Pliocene crustal shortening on the Tyrrhenian side of the northern Apennines: evidence from the Gavorrano antiform (southern Tuscany, Italy)

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Abstract

The northern Tyrrhenian Sea and the inner northern Apennines are classically regarded as a late Miocene-Pleistocene back-arc system developed as a consequence of slab roll-back along active subduction zones. We present new geological and structural data on the Gavorrano antiform, a key sector of the inner northern Apennines. Lying close to the northern Tyrrhenian Sea, it provides clear evidence of Pliocene shortening deformation and magma emplacement. The orientation of σ_1 (N50°E - N80°E) derived by fault slip data inversion is consistent with a general ENE –WSW shortening direction. Furthermore, this ENE-trending orientation of σ_1 is compatible with the compressive deformation recorded in coeval sedimentary basins. On this basis we suggest that the inner northern Apennines were affected by crustal shortening during the Pliocene. This scenario matches well geophysical data suggesting that since the Late Messinian (6 – 5 Ma) subduction rollback and back-arc extension strongly decreased in the northern Tyrrhenian Sea, while they continued as active processes in the southern Tyrrhenian Sea.

Key words: crustal shortening, Alpine tectonics, Pliocene, northern Apennines

The Mediterranean region is an area of Cenozoic continental convergence in which Alpine thrust belts surround back-arc basins developed as a consequence of slab roll-back along active subduction zones. The Balearic, Alboran and southern Tyrrhenian basins are the best examples of back-arc systems in hinterland portions of Alpine chains, in which extension and growth of new oceanic crust were coeval with shortening at the front of the chain (Faccenna *et al.*, 2004, Platt 2007). The Tyrrhenian Sea at the rear of the Apennine chain opened because of the eastward roll-back of the Adria Plate, which had been subducting westward beneath the European margin (Malinverno & Ryan 1986; Royden *et al.* 1987; Rosenbaum & Lister 2004). The opening of the Tyrrhenian Sea started in the Late Miocene and culminated with seafloor spreading in the south Tyrrhenian during the Pliocene – Pleistocene (Nicolosi *et al.*, 2006; Rosenbaum & Lister 2004).

In this scenario, the northern Tyrrhenian Sea basin and the inner northern Apennines are classically regarded as a late Miocene-Pleistocene back-arc system characterised by crustal extension and acidic magmatism coeval with shortening at the front of the chain (Carmignani *et al.*, 1994; Jolivet *et al.*, 1998). In the northern Tyrrhenian Sea, the occurrence of asthenospheric mantle at a depth of 25 km testifies to lithosphere thinning, which is ascribed to slab roll back (Della Vedova *et al.* 1991). Asthenospheric upwelling beneath the Late Miocene chain produced a regional-scale positive thermal anomaly (Baldi *et al.* 1994) which triggered the development of Late Miocene - Quaternary magmatism (Fig. 1), represented by intrusive and volcanic rocks distributed over a wide area between the northern Tyrrhenian Sea and the inner northern Apennines (Innocenti *et al.* 1992).

According to Carmignani *et al*. (1994) and Decandia *et al.* (1998), proof of Late Miocene –Pliocene crustal extension in the inner northern Apennines is provided by low- and high-angle normal faults that controlled the development of sedimentary basins (Carmignani *et al.* 1994; Keller *et al.* 1994; Brogi *et al.* 2003) and the emplacement of Neogene intrusions

(Acocella & Rossetti 2002), whose emplacement ages indicate an eastward migration of magmatism from the Tyrrhenian Sea (6–7 Ma) inland (4–0.5 Ma).

In contrast, there are several examples of compressive structures (folds and faults) in Upper Miocene – Pleistocene sedimentary basins (e.g. Meletti *et al.* 1995; Boccaletti *et al.* 1997; Boccaletti & Sani 1998). These structures have been interpreted as evidence that crustal shortening was still active in the inner northern Apennines during the opening of the northern Tyrrhenian Sea. Furthermore, recent seismic anisotropy data question the role of subduction in the northern Tyrrhenian sea, indicating the presence of true back-arc basins only in the southern Tyrrhenian sea (Plomerova *et al.*, 2006; Levin *et al.*, 2007; Salimbeni *et al.*, 2007).

This paper aims to unravel the nature of Pliocene tectonics in the inner northern Apennines. New data and interpretations arise from the analysis of the Gavorrano antiform (Fig. 2) near the Tyrrhenian coast of southern Tuscany. In this structure, a complete sequence of the nappe pile resulting from Miocene deformation is well exposed together with Pliocene intrusive rocks and Upper Miocene – Upper Pliocene - Pleistocene sedimentary deposits. By combining new data with published findings, we develop a coherent framework for Pliocene shortening in the northern Apennines.

Geological setting of northern Apennines in southern Tuscany

The northern Apennines (Fig. 1), a fold-thrust belt of the Alpine orogen, resulted from the Cenozoic continental collision between the European margin (Corsica-Sardinia microplate) and the Adria Plate after closure of the Tethyan Ocean (Boccaletti *et al.* 1971). In the inner northern Apennines (Tuscan domain), the fold belt consists of a nappe stack of Meso-Cenozoic sedimentary and metamorphic tectonic units derived from an oceanic domain (Ligurian Units) and the Adria continental margin (Tuscan Nappe and Tuscan Metamorphic Complex). The nappe stack was produced by Late Oligocene – Early-Middle Miocene deformation, during which the tectonic units experienced polyphase deformation with the development of eastward-facing fold and thrust structures.

Southern Tuscany is a portion of the inner northern Apennines located south of Monti Pisani and extending southward to the Monte Argentario promontory; the northern Tyrrhenian Sea borders the area to the west (Fig. 1). In this region the Apennine nappe stack consists of two structural and metamorphic levels (Fig. 1). The upper level is made up of sedimentary or very low-grade metamorphic thrust sheets belonging to Ligurian Units and the Tuscan Nappe. The lower level is the Tuscan Metamorphic Complex, which is represented by low-grade metamorphic rocks derived from reworked Paleozoic basement and a Permian–Triassic sedimentary sequence (Musumeci *et al.* 2002). The Tuscan Metamorphic Complex, which experienced alpine deformation under Barrovian (MP/MT) metamorphic conditions (Franceschelli *et al.* 1986), crops out along the Mid-Tuscan Ridge (Fig. 1) but more widely occurs as units buried at depths below 2 km in the Larderello geothermal field, where it has been penetrated by deep geothermal boreholes. The earlier nappe stacking was followed in the Middle Miocene (Langhian – Serravallian) by renewed deformation, which led to the tectonic omission of large part of the Tuscan Nappe stratigraphic sequence and the anomalous superpositioning of Ligurian Units directly onto the basal (Triassic) formation of the Tuscan Nappe or, in some instances, directly onto the metamorphic rocks of the Tuscan Metamorphic Complex. This structural setting (the so-called “Serie ridotta”; Giannini *et al.* 1971; Bertini *et al.* 1994) has been interpreted as the result of either Middle Miocene extension of the chain (Carmignani *et al.* 1994; Jolivet *et al.* 1998) or crustal shortening with the development of an out-of-sequence thrust at the base of the Ligurian Units (Finetti *et al.* 2001). At the scale of the whole northern Apennines, Middle Miocene deformation was possibly responsible for formation of the Alpi Apuane core complex (Carmignani & Kligfield, 1990). Alternatively, the Alpi Apuane structure was produced by out-of sequence thrusts (Storti, 1995; Boccaletti & Sani, 1998).

