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Kinematics and geometry of Miocene low-angle detachments and exhumation of the metamorphic units in the hinterland of the Northern Apennines (Italy)

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Abstract

This paper deals with the lateral segmentation (crustal boudinage) and exhumation of the metamorphic units in the hinterland of the Northern Apennines during the Late Miocene extension. The study area (Mt. Leoni area) is part of the Middle Tuscan Ridge, a regional morpho-tectonic feature in which the deepest tectonic units of the Northern Apennines are broadly exposed. Crustal seismic profiles and deep boreholes indicate that the Middle Tuscan Ridge coincides with the outcropping part of a laterally discontinuous geological body, mainly made up of HP-LT and greenschist facies metamorphic units. Extensional detachments characterised by top-to-the-East sense of shear and staircase geometry produced the lateral segmentation of the metamorphic units. Their activity can be ascribed to Late Tortonian–Late Messinian times. Geometry and kinematics of the extensional detachments have been compared with the Miocene extensional structures developed at shallow depths in the overthickened crust of the Northern Apennines, allowing understanding of the extensional tectonic evolution which reorganised the hinterland Northern Apennines collisional belt.

Keywords: Exhumation; Low-angle normal faulting; Crustal boudinage; Kinematics; Northern Apennines

1. Introduction

One of the common characteristics of collisional belts is that extension may produce their collapse after building (Platt and Vissers, 1989; Jolivet and Goffé, 2000; Marshak et al., 2006) and explains the high-pressure rock exhumation during the orogenic building (Azañón and Crespo-Blanc, 2000; Martínez-Martínez et al., 2002; Booth-Rea et al., 2004; Rossetti et al., 2005; Michard, 2006). For instance, in several collisional belts around the world, it has been documented that different generations of extensional structures, such as low-angle detachments and late high-angle normal faults, affected the overthickened crust and produced thinning of the orogen, and exhumation of the deeper metamorphic rocks (Davis and Coney, 1979; Lister et al., 1984; Platt, 1986; Lister and Davis, 1989; Carmignani and Kligfield, 1990; Jolivet et al., 1994, 1998; Rossetti et al., 1999, 2005; Sedlock, 2002; Booth-Rea et al., 2004; Cagnard et al., 2004). During this geodynamic process, strain rates and rheologies largely control the style of extension (Wernicke, 1981; Wernicke and Burchfiel, 1982; Lavecchia et al., 1984; Jackson et al., 1988; Friedman and Burbank, 1995; Storti, 1995; Caby et al., 2001; Bahroudi et al., 2003; Booth-Rea et al., 2004). In particular, weak crustal horizons, coinciding with evaporitic, clayey or phyllitic levels, may strongly influence the trajectories of the faults, as also demonstrated by analog models (Gartrell, 1997). Furthermore, if a high strain rate is associated with a multilayered setting, a very articulated fault pattern may occur (Friedman and Burbank, 1995).

In the hinterland of the Northern Apennines (Fig. 1), good examples of lithologically controlled normal faults affecting the shallowest part of the tectonic pile have been recently described (Bertini et al., 1991; Decandia et al., 1993; Carmignani et al., 1994; Collettini and Barchi, 2002; Brogi, 2004c; Bonciani et al., 2005; Brogi et al., 2005a; Collettini et al.,

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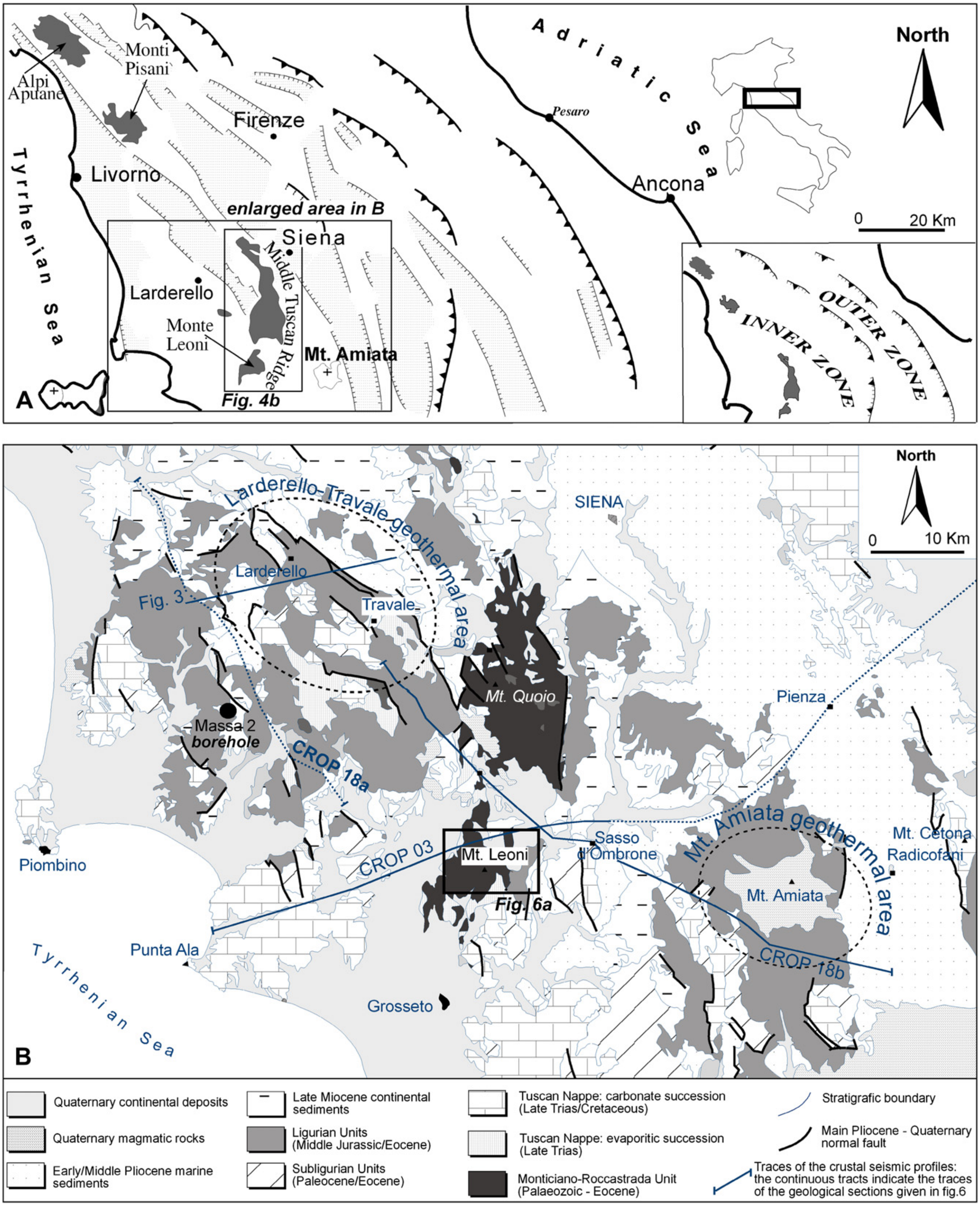

Fig. 1. (A) Location of the study area (from Decandia et al., 1998, modified). (B) Geological sketch map of southern Tuscany. The traces of the CROP18 and CROP03 crustal seismic profiles given in Fig. 5 are shown.

2006). It has been documented that Miocene low-angle normal faults (LANFs) accommodated within weak horizons located at different depths in the tectonic pile, and were connected by extensional ramps dissecting the most competent horizons, giving rise to their lateral segmentation, similarly to the boudinage for ductile deformation. Lateral segmentation has been profusely described for the Tuscan Nappe, the deepest non-metamorphic tectonic unit of the tectonic pile (Fig. 2A), broadly exposed in southern Tuscany as isolated and discontinuous extensional horses (known as the Tuscan Nappe boudins). In contrast, scarce data are available for the mechanism which produced the lateral segmentation of the deeper crustal levels, widely documented by deep boreholes drilled in the Larderello-Travale geothermal area (Baldi et al., 1994), because they are so poorly exposed. In fact, in the inner Northern Apennines the metamorphic units crop out only in the Middle Tuscan Ridge, a regional morphotectonic feature striking mainly N–S (Fig. 1). Borehole logs highlighted that elision, producing the direct superposition of younger on older rocks, is also a common feature for the metamorphic units (Bertini et al., 1991; Baldi et al., 1994). An alternative hypothesis explaining the Tuscan Nappe lateral segmentation and the Neogene-Quaternary tectonic regime of the hinterland Northern Apennines was given by Finetti et al. (2001). This hypothesis will be discussed later.

Fieldwork, boreholes logs and interpretations of seismic profiles all suggest that the Middle Tuscan Ridge is the shallower part of a laterally segmented body, mainly composed of Triassic metasiliciclastic rocks (Decandia et al., 1998; Liotta et al., 1998; Lavecchia et al., 2004; Brogi et al., 2005a,b) imbricated in duplex structures (Costantini et al., 1988; Lazzarotto et al., 2003). This segmented body is laterally delimited by zones where the highest tectonic units of the orogenic pile (Ligurian Units) directly overlie on the Palaeozoic phyllites. This feature makes the Middle Tuscan Ridge a key area to understand the mechanism which produced the lateral segmentation of the metamorphic units, and to compare the extensional structures developed at different structural levels in the crust, in terms of geometry, development mechanism and kinematics.

In this paper I describe and discuss kinematics data and geometric setting of extensional detachments which affected the metamorphic successions exposed in the Middle Tuscan Ridge (Mt. Leoni area, Fig. 1), providing a hypothesis on the dynamics and development mechanism which produced the lateral segmentation and exhumation of the metamorphic units. Additionally, this model has been compared with that described for the shallowest units, such as the Tuscan Nappe, and with the mechanisms described in other extended regions around the world.

2. Geological outline

2.1. The inner Northern Appennines tectonic pile

The Northern Apennines is a fold-and-thrust belt originated from the convergence and collision (Cretaceous–Early Miocene) of the African (Adria microplate) and the European plate, represented by the Sardinia-Corsica Massif (Boccaletti et al., 1971; Castellarin et al., 1992; Faccenna et al., 2001). This geodynamic process determined the eastward stacking of several tectonic units derived from oceanic and epicontinental palaeogeographical domains (Fig. 2A). They are composed of, from top to bottom (Fig. 2B): (a) Ligurian and Subligurian Units consisting of remnants of Jurassic oceanic crust and Cretaceous-Oligocene sedimentary cover involved in multiple thrust sheets; (b) Tuscan Units including sedimentary (Tuscan Nappe) and metamorphic (Monticiano-Roccastrada Unit) sequences ranging in age from Palaeozoic to Early Miocene. The Tuscan Nappe consists of, from the bottom: an evaporitic horizon (Late Triassic, TN_1 in Fig. 2B), a carbonate-siliceous succession (Early Jurassic–Early Cretaceous, TN_2 in Fig. 2B) and a clayey and turbiditic succession (Cretaceous–Early Miocene, TN_3 in Fig. 2B). This stratigraphic succession tectonically overlies a mainly continental siliclastic sequence (Verrucano Group), described in the next paragraph, belonging to the Monticiano-Roccastrada Unit (MRU in Fig. 2B). Both the Tuscan Nappe and the Monticiano-Roccastrada Unit were imbricated in duplex structures (Pandeli et al., 1991; Brogi, 2004a), and thrust eastwards over the Umbria-Marchigian units (Carmignani et al., 2001, and references therein). At the base of the stacked tectonic units, the Gneiss Complex consisting of the African basement, was encountered by geothermal boreholes (Bertini et al., 1991). The Northern Apennines tectonic pile contains several horizons with ductile behaviour occurring at different depths: (i) the clayey successions of the Ligurian and Subligurian Units (L in Fig. 2B); (ii) the Triassic evaporites occurring at the base of the Tuscan Nappe; and (iii) the Palaeozoic phyllite levels tectonically interbedded at different levels within the Monticiano-Roccastrada Unit. Most authors agree that from the Early–Middle Miocene, the multilayered tectonic pile forming the inner Northern Apennines, with the Ligurian Units at the top, was affected by extension (Carmignani et al., 1994; Jolivet et al., 1998; Brunet et al., 2000) acting coevally with compression in the outer Northern Apennines (Elter et al., 1975; Lavecchia et al., 2004; Barchi et al., 2006). Few other authors denied the Neogene extension: they hypothesised that the Northern Apennines was affected by compressional tectonics until Quaternary (Finetti et al., 2001 and references therein). Their point of view will be discussed later.

