_2-folds vergence conflicts with the sense of shear.

The very low metamorphic grade of the structures related to D_2 suggests that it developed during the extensional stage that led to the exhumation of the metamorphic rocks of the Tuscan metamorphic complex (early–middle Miocene: Carmignani and Kligfield, 1990; Carmignani et al., 1994). Extensional, eastward-dipping shear zones were recognised in different areas throughout the Northern Apennines metamorphic belt (Jolivet et al., 1991; Storti, 1995; Daniel et al., 1996; Keller and Coward, 1996; Jolivet et al., 1998) while almost symmetrical mega-boudinage and conjugate extensional shear zones characterise the structure of the Alpi Apuane core complex (Carmignani and Kligfield, 1990; Carmignani et al., 1994).

5. Conclusions

In D_2 asymmetric folds with a thick and steep limb, vergence may not be the best kinematic indicator. Microstructural and meso-structural observations can help show that their vergence can actually be opposite to the sense of shear.

As regards the vergence meaning of the D_2 folds in the study area, no firm conclusion can be reached. However, the fact that no other foliation normal to the inclined stylolitic teeth was recognised, suggests that the D_2 folds result from the combined effects of partitioned rightward shear strain and dissolution processes, the latter being dominant: hence, the vergence of D_2 folds seems to be opposite to sense of shear.

Since the stratigraphic setting of the Montagnola Senese area is comparable with the stratigraphic setting at the eastern side on the Alpi Apuane core complex, the study area may be considered as the southward elongation of the eastern Alpi Apuane region: in this view, the eastward sense of shear represents a part of the conjugate extensional shear zones, which characterise the evolution of the Tuscan crust during the early–middle Miocene extensional stage (Fig. 13).

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