Whatever the process, as a result of Middle Miocene deformation the sedimentary sequence of the Tuscan Nappe is often largely omitted in southern Tuscany; it is almost completely preserved in only a few areas. These correspond to the cores of km-scale N- and NNW-trending antiforms that are best exemplified by the Campiglia and Gavorrano antiforms along the Tyrrhenian coast and by the Cornate – Travale antiforms in the Larderello geothermal field (Fig. 1). The tectonic units are covered by Neogene (Late Miocene – Pleistocene) sediments that were deposited within hinterland sedimentary basins filled by continental (conglomerates) and shallow marine (evaporites, limestones) deposits.

In the Pliocene, intrusive and volcanic rocks (Innocenti *et al.* 1992) were emplaced in the nappe stack. The latter are rhyolites and trachytes, which are mainly exposed on the Mt. Amiata volcano. Intrusive rocks crop out as small bodies in the Campiglia and Gavorrano areas, or as shallow (3 – 5 km) buried intrusions in the Larderello geothermal field (Bertini *et al.* 2006; Dini *et al.* 2004; Gianelli *et al.* 1997). Granite emplacement within the Tuscan Metamorphic Complex and Tuscan Nappe sequences led to the development of LP/HT contact aureoles with hydrothermal and ore deposits (Carella *et al.* 2000; Musumeci *et al.* 2002). The age of magmatism in southern Tuscany is bracketed between 4.4 Ma (Castel di Pietra and Gavorrano Granite; Serri *et al.* 1993) and 02–0.3 Ma (Mt. Amiata trachytic dacite; Savelli 2000).

Geological setting of the Gavorrano structure

The Gavorrano antiform lies south of the Larderello geothermal field and close to the Tyrrhenian coast (Fig. 1). It is a NNW-trending antiform in which a complete sequence of tectonic units (from the Tuscan Metamorphic Complex to the Tuscan Nappe and Ligurian Unit) as well as Pliocene intrusive rocks crop out (Fig. 2).

The lowermost unit (Tuscan Metamorphic Complex) consists of low-grade phyllites and metasandstones of the Mid-Late Triassic Verrucano Formation. This unit is tectonically overlain by the Tuscan Nappe (Burgassi *et al.* 1983), a unit representing a complete sedimentary sequence of Upper Triassic evaporites (Burano Formation) to Upper Oligocene–Lower Miocene arenaceous flysch (Macigno Formation). The Burano Formation (anhydrites and dolomites) at the base of the sequence represents the décollement surface along which the Tuscan Nappe was detached from its substratum and is in tectonic contact with the underlying Tuscan Metamorphic Complex. A sedimentary sequence with a thickness of nearly 1400 m lies above the Burano Formation; it consists of Upper Triassic-Jurassic platform and pelagic carbonate deposits (Calcare e marne a Rhetavicula Formation., Calcare massiccio Formation, Rosso ammonitico Formation, Calcare selcifero Formation and Marne a Posidonia Formation). This sequence is followed by Upper Jurassic pelagic siliceous sediments (Diaspri Formation) and finely laminated limestone (Maiolica Formation). The uppermost portion of the sequence consists of Cretaceous to Oligocene red-green argillites with intercalated limestone (Scaglia Formation), followed by Upper Oligocene–Lower Miocene arenaceous flysch (Macigno Formation). Most of the sedimentary sequence consists of Lower Jurassic carbonate and Cretaceous to Oligocene pelagic sediments, which maintain constant thicknesses of nearly 600 m and 500 m, respectively. In contrast, the Jurassic and Cretaceous pelagic deposits are relatively thin (30 – 100 m) with strong lateral variations. The uppermost tectonic unit, the Ligurian Unit, consists of Cretaceous to Eocene argillites and calcareous-marly flysch sequences belonging to the Santa Fiora Unit. They represent the pelagic sedimentary cover of Jurassic to Cretaceous ophiolitic complexes. The tectonic contact with the underlying Tuscan Nappe corresponds to a metre-sized fault zone with tectonized blackish argillites, siltites and silicified limestone.

The intrusive rocks cropping out in the core of the antiform correspond to the Gavorrano Granite, which consists of two facies: (i) a dominant porphyritic monzogranite hosting (ii) decametre- to hectometre-sized tourmaline-bearing leucogranite dikes (Mazzarini *et al.* 2004). The overall shape of the intrusion corresponds to a NNW-SSE elongated laccolith parallel to the antiform axis and emplaced along the tectonic contact between the Tuscan Metamorphic Complex and the Tuscan Nappe. As reported by Mazzarini *et al.* (2004), the flat base of the intrusion is in contact with the Tuscan Metamorphic Complex, whereas the roof intrudes the evaporitic décollement level (Burano Formation) at the base of the Tuscan Nappe, where marble and calc-silicate hornfels represent a hectometre-thick contact aureole developed in the Upper Triassic-Lower Jurassic carbonate formations.

The Gavorrano structure is covered by Neogene continental clastic deposits that crop out on the northern and south-eastern sides. These deposits comprise an Upper Miocene conglomerate and Upper Pliocene-Pleistocene conglomerate (Bossio *et al.* 1993). The Upper Miocene conglomerate consists of clast-supported red conglomerates derived from Ligurian Units with alternating sand and clay horizons. The Upper Pliocene-Pleistocene conglomerate is a poorly sorted, matrix-supported polygenic conglomerate composed largely of clasts derived from Tuscan Nappe Mesozoic formations and the Gavorrano Granite.

Structural setting of the antiform

The antiformal shape of the Gavorrano structure is indicated by the opposing dips of foliations in the Tuscan Nappe formations cropping out on both the western and eastern flanks (Figs. 2 and 3). The folded foliations are (i) the S_0 sedimentary bedding, (ii) an S_1 foliation and (iii) a hornfels texture in the contact aureole. The S_1 foliation is well-developed in the pelitic and marly rocks of the Tuscan Nappe formations; it is the axial plane schistosity of tight to isoclinal recumbent folds that almost completely transposed the S_0 sedimentary layering. In agreement with Carmignani *et al.* (1994), we interpret these earlier structures as related to nappe stacking. In the contact aureole, the hornfels texture in marbles and calc-silicates is characterised by a coarse-grained, equant granoblastic polygonal texture resulting from the recrystallization of lower Mesozoic carbonate sedimentary bedding.

As shown in cross-section, the Gavorrano antiform is a NNW-trending open anticline dissected by reverse and normal faults (Fig. 3) with a steeply dipping axial plane and a N160°E-trending fold axis (Fig. 4). On the western flank there are two minor structures of hectometre wavelength: an open anticline and a syncline (Fig. 2) with axes that plunge gently to the SE.

F2 fold structures

At the mesoscopic scale, the antiform-related structures are represented by small-scale NNW-trending folds (F_2) with amplitudes of metres to decametres. They occur on both flanks, and the best exposures are in the hinge zone and in the western flank of the antiform. The F_2 folds are well expressed in the Diaspri and Maiolica formations cropping out on the western flank of the antiform (Fig. 2). Here the F_2 folds range from open to tight upright folds of metre to decametre amplitude and wavelength (Figs. 5a). Their steeply dipping axial planes are often gently overturned to the east, and the NNW-trending fold axes plunge gently to the south (Fig. 5b). The axial plane foliation consists of disjunctive cleavage ranging from fracture to crenulation cleavage according to lithology. As shown in Figs. 5, F_2 folds are characterised by extreme variations in shape (open to tight), even within the same lithology, and by axial plane cleavage generally in the hinge zone of tight folds. On both the eastern and western flanks of the antiform, where more competent and roughly stratified carbonate formations crop out, the NNW-trending F_2 folds are open folds of metre to decametre amplitude and wavelength with steeply dipping axial planes. The F_2 folding also affects the marble and calc-silicate hornfels in the contact aureole of the Gavorrano Granite (Mazzarini *et al.* 2004; Musumeci *et al.* 2005), which is exposed in the antiform hinge zone west and south of Ravi village (Fig. 2). In this area, the massive hornfels fabric is concentrically folded by F_2 metre-scale upright open folds that are sometimes gently overturned to the east.