The extension produced significant tectonic elisions within the tectonic pile, modifying the architecture of the Northern Apennines. The collisional structures were preserved within crustal boudins (Brogi, 2004a; Brogi et al., 2005a).

Although extension in the inner zone of the Northern Apennines was a continuing process, two main extensional events were regionally recognised (Bertini et al., 1991; Carmignani et al., 1994, 1995). The first event caused the thinning of the Ligurian Units and the lateral segmentation of the deeper sedimentary and metamorphic units (Carmignani et al., 1994; Baldi et al., 1994). In the gap between the segmented units, the Ligurian Units, the highest units in the orogenic pile, overlie the Late Triassic evaporites and/or the Palaeozoic phyllites (Fig. 3). In these delaminated areas, characterised by upward concave shape, syntectonic continental to marine Middle–Late Miocene sediments were unconformably deposited on the Ligurian Units (Brogi, 2004b; Brogi et al., 2005a,b; Brogi and Liotta, 2006). The later extensional event (Early Pliocene–Quaternary) produced mainly high-angle normal and transtensional faults which cross-cut all the previous structures, such as thrusts and low-angle normal faults (Brogi et al., 2003), and gave rise to tectonic depressions (Martini

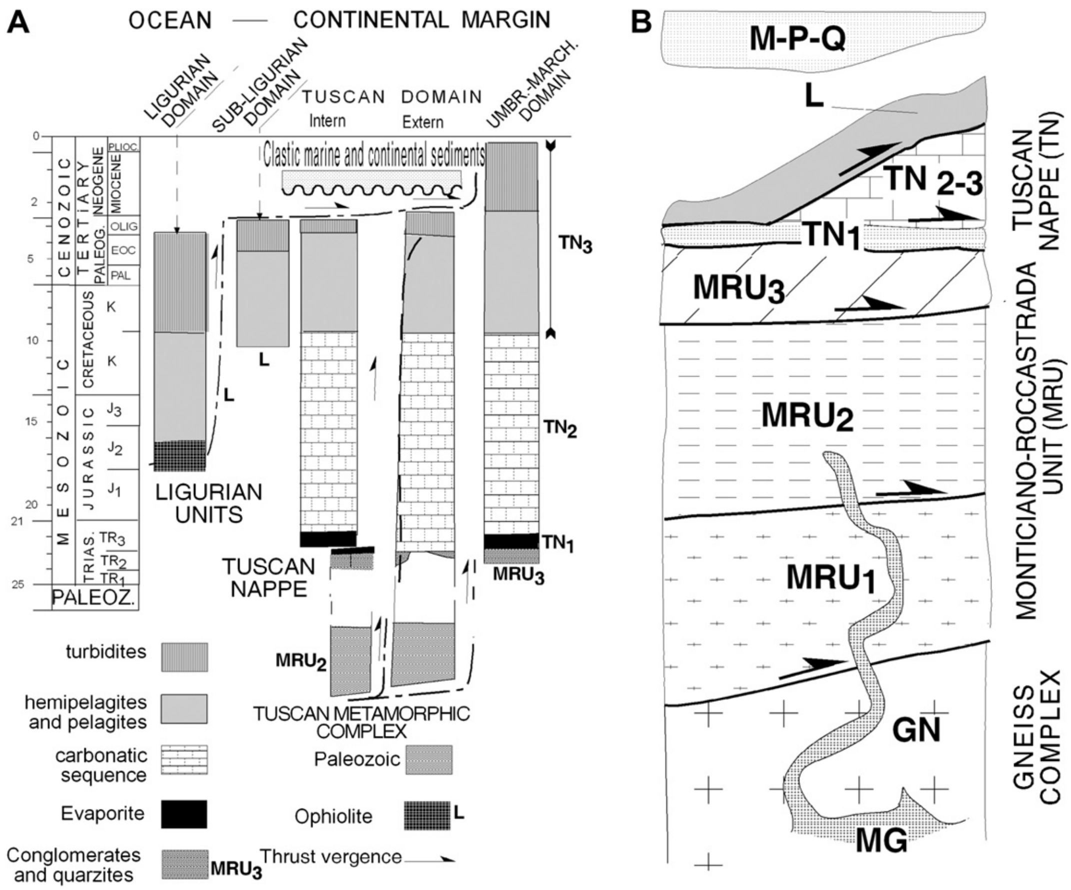

Fig. 2. (A) Relationships between the different tectonic units of the Northern Apennines and related palaeogeographical domains. (B) Tectonostratigraphical units drilled by boreholes in the Larderello-Travale geothermal area and partially exposed in the study area. Symbols: MPQ. Miocene, Pliocene and Quaternary sediments; Tuscan Nappe (TN): TN_3, Early Miocene–Cretaceous pelagic–turbitic succession; TN_2, Cretaceous–Rhaetian carbonate succession; TN_1, Late Triassic evaporites; Monticiano-Roccastrada Unit (MRU): MRU_3, Mesozoic–Palaeozoic Group, made up of dolostones and limestones (Late Triassic), quartz metaconglomerates, quartzites and phyllites (Verrucano Group, Middle–Early Triassic), sandstones, phyllites (Middle–Late Carboniferous–Early Permian); MRU_2, Phyllitic–Quartzitic Group; MRU_1, Palaeozoic Micaschist Group; GC, Gneiss Complex; MR, magmatic intrusions. (After Batini et al., 2003.)

and Sagri, 1993) mainly infilled by marine to continental sediments during the Pliocene and Pleistocene (Fig. 3). Furthermore, the extension produced: (a) thinning of the continental crust and lithosphere in the hinterland of the Northern Apennines (Tyrrhenian Sea and southern Tuscany), resulting in a thickness of about 20–22 and 30–50 km, respectively (Calcagnile and Panza, 1981; Locardi and Nicolich, 1992); (b) a positive regional Bouguer anomaly (Giese et al., 1981); (c) widespread magmatism (Serri et al., 1993; Peccerillo et al., 2001; Peccerillo, 2002; Dini et al., 2005); (d) high heat flow (Della Vedova et al., 2001); (e) localised and regional uplift (Dallmeyer et al., 1995; Dallmeyer and Liotta, 1998).

2.2. The Middle Tuscan Ridge

The Middle Tuscan Ridge is an arcuate morpho-tectonic feature extending from the Alpi Apuane to the Argentario Promontory, located south of the Mt. Leoni (Fig. 1). In the

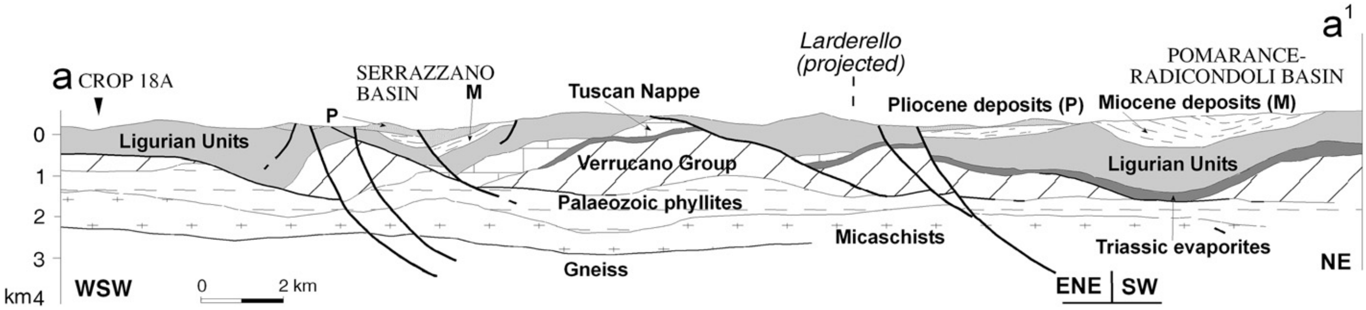

Fig. 3. Geological section across the Larderello-Travale geothermal area. Its location is given in Fig. 1B (after Baldi et al., 1994, modified).

northern part (Alpi Apuane and Monti Pisani areas), Jurassic–Eocene metacarbonates (marble and calcschist) and Palaeozoic–Triassic metasiliciclastics are exposed, while the southern tract is mainly characterised by Palaeozoic–Triassic metasiliciclastic successions of the Monticiano-Roccastrada Unit (Costantini et al., 1988). The Monticiano-Roccastrada Unit consists of three stratigraphic groups (Batini et al., 2003 and references therein): (a) the Triassic Verrucano Group (MRU_3 in Fig. 2B); (b) the Palaeozoic Phyllite-Quartzitic Group (MRU_2 in Fig. 2B); and (c) the Micaschist Group (MRU_1 in Fig. 2B). The Verrucano and Phyllite-Quartzitic Groups are broadly exposed in the Middle Tuscan Ridge, while the Micaschist Group and the Gneiss Complex are known through boreholes drilled in the Tuscan geothermal areas (e.g. Larderello-Travale and Mt. Amiata), penetrating the crust down to about 4.5 km (Batini et al., 2003, and references therein). The Monticiano-Roccastrada Unit was affected by HP/LT (Giorgetti et al., 1998; Brunet et al., 2000) to greenschist facies (Franceschelli et al., 1986) metamorphism during the Northern Apennines collisional event and later extension (27–11 Ma; Giglia and Radicati di Brozolo, 1970; Kligfield et al., 1986; Deino et al., 1992; Brunet et al., 2000). Furthermore, HT/LP metamorphism has been documented in restricted areas where Late Miocene–Quaternary magmatic intrusions were emplaced at shallow depths in the middle-upper crust (Villa and Puxeddu, 1994; Dini et al., 2005).

In the Middle Tuscan Ridge, the Monticiano-Roccastrada Unit is discontinuously covered by klippens mainly made up of the basal succession of the Tuscan Nappe: the Late Triassic evaporites known as the Burano Fm (Martinis and Pieri, 1964). This succession is mainly represented by its alteration products consisting of a carbonate breccia named as the Calcare Cavernoso Fm.