Fault zones

The antiform and associated intrusive rocks are dissected by several fault zones (Figs. 2 and 3) showing reverse-transpressive or normal movements, with normal faulting postdating reverse faulting (Musumeci *et al.* 2005). The reverse fault zones correspond to the Palaie Fault and Mt. Calvo Fault on the western flank and the Rigoloccio Fault in the hinge zone.

The Palaie Fault is a N-S trending fault zone extending for at least 5 km along the western flank of the antiform. Fault planes steeply dipping to the east have oblique to down-dip slickenside striae that indicate a dextral transpressive movement with westward reverse faulting (Fig. 6a). The latter displacement is dominant in the northern and central portion of the fault zone. Moreover, southwest of Mt. Calvo, several reverse and/or transpressive metre-scale fault zones with top-to-the-west movement occur east of the Palaie Fault in the roughly stratified and/or massive Jurassic carbonate formations of the Tuscan Nappe.

The Mt. Calvo Fault, a system of multiple N- to NW-trending reverse faults that dip gently to moderately to the east, is traceable for for nearly 2 km. Fault planes in the Liassic carbonate formations cross-cut the bedding which dips moderately to steeply to the west (Fig. 7). Faults correspond to centimetre-thick zones of brittle deformation that affect the rock extensively, as highlighted by the occurrence of decimetre-spaced fractures parallel to the fault planes up to several meters away from the faults. Down-dip to slightly oblique slickenside striae (Figs. 7a and c) highlight the dominant westward reverse movement in this fault zone (Fig. 6b).

The Rigoloccio Fault is a decametre-wide fault zone affecting the intrusive rocks at the core of the antiform. NW-SE trending fault planes dip moderately to steeply to the NE and SW. Down-dip to oblique slickenside striae and kinematic indicators reveal top-to-east and top-to-west reverse movements with dominant top-to-east displacement (Fig. 6c) .

On the eastern flank of the antiform, the Mesozoic carbonate formations are affected by several reverse faults with down-dip to oblique slickenside striae. In contrast to the western flank, these fault planes show highly variable orientations ranging from N30E to N150E, and their distributions do not clearly define fault systems (Fig. 6d).

The Caldana-Monticello Fault and Gavorrano Fault are normal faults on the eastern flank and in the hinge zone of the antiform, respectively. As shown in figures 2 and 3, they cross-cut the reverse faults and are generally characterised by moderate displacement (100 – 200 m). As documented by Musumeci *et al*. (2005), the Caldana-Monticello Fault is characterised by transtensive movements with normal faulting in its northern portion, while the central-southern portion is characterised by transtensive to dextral strike-slip movements.

Inversion of fault slip data for the reverse faults was performed searching for the three principal stress directions and the stress tensor ratio R (σ_2-σ_1/σ_3-σ_1) that best fit the fault-slip data (Gephart, 1990a, 1990b). Inversion of fault data reveals that reverse faulting is consistent with a NE – ENE direction of σ_1 that ranges from N50°E for the Mt. Calvo Fault to N80°E for the Palaie Fault (Fig. 6 and Table 1). On the eastern flank of the antiform, although fault planes have different orientations, the N80°E direction of σ_1 (Fig 6d) is consistent with that of the other fault zones.

Discussion

Gavorrano antiform: evidence of Pliocene shortening

The Gavorrano antiform, although dissected by several fault zones, has an amplitude of at least 4 km with an along strike length of at least 15 km (Fig. 2). In agreement with Musumeci *et al.* (2005), it is here interpreted as a thrust ramp fold exploited by the Gavorrano granite during passive emplacement. Folding resulted from activation of the thrust plane in the Tuscan Metamorphic Complex and in the evaporitic décollement layer at the base of the Tuscan Nappe. Deformation and folding of the hornfels fabric indicate that the growth of the antiform was coeval with granite emplacement (Musumeci *et al.* 2005). On this basis the antiform formed during the Pliocene, and its development is bracketed between 4.4 Ma and 1.65 Ma. The former is the age of the Gavorrano Granite (Serri *et al.* 1993), the latter the age of Upper Pliocene-Pleistocene conglomerate deposit containing clasts of granite and Tuscan Nappe rocks.

The mesoscopic structures described above indicate that shortening was achieved through folding along with reverse and transpressive faulting. The distribution of deformation structures reveals that folding is the dominant deformation within the well stratified, less competent formations. Thrusting and reverse faulting is mainly located within the roughly stratified carbonate formations, as the multiple fault zones on both the eastern and western flanks indicate (among which the Mt. Calvo reverse fault zone is the best example). The distribution of folding and faulting structures can be related to the differing competencies of the Tuscan Nappe formations, with heterogeneous brittle deformation in the lower Mesozoic carbonate deposits and more homogeneous folding in the upper Mesozoic-Paleogene pelagic deposits. Likewise, differences in the wavelength and amplitude of F_2 folds suggest poly-harmonic folding driven by the different competence and thickness of Jurassic and Cretaceous-Cenozoic formations of the Tuscan Nappe. In this context, the Mt. Calvo and

Palaie faults represent two main tectonic structures whose development was mainly determined by bulk deformation accompanying the growth of the antiform. Indeed both fault zones can be interpreted as westward backthrust structures characterised by dominant reverse and transpressive movements. The fact that the Mt. Calvo Fault cross-cuts the westward-dipping sedimentary bedding in the western flank of the antiform indicates that backthrusting occurred after nucleation of the antiform and in the late stages of antiform growth. As for the Palaie Fault, this structure provides clear evidence that westward reverse movements along steep splay segments were coupled with dextral strike-slip and oblique movements. A dominant strike-slip movement can account for the juxtaposition along this fault of the Tuscan Nappe Lower Jurassic formation and the Cretaceous sediments of the Ligurian Unit, with an apparent vertical displacement of at least 600 – 700 m.

The orientation of σ_1 (N50°E - N80°E) derived by fault slip data inversion is consistent with a ENE –WSW shortening direction that is compatible with the NNW-SSE orientation of F_2 fold axes. The orientation of the stress field and, in particular, the sub-horizontal attitude of σ_1 indicate that granite emplacement did not contribute to the final structure of the antiform. Indeed, the upright attitude of all F_2 folds and the presence of backthrust and reverse fault zones and their diffusion throughout the antiform (i.e. not restricted to the intrusion) clearly indicate that the antiform resulted from regional-scale ENE-WSW sub-horizontal shortening.

Comparison with regional-scale structures

At a regional scale the relevant elements of the Gavorrano antiform are (i) its axial direction, (ii) the orientation of σ_1 and (iii) mesoscopic structures. The NNW strike of the antiform and related folds and fault zones is parallel to the regional-scale orientation of Neogene tectonic structures and Upper Miocene-Pleistocene sedimentary basins (Fig. 8). The former are NNW-

SSE-trending thrust-related anticlines that deform Upper Miocene-Pliocene deposits. The best examples are the Mt. Pozzachera anticline (Cerrina Feroni *et al.* 2006) along the Tyrrhenian coast (Fig. 8), the Mid-Tuscan Ridge Thrust (Fig. 8a) and, farther east, the Cetona Thrust (Boccaletti & Sani 1998). Sedimentary basins filled by Upper Miocene – Pleistocene deposits are likewise oriented NNW-SSE. The sedimentary sequences within these basins record several phases of deformation closed by stratigraphic unconformities that separate deposits of different ages, with the development of reverse faults and open folds as well as fractures and joint systems. According to Boccaletti & Sani (1998), deformation in the Neogene – Quaternary basins of southern Tuscany was linked to four short-lived compressive phases dated to the (i) Messinian (5.6 Ma), (ii) Early Pliocene (3.8 Ma), (iii) Late Pliocene (2.4 Ma) and (iv) Middle Pleistocene (0.8 Ma).

The Pliocene deformation of sedimentary basins is clearly documented in the Volterra basin, a wide syncline (Fig. 8) where sediments are affected by NW-trending reverse faults (Moratti & Bonini 1998). The shortening directions range from NE-SW (Early Pliocene) to E-W (Late Pliocene). To the south, additional data on Pliocene deformation derive from the Perolla basin (Fig. 8) some kilometres northeast of the Gavorrano antiform (Moratti & Bonini 1998). In this basin, Upper Messinian and Lower Pliocene conglomerates are deformed by open folds whose orientation is consistent with a ENE direction of shortening. Moreover, the Perolla basin corresponds to a NNW- striking open syncline (Fig. 8) in which conjugate joints and stylolitic pits indicate a NNE shortening direction. In this context, the NE to ENE shortening direction of the Gavorrano antiform is consistent with the Early Pliocene deformation recorded in the sedimentary basins (Boccaletti & Sani 1998; Moratti & Bonini 1998).

The data reported here relating to the Gavorrano antiform, along with the deformation recorded in the Upper Miocene – Pleistocene sedimentary basins, indicate that the inner northern Apennines experienced an Early Pliocene phase of crustal shortening. The fact that the Gavorrano antiform is a thrust ramp fold with the thrust ramp located in the metamorphic unit below the Tuscan Nappe (Musumeci *et al.* 2005) supports the hypothesis that Neogene deformation was triggered by the development and/or reactivation of basement thrusts (Boccaletti & Sani 1998). According to this model, basement thrusting led to the reactivation of the cover thrust and the development of sedimentary basins in footwall synclines subsequently deformed during thrust reactivation. The position of the Gavorrano antiform west of the Mid Tuscan Ridge Thrust (Fig. 8a), i.e. in a more internal position with respect to the other tectonic structures, suggests the following:

(i) Pliocene deformation affected the whole Tuscan domain, from the outer portion (Cetona Thrust; Fig. 8a) to the inner one close to the Tyrrhenian coast;

(ii) basement-involved thrusting was the main mechanism responsible for deformation of both tectonic units and Upper Miocene-Pliocene sedimentary basins.

(iii) basement-involved thrusting led to reactivation of the outer thrusts (Mid Tuscan Ridge Thrust and Cetona Thrust) as out-of-sequence thrusts. In the inner portion (Tyrrhenian coast), the development of new thrusts led to the growth of antiformal structures represented best by the Gavorrano antiform.

Shortening vs. extension: implications for the Neogene evolution of the Northern Apennines

The above-documented regime of crustal shortening during the Pliocene argues against the model of a general extensional regime extending from the northern Tyrrhenian Sea to the inner northern Apennines (represented by southern Tuscany) for the same period (Carmignani *et al.* 1994, Decandia *et al.* 1998). Evidence for crustal extension is mainly based on the occurrence of (i) normal faults within Neogene sedimentary basins and (ii) low- and high-angle normal faults in the subsurface of the Larderello geothermal field (Brogi *et al.* 2003).

Detailed field data reported by Boccaletti *et al.* (1999) reveal that normal faults in the sedimentary basins cross-cut both the sedimentary sequences and compressive structures. This means that normal faulting postdates the deposition of sedimentary sequences within the basins, the development of which is therefore not likely linked to an extensional regime. The presence of low- and high-angle normal faults in the subsurface of the Larderello geothermal field was deduced from seismic lines where weak NE-dipping reflections were interpreted as low-angle normal faults which flatten at a depth of 4 – 5 km corresponding to that of a major seismic reflector (K-horizon) considered to be a major extensional shear zone (Brogi *et al.* 2003 and references therein). However, the K-horizon, recently renamed H-horizon (Bertini *et al.* 2006), is characterised by a sharp bright spot feature (Gianelli *et al.* 1997) that has been interpreted as a fluid-saturated zone corresponding to the top of Pliocene intrusions and related contact aureoles, without any connotation of tectonic structure (Bertini *et al.* 2006). The low-angle faults imaged by seismic profiles are interpreted as tectonic structures that developed at the top of structural highs (e.g. the basement anticline in the geothermal field; Fig. 8) and channel geothermal fluids from depth to the surface (Bertini *et al.* 2006). Since the low-angle faults sometimes displace the H-horizon, their development postdates the Pliocene intrusions and can probably be ascribed to Quaternary activity. Likewise, the field expression of these low-angle faults corresponds to high-angle normal faults that, as reported above, cut through the sedimentary succession of Pliocene-Pleistocene basins. It therefore follows that the normal faults reported as evidence of Late Miocene-Pliocene crustal extension in southern Tuscany correspond to steeply- to low-dipping normal faults of Late Pliocene - Quaternary age with a maximum vertical throw of some hundred metres. These structures cannot account for a long-lasting, regional-scale crustal extension and are better attributed to the final growth and/or collapse of Pliocene compressive structures. This is clearly the case in the Gavorrano antiform, where the development of normal faults on both flanks of the antiform postdates folding and reverse faulting.

In conclusion, the Gavorrano antiform provides clear evidence that during the Pliocene the inner northern Apennines experienced compressive tectonics which affected both the nappe stack and the Neogene sedimentary cover. On this basis, the Late Miocene-Pliocene period in the inner northern Apennines can be regarded as one of crustal shortening rather than extension. High rock uplift rates (> 1.7 mm/yr) for the Alpi Apuane derived from thermochronological data (Balestrieri *et al.*, 2003) well fit the proposed Pliocene shortening phase. According to Molli & Vaselli (2006) and Molli (2007), these data indicate that crustal shortening continued until the Middle Pliocene by means of out-of-sequence thrusts, leading to final exhumation of the metamorphic units in the Alpi Apuane.

This scenario matches well the hypothesis that since the Late Messinian (6 – 5 Ma) the degree of subduction rollback and of back-arc extension have decreased in the northern Tyrrhenian Sea but have increased considerably in the southern Tyrrhenian Sea (Rosenbaum & Lister 2004). The northern Tyrrhenian Sea-inner northern Apennines cannot therefore be regarded as a back-arc system. In additon, seismic anisotropy data indicate that only the southern Tyrrhenian Sea, floored by oceanic crust, represents a true back-arc basin (e.g. Salimbeni et al., 2007). Although slab roll-back had largely ceased in the Late Miocene (e.g. Levin et al., 2007), the proposed Pliocene shortening in the inner northern Apennines suggests that the lower crust could have been the site of crustal attenuation, heat softening and magma generation, whereas the upper crust continued to behave as a rigid body that sustained most of the strain arising from the convergence between the Adria and European plates.

Conclusions

The Gavorrano antiform formed through Pliocene shortening of the northern Apennine nappe stack; its development is linked to basement thrusting with associated ramp-thrust folding. The position of the Gavorrano antiform within the inner domain of the northern Apennines suggests that the whole sector was affected by crustal shortening during the Pliocene. Moreover, the occurrence of ramp-thrust folds and the synkinematic emplacement of granites provides new insight into the tectonic evolution of the inner northern Apennines. These new data call for a thorough revision of the Neogene tectonic setting of the northern Tyrrhenian Sea – northern Apennine system, and suggest either the presence of different regimes in the upper-middle and lower crust or that the northern and southern sectors of the Tyrrhenian sea – Apennine chain evolved differently.

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Figure captions

Fig 1. Geological sketch map of northern Apennines (modified after Boccaletti & Sani 1998). Small black box: location of map shown in figure 2; large dashed box: location of the Larderello geothermal field. AA: Alpi Apuane; CA: Campiglia Antiform; CTA: Cornate –

Travale Antiform; GA: Gavorrano Antiform; LGF: Larderello geothermal field; MP: Monti Pisani; MTR: Mid Tuscan Ridge; MA: Monte Argentario promontory.