The Middle Tuscan Ridge is characterised by multiple tectonic repetitions of the metamorphic successions (sub-units) developed during collisional thrusting. These mainly involved the Verrucano Group (MRU_3), the Phyllite-Quartzitic Group (MRU_2), and the Triassic evaporites (TN_1), giving rise to a tectonic wedge known as the *Complesso a Scaglie* (Pandeli et al., 1991) which has been profusely drilled by deep boreholes (Fig. 4A). Two main sub-units emplaced during the collisional event are exposed in the Middle Tuscan Ridge (Costantini et al., 1988), which are (Fig. 4B): (a) the inner Monte Pescali–Monte Quoio Subunit, which experienced pressures of about 8–9 kbar and a temperature of about 350 °C; (b) the outer Montagnola Senese–Monte Leoni Subunit, which experienced pressures of about 9–10 kbar and a temperature of about 400 °C (Giorgetti et al., 1998). The tectonic juxtaposition of these sub-units is ascribed to the Late Oligocene–Early Miocene (Bertini et al., 1991; Liotta, 2002).

Multiple deformational events were recorded by the metamorphic rocks of the Monticiano-Roccastrada Unit. They have been widely described in the literature (Meccheri et al.,

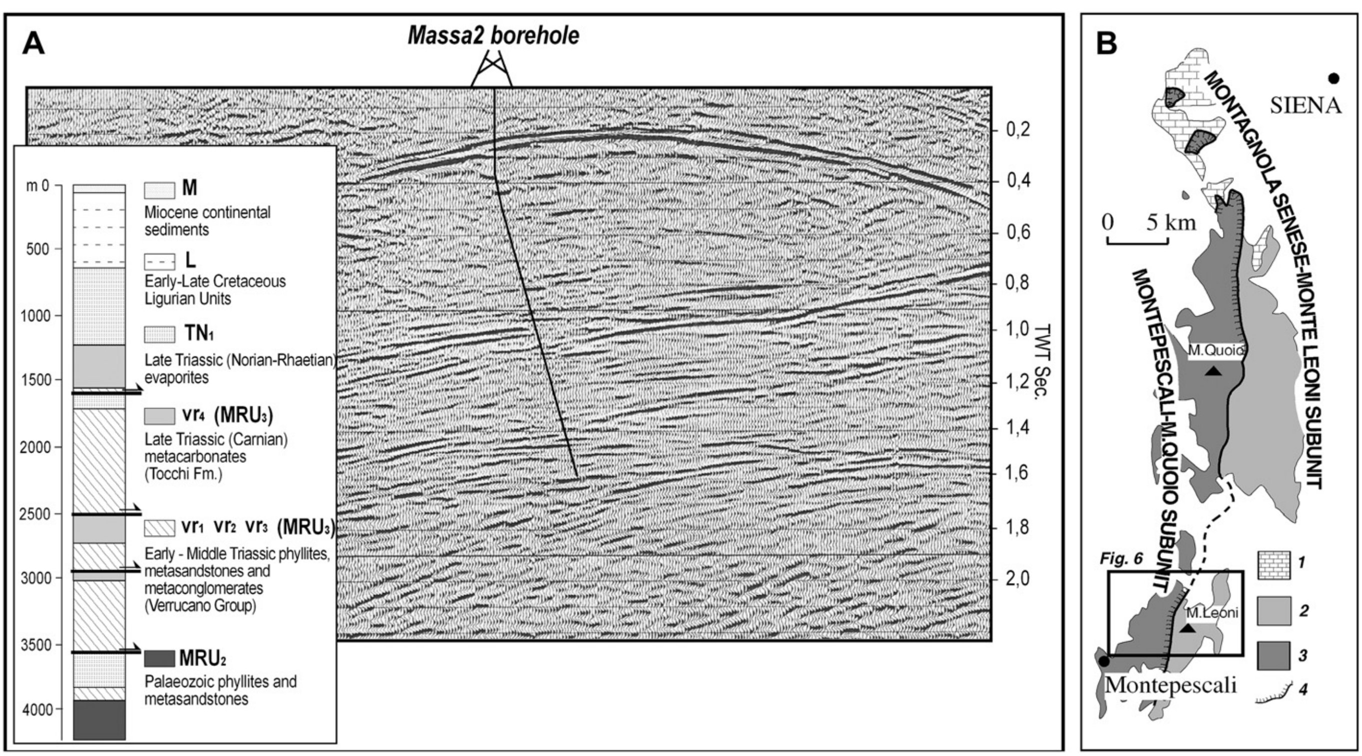

Fig. 4. (A) Seismic image of imbricated tectonic units forming the metamorphic "basement" of the Northern Apennines as indicated by the stratigraphic log from the Massa 2 borehole (after Bertini et al., 1994): see location in Fig. 1B. Symbols: vr_{1-4}, various stratigraphic units belonging to the Verrucano Group: lithology and formational name indicated in the figure. Other symbols as in Fig. 2. (B) Tectonic sketch showing the tectonic subunits cropping out in the Middle Tuscan Ridge (from Lazzarotto et al., 2003, modified). Symbols: Montagnola Senese–Monte Leoni Subunit: 1, Mesozoic Formations; 2, Triassic–Palaeozoic formations. Montepescali–Montequoio Subunit: 3, Triassic–Palaeozoic formations; 4, thrust.

1987; Costantini et al., 1988; Conti et al., 1991; Carosi et al., 2002a, 2002b; Liotta, 2002; Lazzarotto et al., 2003; Brogi, 2006a) and here below summarised. During the first deformation event (DE_1) (Late Oligocene–Early Miocene), thrusts, reverse faults and sub-isoclinal east- and southeast-verging folds (F_1) developed. F_1 folds are typified, at present, by mainly N–S and/or NE–SW striking meso- to map-scale structures. A locally pervasive axial planar tectonic foliation (S_1) is associated with the folds. The succeeding deformational event (DE_2) (Middle–Late Miocene) was typified by meso- to map-scale NNE–SSW striking and east-verging folds (F_2) and an associated tectonic foliation (S_2). A later deformational event (DE_3) (Late Miocene?) produced map-scale gentle folds (F_3) mainly striking NE–SW. They are characterised by a very spaced tectonic foliation (S_3) only developed close to fold hinges. Pliocene-Pleistocene extensional structures dissected the previous structures (Carmignani et al., 1994).

The crustal seismic profiles CROP03 (Decandia et al., 1998; Liotta et al., 1998; Barchi et al., 1998; Lavecchia et al., 2004; Accaino et al., 2006) and CROP18 (Accaino et al., 2005; Brogi et al., 2005a,b; Tinivella et al., 2005; Brogi and Liotta, 2006) show that the Middle Tuscan Ridge, in the Roccastrada and Mt. Leoni area (Fig. 1), represents the outcropping part of a laterally segmented body (Fig. 5) mainly made up of the metamorphic rocks imbricated in duplex structures, belonging to the Verrucano Group (MRU_3 in Fig. 2B).

A very stretched tectonic pile characterises both the western and eastern sides of the Middle Tuscan Ridge, as documented by field and seismic data highlighting that the Ligurian Units overlie the Triassic evaporites and/or the metamorphic rocks (Fig. 5A). In order to understand the kinematics and the development mechanism which produced the lateral segmentation of the metamorphic units, a transect across the Middle Tuscan Ridge has been investigated in the Mt. Leoni area (Figs. 1 and 6A).

3. The Mt. Leoni area

3.1. Stratigrapy

The Mt. Leoni area (Fig. 6a) is characterised by metamorphic rocks of the Verrucano (MRU_3 in Fig. 2B) and Phyllite-Quartzitic Group (MRU_2 in Fig. 2B) (Gelmini, 1969; Franceschelli et al., 1986; Meccheri et al., 1987; Moretti, 1991; Giorgetti et al., 1998; Brunet et al., 2000; Aldinucci et al., 2005). The Tuscan Nappe (TN_1, TN_2 and TN_3 in Fig. 2B) and the uppermost Ligurian Unit (Ophiolitic Unit, part of L in Fig. 2B), locally overlying the metamorphic rocks, consist of klippens discontinuously exposed mainly in the eastern side of Mt. Leoni (Fig. 6A). The metamorphic succession was doubled by a main thrust, giving rise to the aforementioned Mt. Pescali-Mt. Quoio and Montagnola Senese–Mt. Leoni subunits (Costantini et al., 1988; Lazzarotto et al., 2003). In the Monte Leoni, both the

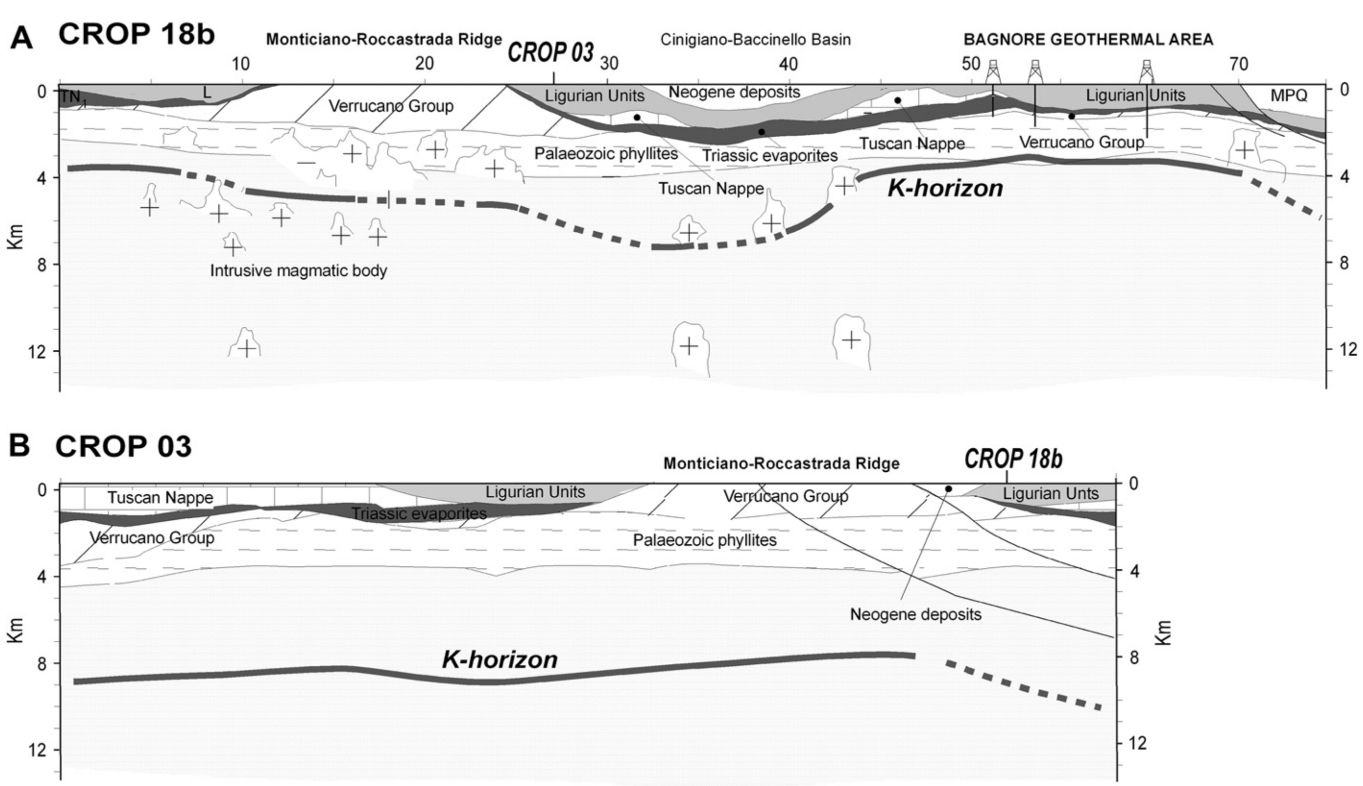

Fig. 5. Geological section from the interpretation of the CROP18 (A) and CROP03 (B) crustal seismic profiles, respectively published by Brogi et al. (2005a,b) and Decandia et al. (1998), Liotta et al. (1998), Barchi et al. (1998). The traces of the geological sections are the continuous lines given in Fig. 1B. K-horizon is a seismic marker characterised by high acoustic impedance and bright-spot feature, interpreted as a crustal shear zone coinciding with the top of the brittle–ductile transition (see Liotta and Ranalli, 1999).

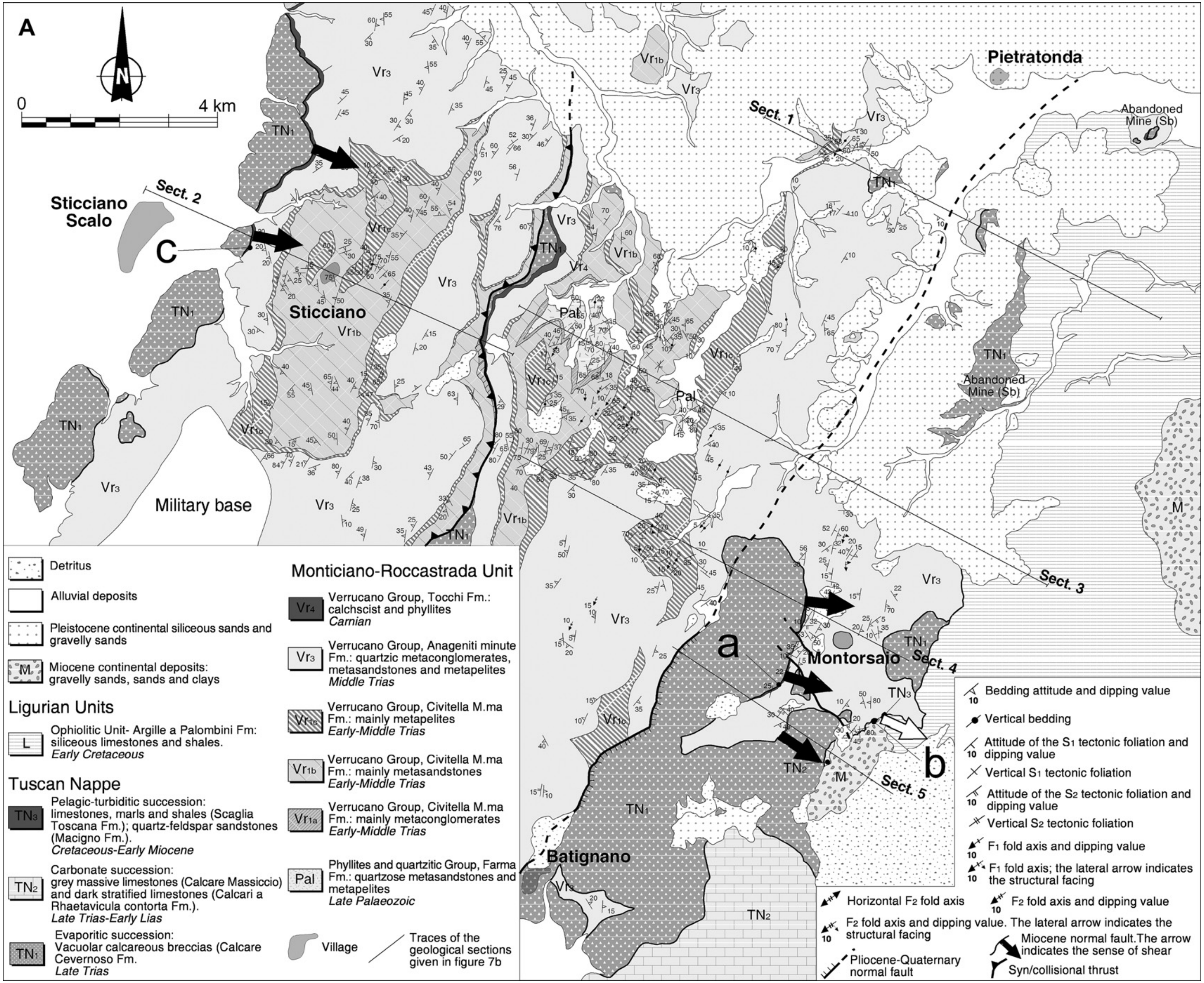

Fig. 6. (A) Geological map of the Monte Leoni area realised after the new fieldwork. Its location is given in Fig. 1B. (B) Geological sections across the Monte Leoni area. Their traces are given in a. Stereoplots (Schmidt diagram, lower hemisphere) of the indicated structural elements. All diagrams show poles and relative contouring.

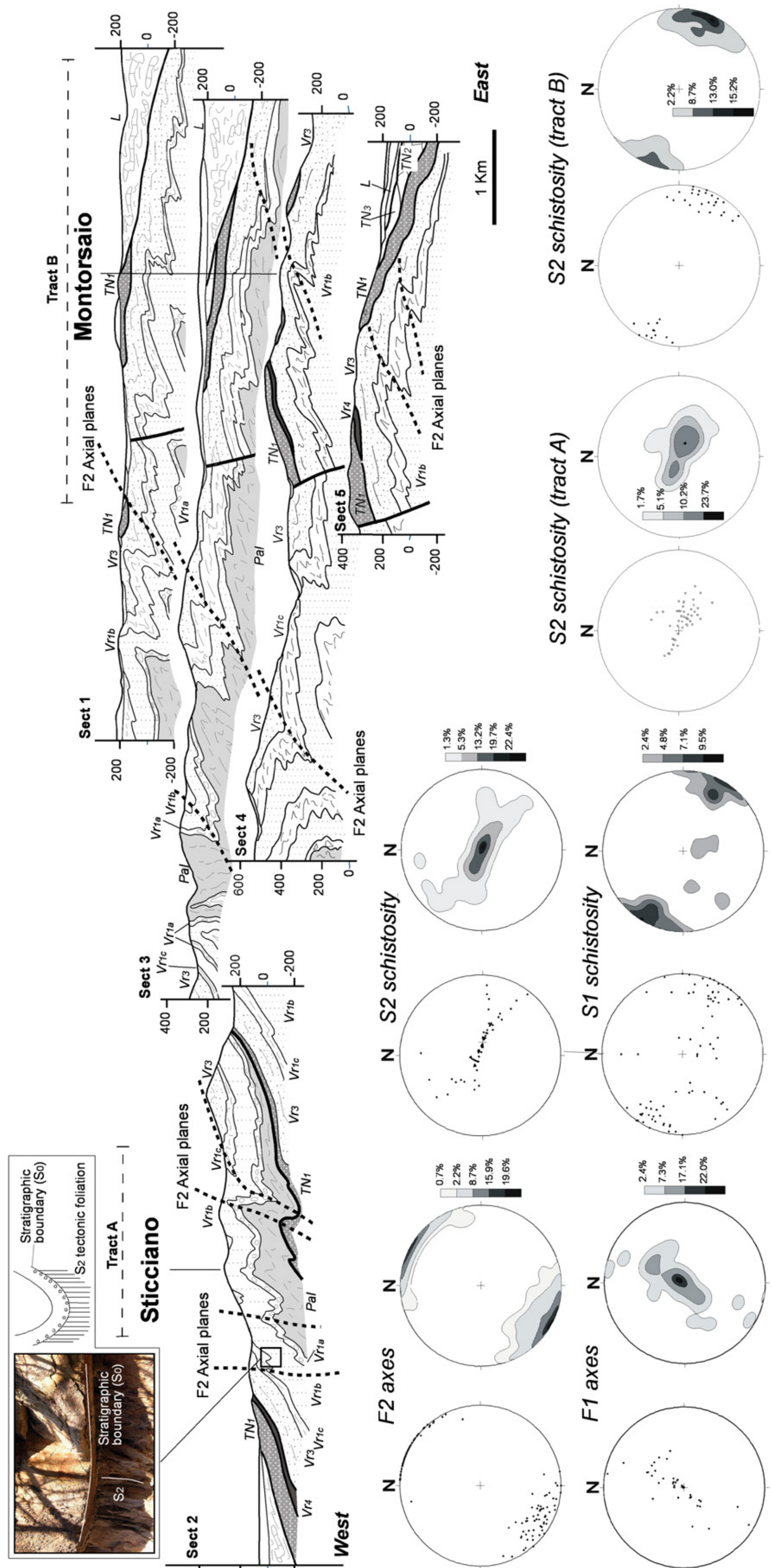

Fig. 6 (*continued*).

sub-units are composed of Palaeozoic (Falsacqua Fm: graphitic metapelites and metarenites with metacarbonate beds at the top—Aldinucci et al., 2005 and references therein) and Triassic metamorphic rocks of the Verrucano Group. This is composed of, from bottom to top (Aldinucci et al., 2005): the Civitella M.ma Fm—continental and transitional metaconglomerates, quartzose metasandstones and metapelites (Early–Middle Triassic); the Anageniti Minute Fm—continental to transitional metaconglomerates and quartzose metasandstones and metapelites (Late Ladinian); the Tocchi Fm—marine metacarbonates and metapelites (Carnian).

The Tuscan Nappe is mainly composed of its basal succession, consisting of a thick sequence (up to 300 m) of carbonate tectonic breccias (Calcare Cavernoso Fm), which overlies both the inner and outer metamorphic subunits (Fig. 6A). The carbonate, clayey and turbiditic (Jurassic–Oligocene) Tuscan Nappe successions are only exposed in the eastern side of Mt. Leoni, where very discontinuous and disrupted outcrops overlie the outer metamorphic subunit (Fig. 6). The Ophiolitic Unit, here composed of the oceanic pelagic cover (Argille a palombini Fm, Early Cretaceous) overlies on both the Calcare Cavernoso Fm and the metamorphic rocks of the outer subunit (Fig. 6A and B).

3.2. Deformation and rock fabric

The metamorphic rocks experienced polyphase deformation giving rise to superimposed folding events and related tectonic foliations (Meccheri et al., 1987; Aldinucci et al., 2005; Brogi, 2006a). The first folding event (DE_1) gave rise to widespread tectonic foliation (S_1), consisting of a pervasive schistosity mainly developed in the fine-grained lithotypes (Fig. 7A). A synkinematic HP/LT metamorphic mineral association (M_1), consisting of quartz + muscovite + chlorite ± paragonite ± phyrophyllite ± albite ± carbonates ± oxides, is associated with S_1. Mg-carpholite developed with quartz veins associated with the F_1 folding. At the microscopic scale, S_1 relates to a continuous schistosity (*sensu* Passchier and Trouw, 1996), mainly defined by elongate quartz grains and non-layered homogeneous distribution of platy mineral grains with a preferred orientation (Fig. 7B). The successive folding event (DE_2), typified by meso- to map-scale east-facing folds (F_2) (Fig. 6), produced pervasive tectonic foliation (S_2) (Fig. 7C). S_2 is a very pervasive schistosity in the pelitic rocks and becomes very discontinuous in the sandstones. Retrograde synkinematic greenschist metamorphism (M_2) is associated with the DE_2 folding event. It consists of a mineralogical association mainly developed in the metapelites, consisting of quartz + muscovite ± oxides. At the microscopic scale, S_2 can be described as spaced schistosity (*sensu* Passchier and Trouw, 1996) (Fig. 7D). A later folding event (DE_3) locally produced map-scale gentle folding (F_3) with axial directions mainly NE-SW oriented. A spaced tectonic foliation (S_3) never accompanied by blastesis developed during the DE_3 event. Microstructural analysis classifies the S_3 as smooth crenulation-cleavage, parallel and graded with 10 vol. % of cleavage domains (*sensu* Passchier and Trouw, 1996) (Fig. 7E and F).