Fig 2. Geological sketch map of Gavorrano structure (modified after Musumeci *et al.*, 2005). LU: Ligurian Unit; TN: Tuscan Nappe; TMC: Tuscan Metamorphic Complex; CMF: Caldana-Monticello Fault; GF: Gavorrano Fault; MCF: Monte Calvo Fault; PF: Palaie Fault; RF: Rigoloccio Fault.

Fig. 3. Geological cross section of Gavorrano structure (modified after Musumeci *et al.*, 2005). CMF: Caldana-Monticello Fault; GF: Gavorrano Fault; MCF: Monte Calvo Fault; PF: Palaie Fault; RF: Rigoloccio Fault.

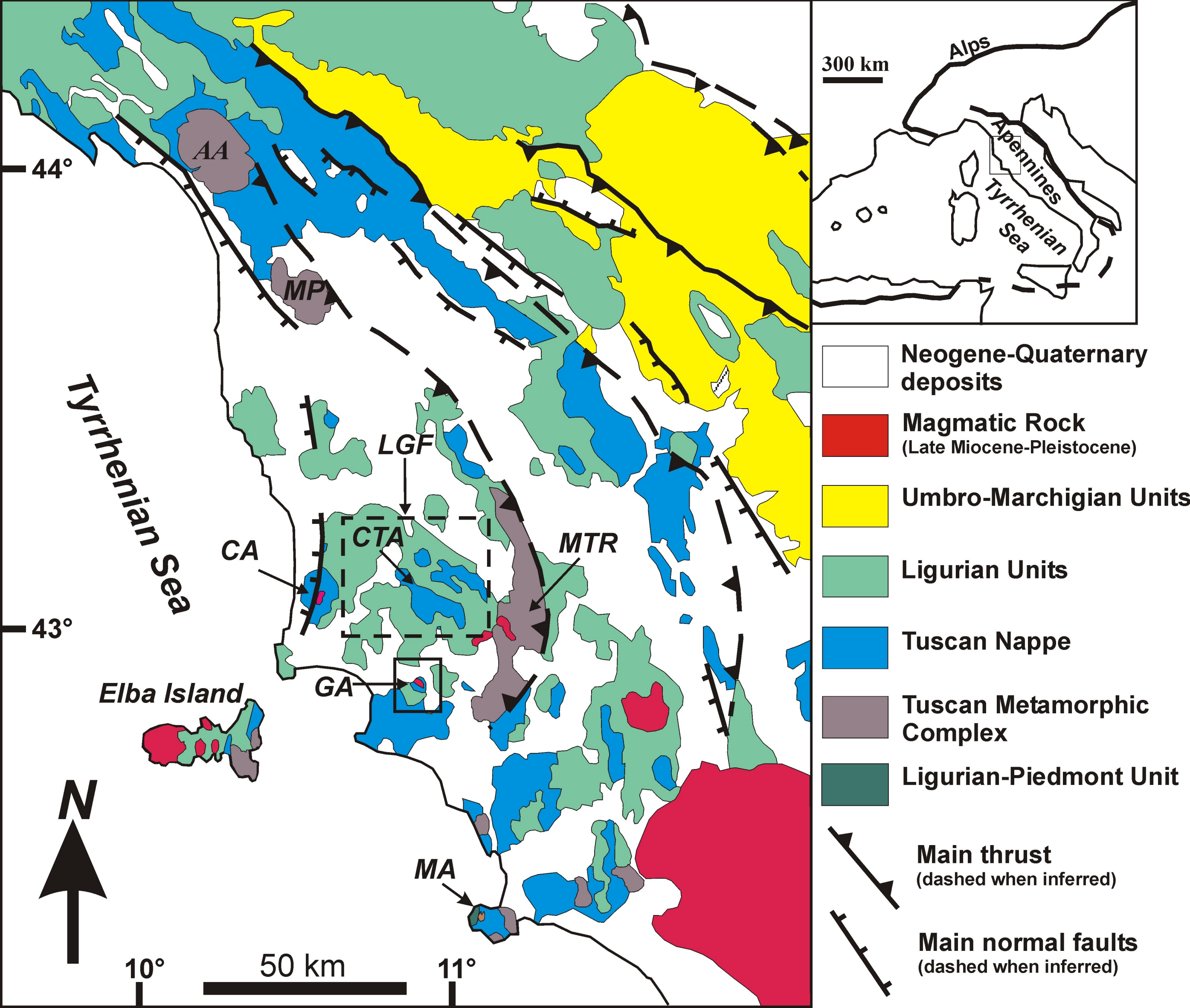
Fig 4. Lower emisphere, equal area projection stereogram of S_0 foliation poles contours. Black circle: calculated F_2 axis.

Fig 5. (**a**) Hand drawing of mesoscopic F2 folds on Diaspri Fm.. (**b**) Lower emisphere equal area projection stereogram of S_0 foliation poles contours. Black circle: calculated F_2 axis, empty circles: measured F_2 axes.

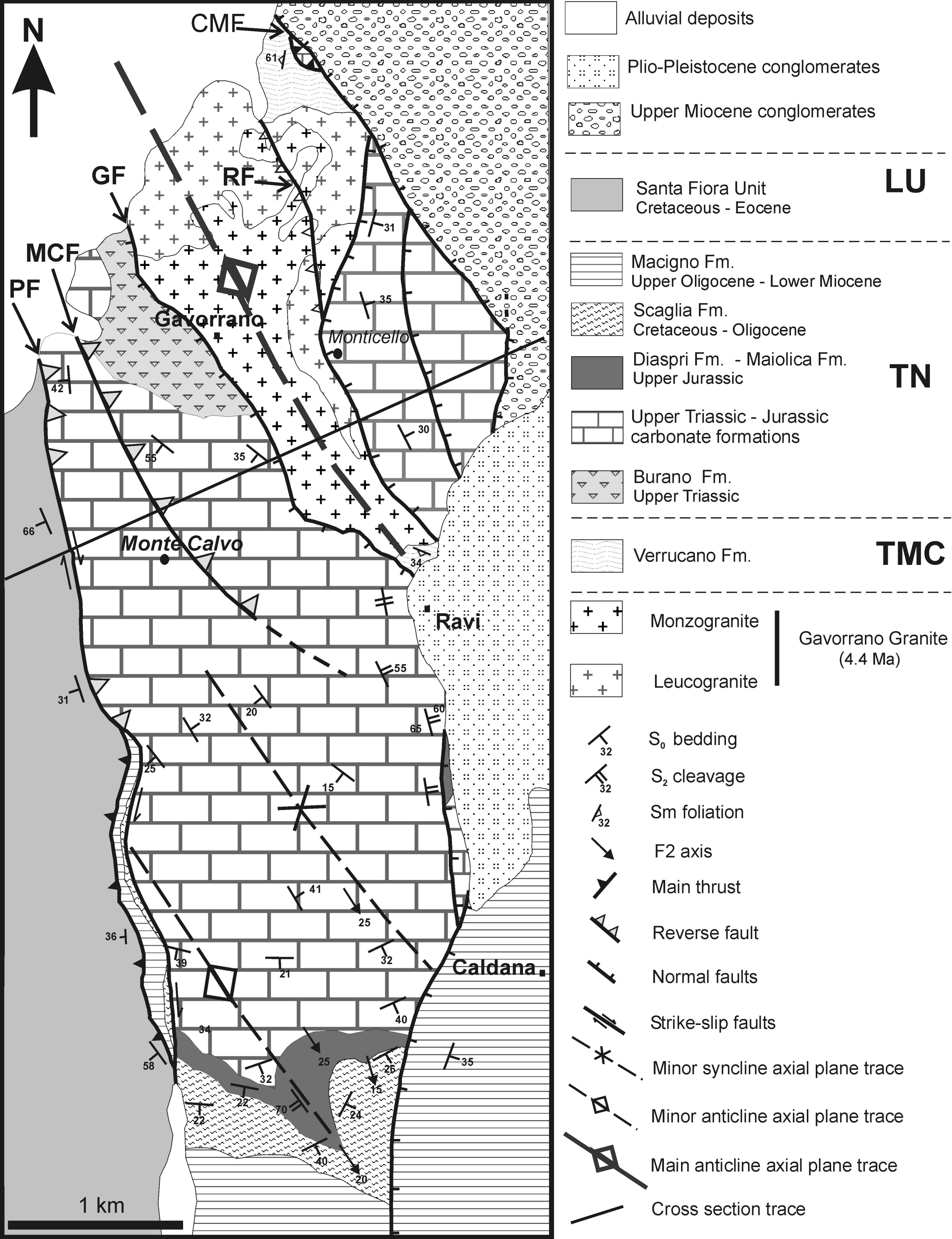
Fig 6. Tectonic sketch map of Gavorrano antiform and stereograms (lower emisphere, equal area projection) of structural elements and slip data in fault zones. (**a**) Palaie Fault. (**b**) Mt Calvo Fault. (**c**) Rigoloccio Fault. (**d**) Eastern flank faults. Fault symbols, great circle: fault planes, small black circle: slickenside striae. Slip data symbols, black triangle: σ_1; black square: σ_2; black circle: σ_3. LU: Ligurian Unit; TN: Tuscan Nappe; TMC: Tuscan Metamorphic Complex; MCF: Monte Calvo Fault; PF: Palaie Fault; RF: Rigoloccio Fault.

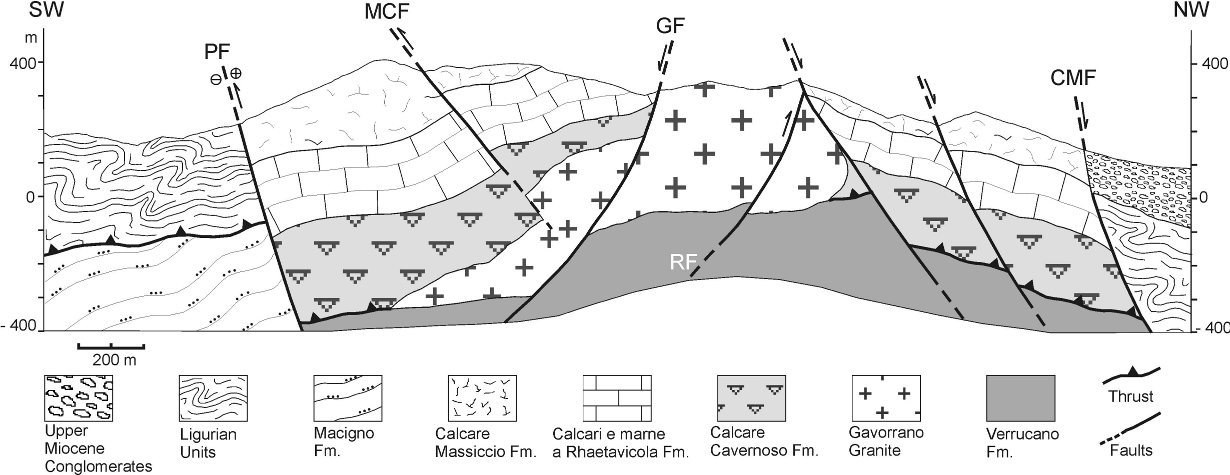
Fig. 7. Field photo of Mt Calvo Fault. (**a**) Reverse fault plane moderately dipping toward east with down-dip slickenside striae (dashed white arrow) and top to the west displacement (half white arrow), scale bar 1,5 m. (**b**) West dipping sedimentary bedding cross-cut by east dipping reverse fault (dashed white line) with top to the west displacement (half black arrow), scale bar 2 m. (**c**) Lower emisphere equal area projection stereogram of Mt. Calvo Fault. Filled circle: poles of sedimentary bedding; filled triangle: poles of fault planes; empty triangle: pole of fractures associated to the fault planes.

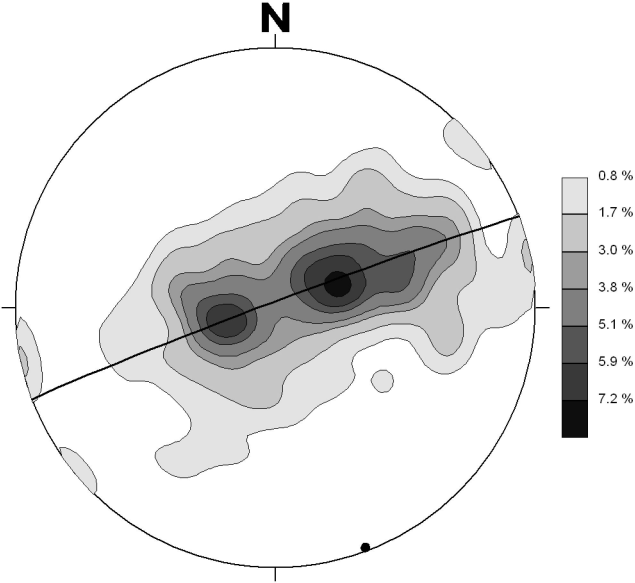
Fig. 8. Geological-structural sketch map of southern Tuscany (modified after Moratti & Bonini 1998) showing position of main anticline and syncline deforming Neogene basins and location of basement anticline structures. Box numbers are referred to the following structures 1: Gavorrano antiform; 2: Campiglia antiform; 3: Mt. Pozzacchera anticline; 4: Larderello anticline, 5: Scarpenata anticline; 6: S. Maria backthrust; 7: Fine syncline; 8: Volterra syncline; 9: Scarpenata syncline; 10: Perolla syncline; 11: Sassa syncline. In the inset (**a**) are reported the position of the northern Apennines main thrust systems : MTRT: Mid Tuscan Ridge Thrust, CT: Cetona Thrust, CFT: Cervarola Falterona Thrust, PAT: Padan Adriatic Thrust.



Alps
300 km
Apennines
Tyrrhenian Sea
44°
43°
10°
11°
50 km
N
Tyrrhenian Sea
AA
MP
LGF
CTA
CA
MTR
GA
Elba Island
MA
Neogene-Quaternary deposits
Magmatic Rock
(Late Miocene-Pleistocene)
Umbro-Marchigian Units
Ligurian Units
Tuscan Nappe
Tuscan Metamorphic Complex
Ligurian-Piedmont Unit
Main thrust
(dashed when inferred)
Main normal faults
(dashed when inferred)


N
CMF
GF
RF
MCF
PF
LU
TN
TMC
Gavorrano
Monticello
Monte Calvo
Ravi
Caldana
1 km
Alluvial deposits
Plio-Pleistocene conglomerates
Upper Miocene conglomerates
Santa Fiora Unit
Cretaceous - Eocene
Macigno Fm.
Upper Oligocene - Lower Miocene
Scaglia Fm.
Cretaceous - Oligocene
Diaspri Fm. - Maiolica Fm.
Upper Jurassic
Upper Triassic - Jurassic carbonate formations
Burano Fm.
Upper Triassic
Verrucano Fm.
Monzogranite
Leucogranite
Gavorrano Granite (4.4 Ma)
S_0 bedding
S_2 cleavage
Sm foliation
F2 axis
Main thrust
Reverse fault
Normal faults
Strike-slip faults
Minor syncline axial plane trace
Minor anticline axial plane trace
Main anticline axial plane trace
Cross section trace