3.3. The structure

The east-facing F_2 folds are the prominent structures occurring in the study area. Fig. 6B highlights different attitudes of F_2 axial planes and S_2 tectonic foliation across the Mt Leoni area: the F_2 axial planes range from subhorizontal to W–NW dipping, respectively in the eastern and western sides of Mt. Leoni; the S_2 foliation shows a mainly vertical or subvertical attitude in the western side of Mt. Leoni, but it is mainly subhorizontal or gently west-dipping in the eastern side. This geometrical attitude is related to the occurrence of a F_3 antiform characterised by a sub-vertical axial plane, which deformed both the F_2 fold system and the tectonic contact separating the Calcare Cavernoso Fm from the metamorphic rocks (Fig. 8). As a matter of fact, the Calcare Cavernoso Fm is exposed in the western, central and eastern sides of the Mt. Leoni area indicating a dome shape (Figs. 6A and 8). Both in the western and central sides, the Calcare Cavernoso Fm, directly overlain by the Ligurian Units, lies on the topmost metamorphic succession (Tocchi Fm) (Figs. 6A and 8). Contrarily, in the eastern side the Calcare Cavernoso Fm was delaminated. Here, the Tuscan Nappe clayey-sandy succession and the uppermost formation of the Ligurian Units (Argille a Palombini Fm) directly overlie on the Anageniti Minute Fm belonging of the outer metamorphic sub-unit (Figs. 6 and 8). This strongly supports for an extensional tectonic process which produced the elision of: (a) the carbonate and pelagic-turbiditic succession of the Tuscan Nappe (TN_2 and TN_3 in Fig. 2B); (b) the Subligurian Unit; and (c) the greater part of the Ligurian Units. In this view the tectonic contact separating the Ophiolitic Unit from the Tuscan Nappe (Calcare Cavernoso Fm) and the Verrucano Group coincides with an extensional detachment (Fig. 8) which affected a previously stacked tectonic pile. Consequently, most of the thrusts developed during orogenic building were reactivated as extensional detachments. These latter accommodated within top-to-the-East brittle–ductile shear zones (see the next paragraph for the kinematic analyses) up to 10 m in thickness, characterised by damaged rocks and cataclasites showing different features: (a) vacuolar calcareous breccias (Calcare Cavernoso Fm); (b) calcareous breccias with dark, millimetre- to centimetre-sized dolostone clasts; (c) silicised breccias with associated mixed sulphides (stibnite, cinnabar, realgar and orpiment), indicating widespread hydrothermal circulation; (d) calcareous breccias with centimetre and decimetre-sized phyllite clasts. The silicised cataclastic rocks are only distributed in the eastern side of Mt. Leoni attesting to the significant permeability of this horizon; (e) foliated clay gouge in the phyllites and clayey rocks; (f) carbonate cataclasites and ultracataclasites.

The extensional detachments, as well as the DE_1, DE_2 and DE_3 structures, were faulted and tilted by high-angle normal faults that show mostly NNE–SSW trending and displacements of tens of metres (Fig. 6A).

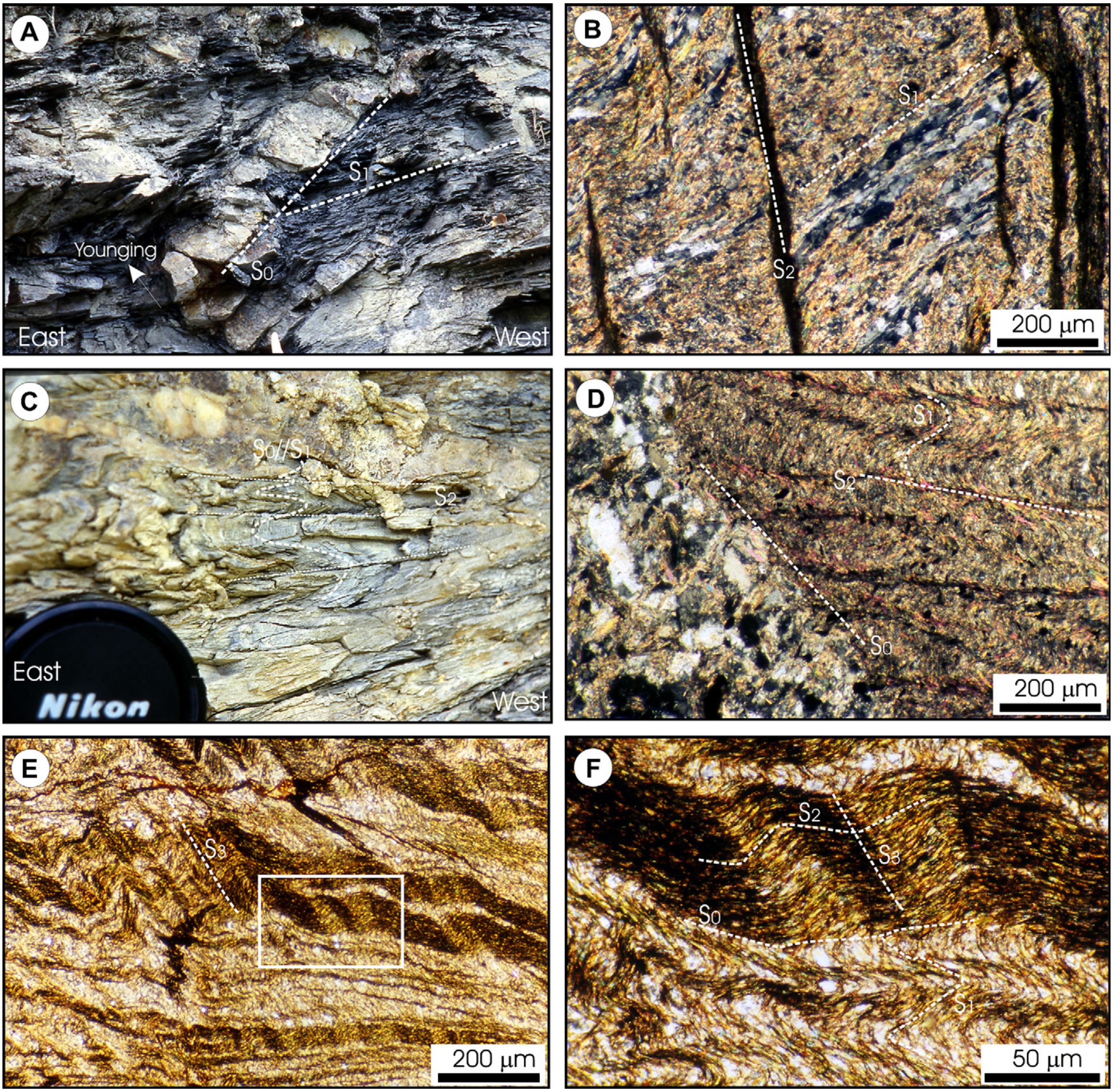

Fig. 7. (A) Bedding/foliation (S_1) relationships at the outcrop scale. (B) Microphotographs (plane-polarised light) of samples affected by S_1 and S_2 tectonic foliations; S_1 consists of a continuous foliation (*sensu* Passchier and Trouw, 1996) showing: (i) strongly flattened quartz grains aligned on the foliation surface; (ii) aligned oxides and opaques; and (iii) preferred orientation of white mica crystals. (C) Relationships between S_1 and S_2 at the outcrop scale. (D) Microphotograph (plane-polarised light) of a sample showing $S_0/S_1/S_2$ relationships. S_2 is only developed in the metapelite and shows rough and smooth crenulation-cleavage (*sensu* Passchier and Trouw, 1996). (E) Microphotograph (plane-polarised light) of a metapelite showing the relationships between S_1, S_3 and S_3 tectonic foliations. S_3 developed only in the phyllosilicate layers and is defined as smooth crenulation-cleavage (*sensu* Passchier and Trouw, 1996). (F) Detail of E.

4. Development mechanism of the metamorphic-units lateral segmentation

4.1. LANFs kinematics

Kinematic analyses (Fig. 9) have been carried out in selected key areas (Fig. 6A) useful for reconstructing the sense of shear of the main detachments. These latter consist of brittle–ductile shear zones separating brecciated-rock volumes with differentiated tectono-metamorphic characteristics. The shear zones commonly detached on the contact between the Triassic evaporites (the base of the Tuscan Nappe, presently the Calcare Cavernoso Fm, TN_1 in Fig. 2) and the Triassic phyllites and calcschists (MRU_3 in Fig. 2), as well as on the

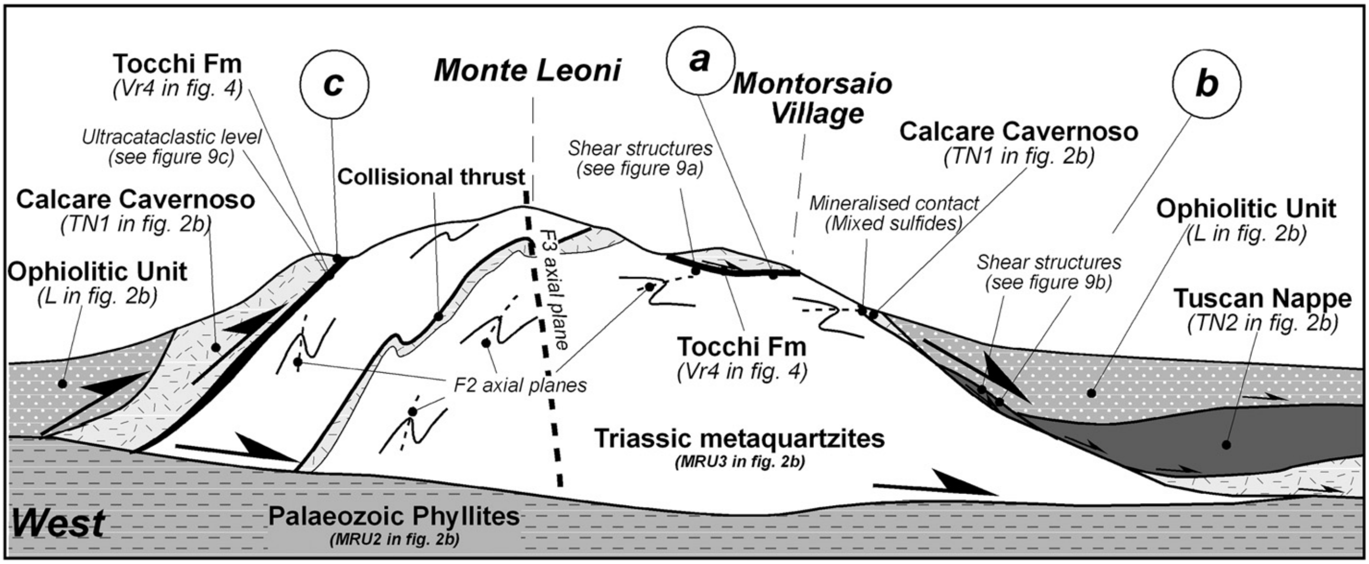

Fig. 8. Cartoon (not to scale) showing the structure of the Middle Tuscan Ridge in the Mt. Leoni area. Note the divergent tectonic contacts separating the sedimentary units from the metamorphic rocks. In the eastern side of Mt. Leoni, a very important tectonic elision can be recognised. Points a, b and c are discussed in the text and located in the geological map given in Fig. 6A.

highly deformed clayey horizons within the Tuscan Nappe, discontinuously sandwiched between the Ligurian Units and the metamorphic rocks. The pelagic-turbiditic Tuscan Nappe succession, cropping out in the eastern side of Mt. Leoni area (Fig. 6A), is characterised by disrupted rocks discontinuously exposed (Figs. 6B and 8). The extensional structures occur distributed from outcrop to map scale.