SW
MCF
GF
NW
m
PF
400
CMF
400
0
0
RF
- 400
- 400
200 m
Upper Miocene Conglomerates
Ligurian Units
Macigno Fm.
Calcare Massiccio Fm.
Calcari e marne a Rhaetavicola Fm.
Calcare Cavernoso Fm.
Gavorrano Granite
Verrucano Fm.
Thrust
Faults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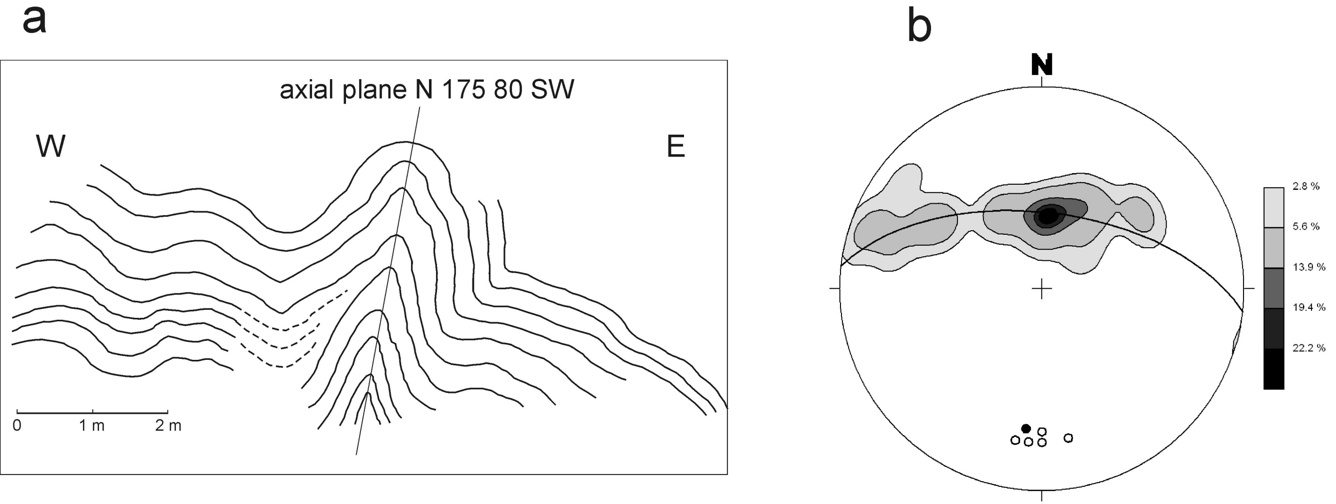
1.7 %
3.0 %
3.8 %
5.1 %
5.9 %
7.2 %


a
axial plane N 175 80 SW
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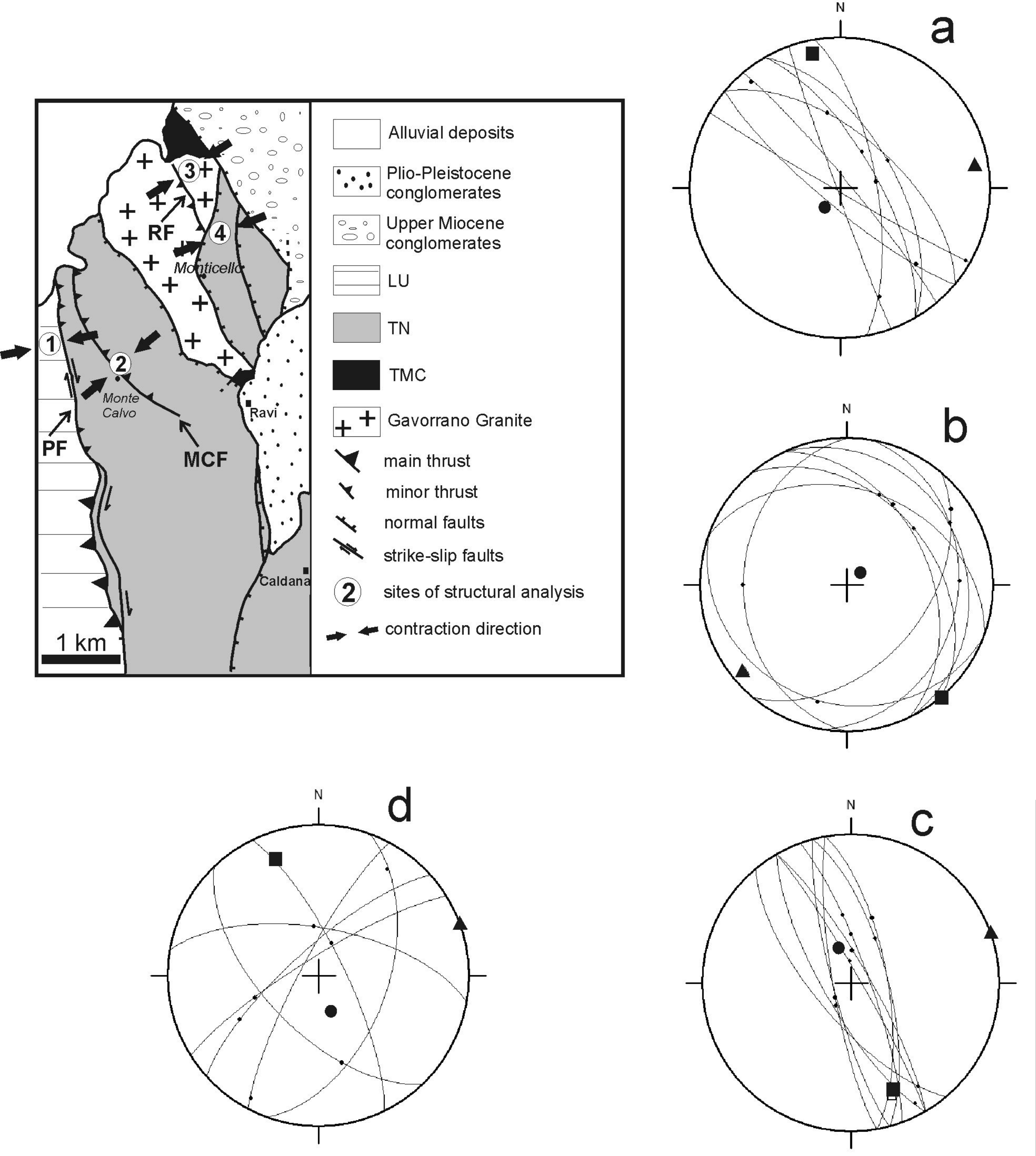
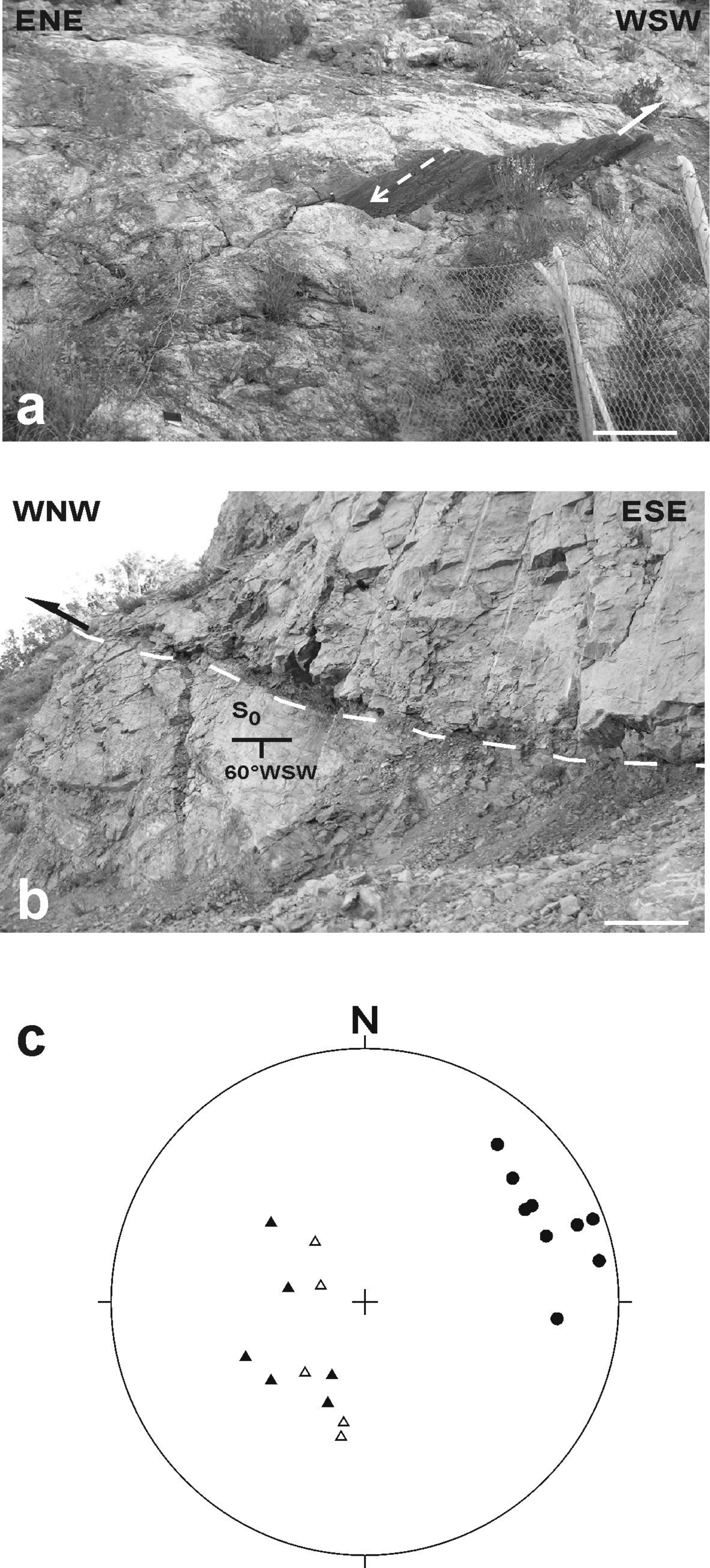
19.4 %
22.2 %



Alluvial deposits
Plio-Pleistocene conglomerates
Upper Miocene conglomerates
LU
TN
TMC
Gavorrano Granite
main thrust
minor thrust
normal faults
strike-slip faults
sites of structural analysis
contraction direction
1 km
RF
PF
MCF
Monticello
Monte Calvo
Ravi
Caldana
1
2
3
4
N
a
b
c
d


ENE
WSW
a
WNW
ESE
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60°WSW
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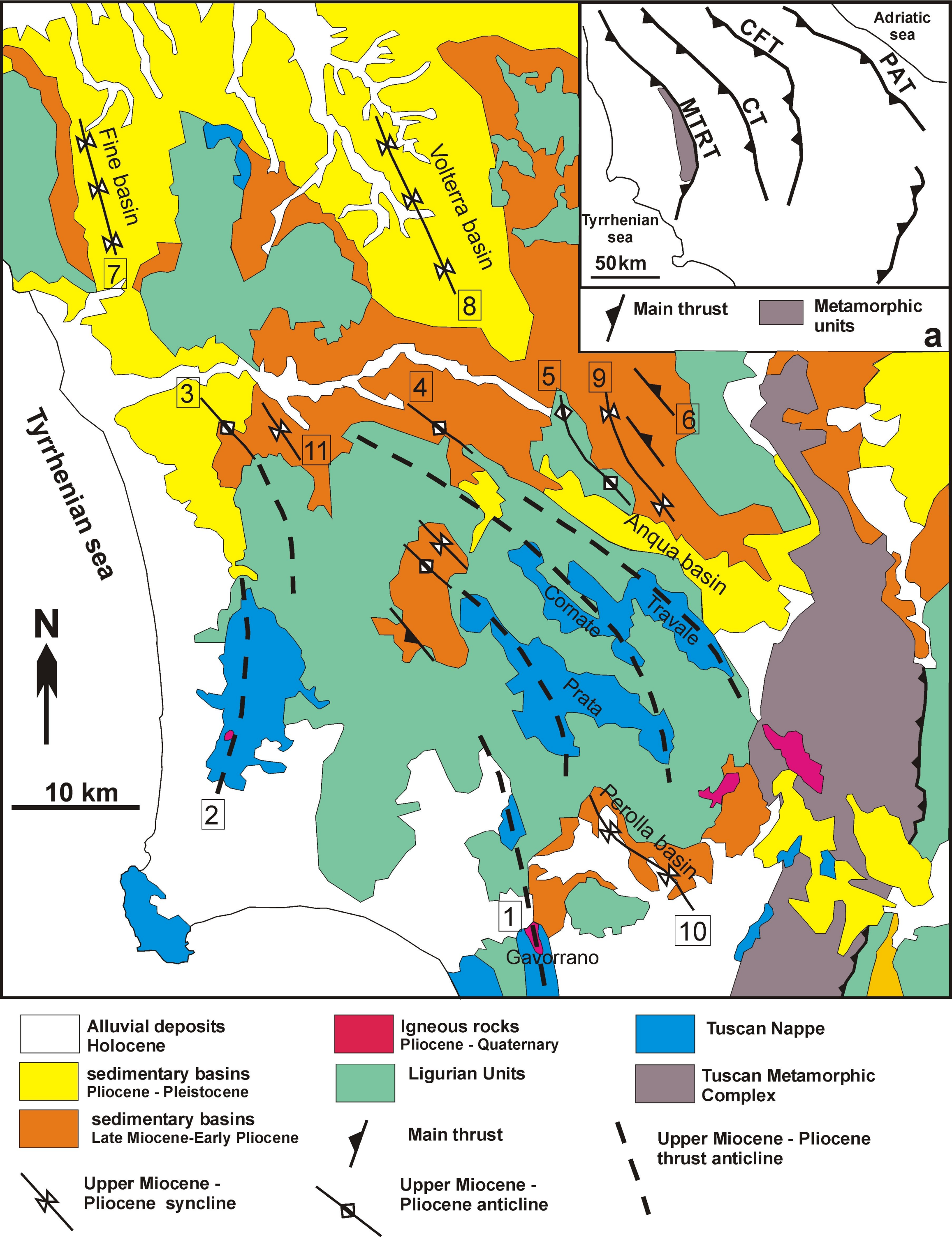

Adriatic sea
CFT
PAT
MTRT
CT
Tyrrhenian sea
50 km
Main thrust
Metamorphic units
a
Fine basin
Volterra basin
7
8
3
4
5
9
6
11
Tyrrhenian sea
Anqua basin
Cornate
Travale
Prata
N
10 km
2
Perolla basin
1
10
Gavorrano
Alluvial deposits Holocene
sedimentary basins Pliocene - Pleistocene
sedimentary basins Late Miocene-Early Pliocene
Upper Miocene - Pliocene syncline
Igneous rocks Pliocene - Quaternary
Ligurian Units
Main thrust
Upper Miocene - Pliocene anticline
Tuscan Nappe
Tuscan Metamorphic Complex
Upper Miocene - Pliocene thrust anticline

Table 1. *Inversion of fault-slip data in the Gavorrano antiform*

site	fault	movement	*trend°/plunge°* σ1	σ2	σ3	Tensor Fit (%)	Ratio Tensor Shape	n faults
1	Palaie	drs	80°/10°	348°/9°	214°/75°	85.9	0.50	8
2	Monte Calvo	r	230°/10°	140°/0°	50°/80°	87.8	0.68	8
3	Rigoloccio	r	70°/0°	160°/20°	340°/70°	76.2	0.75	10
4	Gavorrano East	-	70°/0°	340°/20°	160°/70°	57.3	0.89	7

r: reverse movement; drs: dextral oblique reverse movement; - not defined