The sites where the structural analyses have been performed (points a, b and c indicated in Fig. 6A) are aligned along a transect across the Mt. Leoni area, close to the traces of the geological sections 2 and 5 given in Fig. 6B.

Extensional shear zones deformed the oldest rock fabric, and post-dated the development of the F_2 folds. The shear zone strike varies between N10 and N40° and dip from 10° to 30° toward ESE in the eastern side of the Mt. Leoni, and towards WNW in the western side. At the outcrop scale, different kinematic indicators have been recognised mainly within the shear zones or close to them, where the shear stress was concentrated. Mechanic striae measured on shear planes mainly trend from N80° to N120° and plunge about 10° to 40° mainly toward the ESE, indicating a predominant WNW–ESE extension (Fig. 10A–C). Other kinematic indicators developed in different lithotypes consist of decimetre to metre-scale Riedel shear planes, decimetre-scale S–C structures, and centimetre- to decimetre-scale asymmetrical and detached folds (Fig. 9). R-Riedel shear planes (Fig. 9A) thinned the metasandstones and the calcschists (Tocchi Fm at the A point shown in Fig. 6a). R-Riedel surfaces were connected to R_1 shear fractures. They are characterised by mechanic striae N110° oriented, mainly recognised on the R-surfaces (Fig. 10).

S–C structures have been mainly observed within the Tuscan Nappe clayey rocks exposed in the eastern side of the Mt. Leoni (Fig. 6A). S-planes are NNE–SSW striking and deep toward West (Fig. 9B). C-planes are characterised by a millimetre thick clay gouge developed along the slip surfaces. They show NNE–SSW striking and deep towards east. The intersection between S- and C-planes define lineations perpendicular to the shear direction, which is N115° in average as indicated by mechanic striae on the C-planes (Fig. 10D). The angular relationships between S- and C-planes indicate the top-to-the-East sense of shear (Fig. 9B). Decimetre-scale asymmetrical and detached folds mainly developed within the carbonate breccias. They exhibit axial lines N20° striking and ESE vergence (Fig. 9C).

On the whole, kinematic indicators suggest a common top-to-the-ESE sense of shear of the main extensional detachments occurring both in the western and eastern sides of the Mt. Leoni (Figs. 8 and 9). Note that in the western side of Mt. Leoni (point a in Fig. 6A) the shear structures show a steeply-dipping attitude (Fig. 9C) but they maintain the top-to-the ESE sense of shear.

4.2. Geometric setting and dynamic considerations

The structure of Monte Leoni, coupled with the extensional-structural kinematics and the data from the CROP03 and CROP18 seismic profiles, are indicative of three main points:

(1) the uppermost extensional detachment separating the metamorphic units from the overlying sedimentary units, mainly accommodated at the base or within the Calcare Cavernoso Fm;
(2) this detachment was folded by a map-scale F_3 antiform (Fig. 8);
(3) the eastern side of the Mt. Leoni area corresponds to an elisional east-dipping extensional ramp cross-cutting the metamorphic rocks (Fig. 8).

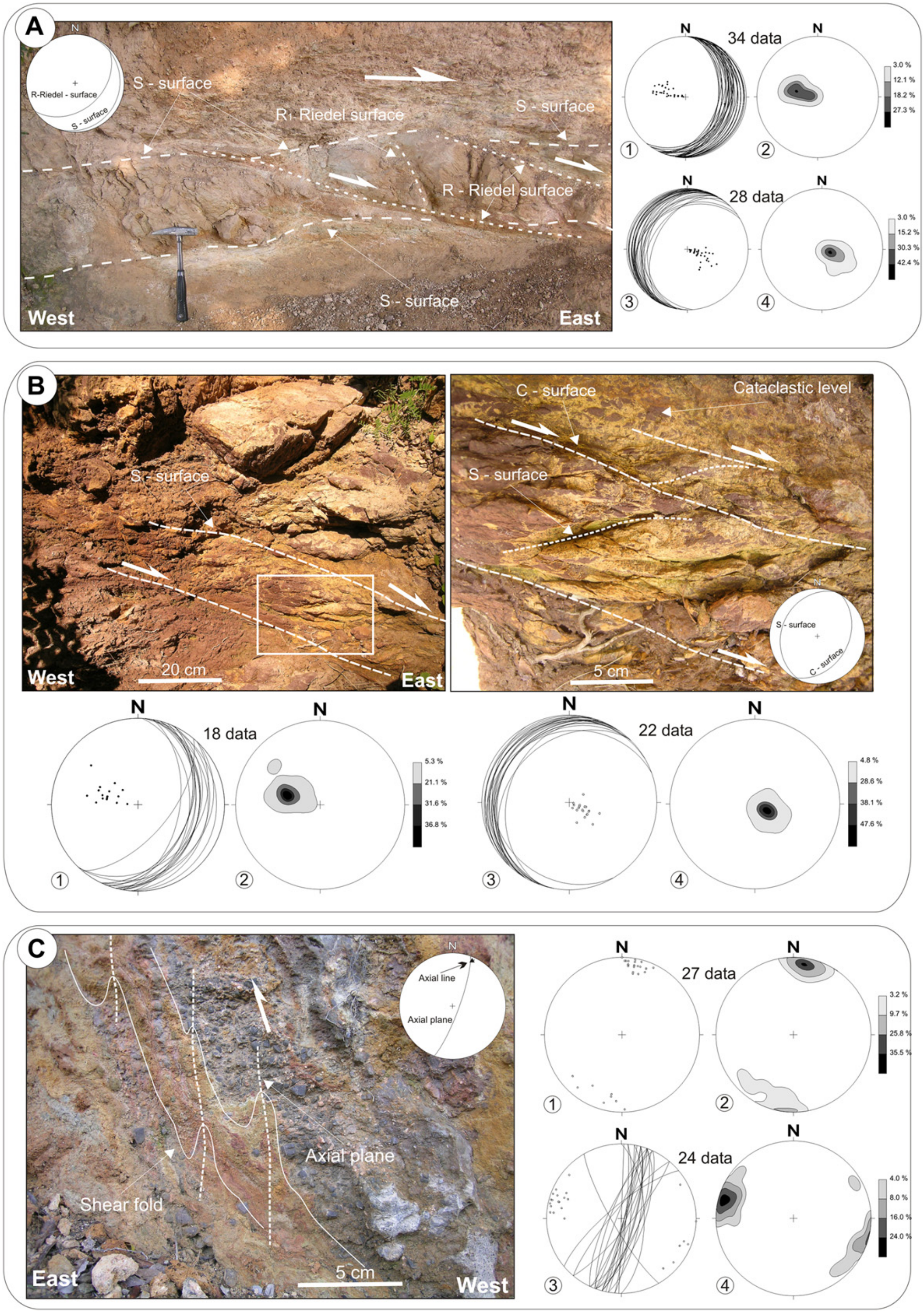

Fig. 9. Structural data (lower hemisphere, Schmidt diagram) carried out along the extensional detachment separating the Tuscan Nappe succession from the metamorphic rocks. The locations of the analysed outcrops are given in Fig. 6A. (A) Shear structures indicating top-to-the East shear which affected the calcschists and phyllites of the Tocchi Fm Stereoplots indicate: (1) cyclographic traces and poles of the C_1 surfaces; (2) relative contouring; (3) cyclographic traces and poles of the S surfaces; (4) relative contouring. (B) Shear structures indicating top-to-the East shear which affected the pelagic−turbiditic Tuscan Nappe succession; stereoplot indicates: (1) cyclographic traces and poles of the R_1-surfaces; (2) relative contouring; (3) cyclographic traces and poles of the R-surfaces; (4) relative contouring. (C) Rotated east-facing shear folds (see the text for discussion) within the cataclasite separating the Tocchi Fm from the Calcare Cavernoso Fm Stereoplots indicate: (1) axes of the folds; (2) relative contouring; (3) cyclographic traces and relative poles of the axial planes; (4) relative contouring.

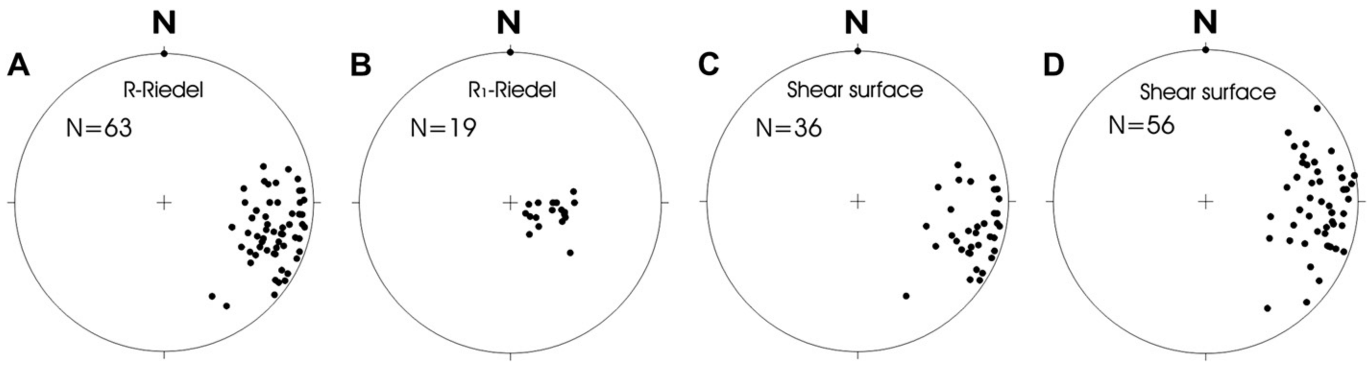

Fig. 10. Projection of mechanic striae (Schmidt diagram, lower hemisphere) recognised along the indicated surfaces. Diagrams A, B and C are from point A indicated in Fig. 6; diagram D is from point B indicated in Fig. 6.

In this view, the eastern extensional ramp could connect the uppermost detachment with an unexposed lowermost detachment sited within the Palaeozoic phyllites. The occurrence of this detachment is necessary because also in the western side of the Middle Tuscan Ridge the Ligurian Units directly overlie on the Palaeozoic phyllites. Additionally, similar features have been described for the subsurface of the Larderello geothermal area (Baldi et al., 1994; Dallmeyer and Liotta, 1998). In this view, the Middle Tuscan Ridge is the outcropping part of an extensional horse delimited by two detachments respectively accommodated within and/or at the base of the Triassic evaporites (presently Calcare Cavernoso Fm) and at the top of the Palaeozoic phyllites as schematically shown in Fig. 11. These detachments were connected through east-dipping extensional ramps crosscutting, at high angles, the metasiliciclastic succession of the Verrucano Group (more competent horizon) comprised between the two detachments. The eastern extensional ramp (footwall ramp) is exposed in the eastern side of Mt. Leoni where the Ophiolitic Unit (the highest tectonic unit of the Ligurian pile) overlie the Triassic metasiliciclastics (Figs. 8 and 11B). The westernmost extensional ramp (hangingwall ramp) is not exposed because it was rotated during faulting. This is suggested by the subvertical attitude of: (a) the F_2 axial planes; (b) S_2 tectonic foliation; (c) the kinematic indicators recognised within the top-most shear zone (point c in Figs. 6A and 11B).

4.3. Chronological consideration

The radiometric age of the mineralogical assemblage related to the retrograde metamorphism (greenschist facies) developed during F_2 folding has been determined as 11-14 Ma in

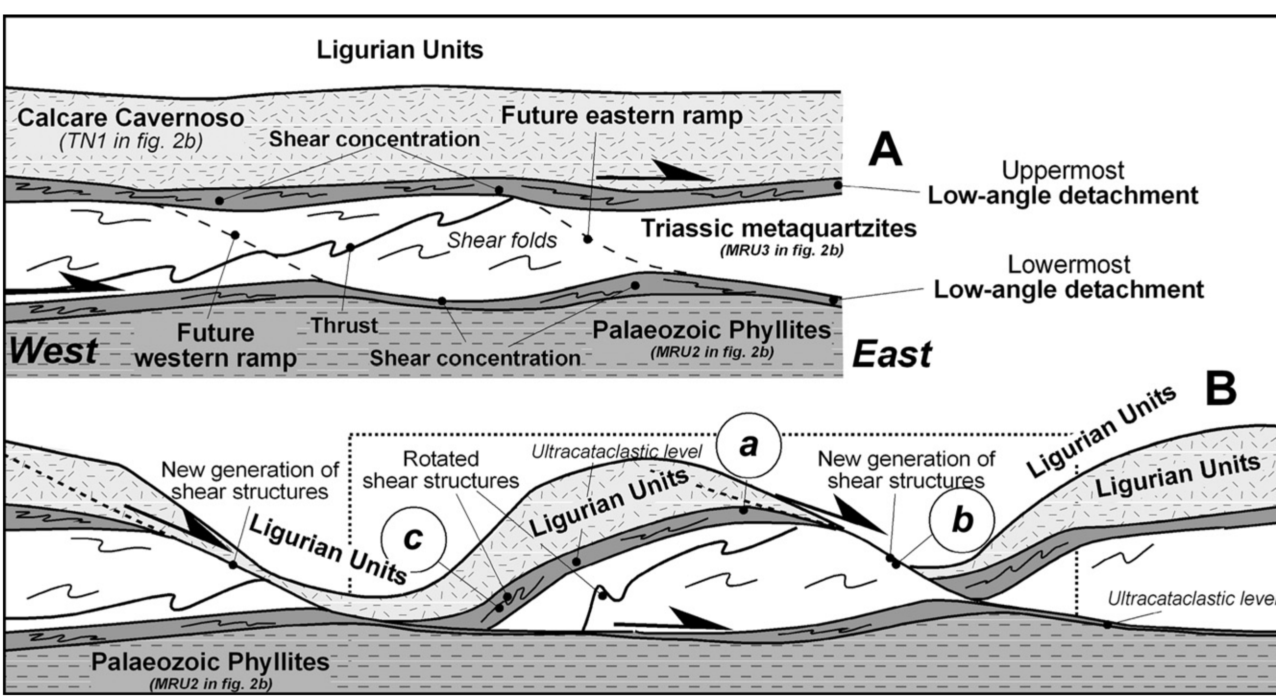

Fig. 11. A,B. Idealised cartoon showing the evolutionary model for the asymmetrical segmentation and related structures which affected the metamorphic succession, as reconstructed for the Mt. Leoni area. Letters (a), (b) and (c) indicate the location of the kinematic indicators given in Fig. 6A whose stereographic diagrams are shown in Figs. 9 and 10.

the Alpi Apuane area (K-Ar and $^{40}Ar/^{39}Ar$ in Giglia and Radicati di Brozolo, 1970; Kligfield et al., 1986), 16 Ma in the Mt. Argentario area (Brunet et al., 2000), and 19.68 Ma (Isola d'Elba, $^{40}Ar/^{39}Ar$ in Deino et al., 1992). No radiometric data are available for the Mt. Leoni area, even if the age inferred for Mt. Argentario (16 Ma) can be considered indicative also for the Mt. Leoni area, taking into account that this area corresponds to the northern prolongation of the Mt. Argentario promontory. Nevertheless, 11 Ma is the younger age related to the F_2 folding which can be considered as a regional value (Carmignani et al., 2001).

Since the F_2 folds passively rotated during the crustal lateral segmentation (Fig. 11B), we can consider the development of the crustal detachments to have occurred later. In the Elba Island the intrusion of the Monte Capanne granodiorite, referred to 6–8 Ma, has been demonstrated to accompany the detachments activity (Pertusati et al., 1993). Additionally, the end of the segmentation coincides with the beginning of formation of the high-angle normal faults which can be referred, on the basis of regional considerations, to the Early Pliocene (Brogi and Liotta, 2006). In fact, in the Mt. Leoni area, the high-angle normal faults dissected the metamorphic-units-boudin and their related detachments (Fig. 6), as well as the Miocene (Tortonian–Messinian) sediments occurring in the eastern side of Monte Leoni. With this in mind, the age of the lateral segmentation can be referred, at least for the study area, to the Early Tortonian–Messinian time span.

5. Discussion

This is focused on three main points: (a) lateral segmentation of the Northern Apennines multilayered crust; (b) the development of the lateral segmentation at different crustal levels during the downwards migration of the brittle/ductile transition, exhumation of the metamorphic rocks and the meaning of the F_2 folds; (c) the scientific debate concerning the Neogene tectonic regime affecting the inner zone of the Northern Apennines;

The multilayered architecture of the hinterland Northern Apennines crust played a fundamental role during extension. In fact, the metamorphic units were involved in multiple thrusts during the orogenic building. This implies that the Triassic evaporites and the Palaeozoic phyllites resulted tectonically alternated with more competent horizons. In this view, the weak horizons occurring at different depths in the tectonic pile accommodated extensional detachments connected by East-dipping extensional ramps during extension (Fig. 11B). This evolution produced a multilayered extensional duplex system which gave rise to extensional horses (Gibbs, 1984), preserving the records of the original tectonic pile, as it is the case for the Mt. Leoni area. This geological evolution is very important for palaeogeographical and stratigraphical studies because the easternmost extensional horses correspond to the highest tectonic units in the tectonic pile, and thus consist of the westernmost palaeogeographical sectors, according to the general eastwards vergence and emplacement of the Northern Apennines tectonic units (Fig. 12).

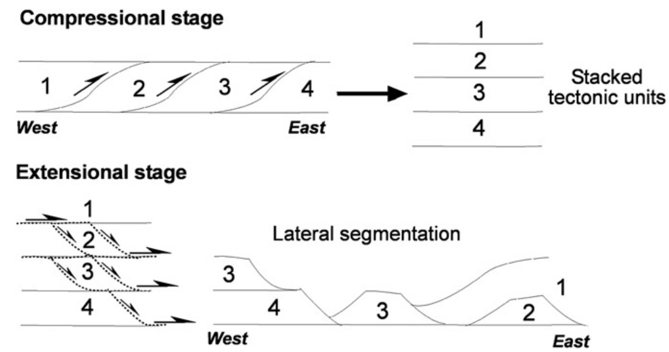

Fig. 12. Cartoon showing the idealised evolution of the lateral segmentation affecting a multilayered tectonic pile derived from the eastward stacking. Note that the eastward asymmetrical segmentation produces extensional horses. The easternmost extensional horse corresponds to the uppermost unit of the tectonic pile, and thus coincides with the westernmost palaeogeographical domain. In this view, the stratigraphic units occurring within the easternmost extensional horses derive from the westernmost palaeogeographical domains.

The extensional structures reconstructed in Mt. Leoni show very similar features with respect to those described for the shallower structural levels as described in the Larderello (Brogi et al., 2005c) and Monte Amiata (Brogi, 2004a, 2004b) geothermal areas, and surroundings. The Tuscan Nappe, the deepest non-metamorphic tectonic unit, was sandwiched by top-to-the-East extensional detachments that accommodated at the base of the Ligurian Units (the uppermost detachment) and within the Triassic evaporites (the lowermost detachment) (see Brogi, 2004c, Fig. 9). Secondary detachments also occurred within, or at the base of the clayey and turbiditic Tuscan Nappe succession (TN_3 in Fig. 2). As described by Decandia et al. (1993) and Brogi et al. (2005a,b) the extensional detachments were connected to conjugate extensional ramps crossing at high angles the Jurassic carbonate succession (TN_2 in Fig. 2). This gave rise to a widespread regional segmentation of the Tuscan Nappe (Brogi et al., 2005a). Rollover folds caused the passive rotation of the uppermost detachment, as documented in the western side of the Tuscan Nappe segmented bodies. This extensional evolution is very similar to that which affected the metamorphic successions in the Mt. Leoni. Consequently, the lateral segmentation of both the Tuscan Nappe and the metamorphic successions can be ascribed to extensional detachments accommodated at different levels within the Northern Apennines tectonic pile (Fig. 13). Nevertheless, different time intervals have been determined for the lateral segmentation of the Tuscan Nappe and metamorphic units, referred to the Langhian–Early Tortonian (Brogi et al., 2005a; Brogi and Liotta, 2006) and Late Tortonian–Messinian, respectively. Additionally, the age of the Tuscan Nappe segmentation corresponds to the age of F_2 folding in the metamorphic rocks (16–11 Ma for southern Tuscany, Kligfield et al., 1986; Brunet et al., 2000). This suggests the coexistence of extensional detachments and folds affecting the non-metamorphic and metamorphic

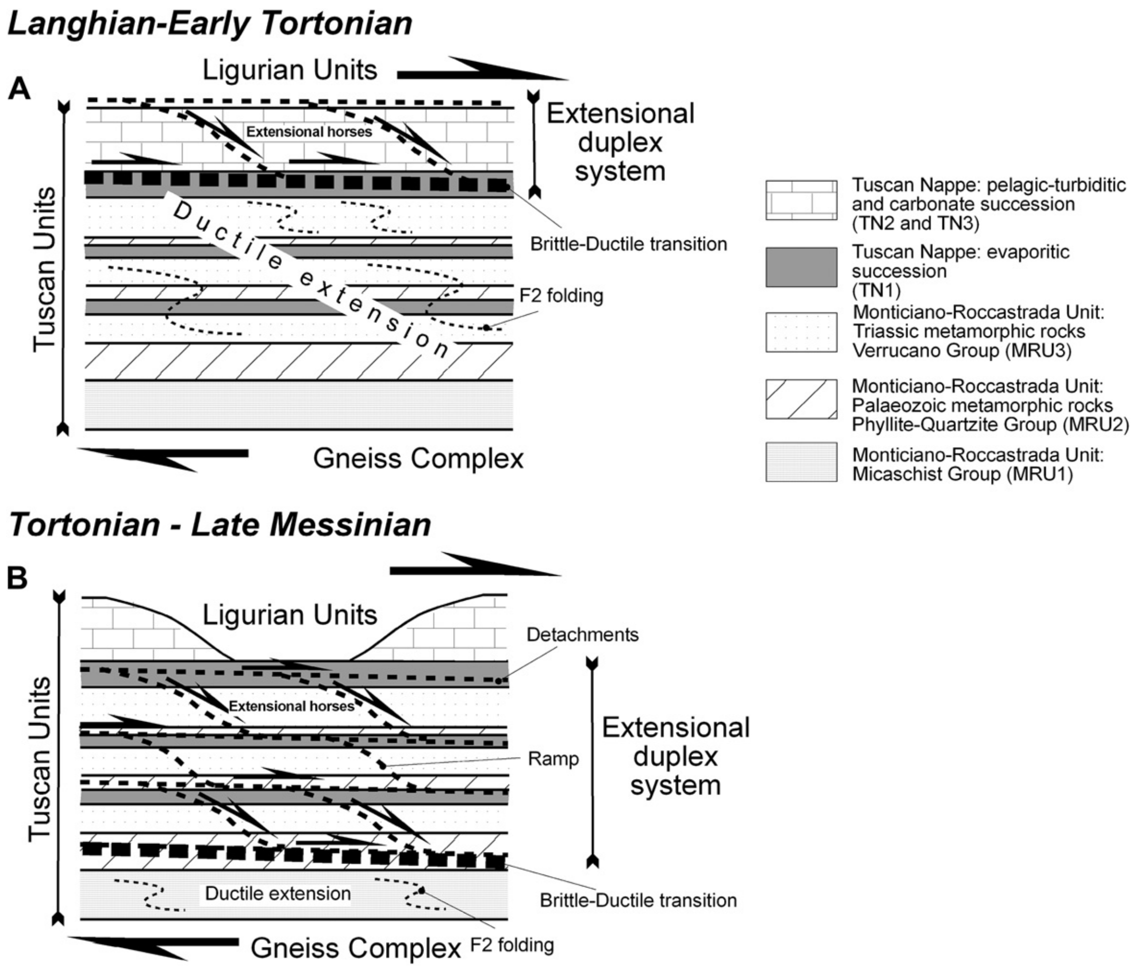

Fig. 13. Cartoon showing the possible evolution through time of the extensional structures which affected the multilayered tectonic pile of the Northern Apennines after the collisional stage. The Ligurian Units are located at the top. During the Langhian–Early Tortonian (A) the brittle/ductile transition corresponded with the Late Triassic evaporites separating rocks affected by HP-LT metamorphism from rocks unaffected by metamorphism. These latter were dissected by staircase normal faults which defined an extensional duplex system. At the same time, the metamorphic units were affected by ductile shearing mainly resulting in asymmetrical folding (F_2 folds in the text). During the Tortonian–Late Messinian (B) the brittle/ductile transition migrated downwards and was located at a deeper level. Staircase normal faults defining multilayered extensional horses dissected the previously developed shear folds, as observed in the Mt. Leoni area.

units, respectively. In this view, two alternative hypotheses can be proposed:

(a) F_2 folds and related greenschist facies retrograde metamorphism developed below the brittle/ductile transition, during the top-to-the-East shearing which produced the lateral segmentation of the Tuscan Nappe at highest structural levels;
(b) F_2 folds developed during contractional tectonics that affected the deepest levels of the orogenic pile contemporaneously with the orogen uplift and related extensional collapse of the highest tectonic units (i.e. Tuscan Nappe).

The interpretation of the tectonic regime in which the F_2 folds took place is still debated. For instance, in the Alpi Apuane region (Fig. 1A) the F_2 folds affecting the metamorphic successions have been interpreted as attributed to extensional (Carmignani and Kligfield, 1990; Carmignani et al., 1994; Molli et al., 2000) or contractional tectonic setting (Carosi et al., 2002a,b, 2004) during exhumation of the Apuan Alps Core complex. Furthermore, concerning the Middle Tuscan Ridge cropping out in southern Tuscany, the F_2 folds have been considered as extensional shear structures (Elter and Sandrelli, 1994; Campetti et al., 1999; Liotta, 2002). My contribution for this debate is not crucial; nevertheless, several considerations can be discussed: I have deduced that the F_2 folds predate the LANFs development. Additionally, F_2 fold vergence and facing (*sensu* Shackleton, 1957; Bell, 1981) as well as F_2 axial trend are coherent with the sense of shear of the LANFs (confront the stereographic diagrams given in Figs. 6B and 9). With this in mind, the F_2 folds could account for extensional shear structures developed below the Triassic evaporites coinciding, at that time, with the brittle/ductile transition (Carmignani and Kligfield, 1990) (Fig. 13A). This agrees with Baldi et al. (1994) and Dallmeyer and Liotta (1998) who hypothesised that, for the Larderello area, the lateral segmentation of the Tuscan Nappe and metamorphic units developed at different times, contemporaneously with the downward migration of the brittle-ductile transition. They hypothesised that during the segmentation of the Tuscan Nappe, the brittle/ductile transition was located within the

Triassic evaporites (Carmignani and Kligfield, 1990), and within the Palaeozoic phyllites during the segmentation of the metamorphic units (Dallmeyer and Liotta 1995, 1998), suggesting its progressive downwards migration (Fig. 13B) due to the uplift exhumation. If this is true, then the F_2 folds are extensional structures developed within extensional shear zones which accompanied the exhumation of deep crustal levels, coupled with the retrograde synkinematic M_2 metamorphism (Franceschelli et al., 1986).

Exhumation of deep crustal levels related to the activity of extensional detachments has been described for several orogens around the world (Lister et al., 1984; Lister and Davis, 1989; García-Dueñas et al., 1992; Jolivet et al., 1994,2003; Martínez-Martínez et al., 1997; Caby et al., 2001; Platt et al., 2003; Booth-Rea et al., 2003, 2004). In particular, similar extensional features, as described for the Mt. Leoni area, have been documented in the Edough metamorphic core complex (Megrebidian orogen, eastern Algeria) and in the Alpujarride and Malaguide complexes (northeastern Betics, Spain), representing two polymetamorphic complexes exhumed during the Miocene extension which affected the Mediterranean Region (Mantovani et al., 1995; Doglioni et al., 1999a; Faccenna et al., 2004; Michard, 2006).

These metamorphic complexes were exhumed through tectonic denudation caused by superposed extensional systems influenced by rheological heterogeneities occurring within the tectonic pile, similarly with the Mt. Leoni area. Furthermore the complete exhumation of the metamorphic units was related to the later extensional structures, which tilted the previously developed detachments and exhumed them in the core of km-scale elongated extensional domes.

The extensional geological framework affecting the southern Tuscany has been confirmed by numerous field and laboratory studies, and supported by geological interpretations of the CROP03 (Decandia et al., 1998; Liotta et al., 1998; Lavecchia et al., 2004; Accaino et al., 2006) and CROP18 (Accaino et al., 2005; Brogi et al., 2005a, 2005b; Tinivella et al., 2005) deep reflection seismic profiles. Nevertheless, Finetti et al. (2001); Bonini and Sani (2002); and references therein) and Finetti (2006) stated that compression better that extension can explain the Neogene-Quaternary geological evolution of the hinterland Northern Apennines. In their point of view, Finetti et al. (2001) have proposed an alternative model to explain the lateral segmentation of the Tuscan Nappe. These authors proposed that Miocene-Pleistocene out-of-sequence thrusting (Boccaletti et al., 1999; Bonini, 1999; Bonini and Sani, 2002) could explain the tectonic delamination within the tectonic pile. Their hypothesis has been discussed in several recent papers mainly dealing with the structural setting of the non-metamorphic tectonic units (Brogi et al., 2005a,b; Brogi, 2006b; Brogi and Liotta, 2006). Nevertheless, in the Finetti et al. (2001) hypothesis only the Tuscan Nappe segmentation can be explained by the out-of-sequence thrusting, while deeper tectonic metamorphic units are not considered. From their schematic model (see Fig. 5 in Finetti et al., 2001) we deduce that the metamorphic units must be affected by thickening only, contrasting with the data presented in this paper and the stratigraphic logs of the deep geothermal boreholes drilled in the Larderello-Travale area (Fig. 3). Thickening of the metamorphic units has been largely documented by borehole logs (Pandeli et al., 1991; Bertini et al., 1994) and by field data (Costantini et al., 1988; Liotta, 2002; Lazzarotto et al., 2003). Additionally, thickening has been also proved by this study. Nevertheless, radiometric data indicate that thrusting and related contractional structures (DE_1 in Carmignani et al., 2001) developed during the Oligocene–Early Miocene (Kligfield et al., 1986; Brunet et al., 2000), and thus during the collisional event, before the activity of the extensional detachments which produced the lateral segmentation of non-metamorphic and metamorphic units, started from the Middle Miocene. Presently, the Oligocene–Early Miocene thrusts consist of relict structures within the extensional horses, as described for Mt. Leoni and geothermal areas of Tuscany (Baldi et al., 1994; Brogi, 2004a,b; Brogi et al., 2005c). In conclusion, the hypothesis that thinning and lateral segmentation of the metamorphic units in the hinterland of the Northern Apennines was related to the Pliocene-Pleistocene out-of sequence thrusting cannot be accepted.

6. Concluding remarks

The main result reported in this paper allows to define the mechanism that produced the uplift and exhumation of the Middle Tuscan Ridge in the extensional framework of the hinterland Northern Apennines. In fact, it has been demonstrated that the imbricated metamorphic units exposed in the Middle Tuscan Ridge, underwent protracted extension from the Middle Miocene to the Pliocene. Extension produced two superposed systems of normal faults that accommodated the thinning of the original tectonic pile and produced the uplift and their exhumation. During faulting, strain concentrated within less competent stratigraphic levels in the tectonic pile, such as the weaker Palaeozoic phyllites and Late Triassic evaporites, leading to the development of several extensional detachments linked to extensional ramps crosscutting the more competent level represented by the stronger siliciclastic rocks. Presently, the Mt. Leoni area consists of an elongated extensional dome mainly made up of metasiliciclastic rocks, sandwiched by extensional detachments. The uppermost detachment, discontinuously exposed at the top of the metamorphic units, was folded by F_3 folds. Folding was produced by passive rotation (rollover) of the hangingwall which took place in the western side of the extensional horse during its progressive lateral segmentation from the east-dipping extensional ramps. This extensional evolution affecting the metamorphic units and contributing to their exhumation is very similar to that described for the shallowest non-metamorphic units (Tuscan Nappe) in terms of geometry and kinematics. This indicates that extension in the hinterland of the Northern Apennines was a continuous process which interested the whole overthickened crust. Accordingly, the extension was a regional process and not the consequence of the collapse of the shallow units during orogenic building.

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