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From a deformed Peri-Tethyan carbonate platform to a fold-and-thrust-belt: an example from the Central Apennines (Italy)

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Abstract

In the Central Apennines of Italy, the relationships between the foreland deformation of a Peri-Tethyan carbonate platform (Lazio–Abruzzi domain) and the subsequent contractional pattern have been clearly documented by means of stratigraphic and structural evidence. Stratigraphic and structural data point out the occurrence of pre-thrusting normal fault systems, and allow us to define their relationships with contractional structures. Miocene normal faults are particularly well documented by thickness and facies variation of foredeep deposits and by structural evidence. These faults controlled sedimentation during Tortonian–Early Messinian times (foredeep stage), and produced most of the accommodation space for clastic deposits in their hanging-walls. On the contrary, the subsequent positive inversion appears to be quite limited, and generally the hanging-wall sequences are not uplifted above the regional. Clear evidence that normal faults formed first and were later cut and/or rotated during thrusting is supported by analyses carried out along the main fault surfaces. The restoration of a balanced geological section across the study area, based on the inference of an extended foreland affected by later contraction, provided a total, small shortening value. This is lower than the previous estimated by several authors, for the same foreland-fold-and-thrust-belt.

Keywords: Foreland deformation; Foredeep basin; Balanced geological cross-section; Central Apennines; Neogene thrust belt

1. Introduction

Over the last few years, the role of foreland deformation in the subsequent evolution of fold and thrust belts has provoked ever-increasing interest. For this reason, progressively more complex geological-structural settings have been considered in the restoration of thrusts propagating through previously faulted continental margins.

Advances in inversion tectonics have provided examples of how inherited deformation occurring in the foreland can be the main controlling factor for the style of contractional fold and thrust belts at different scales (Welbon, 1988; McClay et al., 1989; Welbon and Butler, 1992). The role of syn-sedimentary normal faults on the geometry of later thrust evolution is also becoming clearer (Gillcrist et al., 1987; Hayward and Graham, 1989; Tavarnelli, 1996).

While inverted basins have been identified from seismic interpretation (Bally, 1984; Badley et al., 1989), a number of field studies have also recognized inversion structures. Regions of tectonic inversion are documented in a number of fold-and-thrust belts, including the Andes, the Appalachians and the Rocky Mountains as well as in Northern Europe (McClay et al., 1989; Powell and Williams, 1989; Dart et al., 1995; Ramos et al., 1996; Smith and Hatton, 1998; Bailey et al., 2002).

The interaction between pre-existing structures in the foreland and the structural style of subsequent thrust-belts is also well documented in the Mediterranean region, where the rift/wrench basins and passive margins of Peri-Tethyan platforms of Europe and Africa/Arabia were incorporated into the Alpine–Mediterranean orogenic belt systems (Alps, Apennines, Carpathian, Betic Chain and Magrebide belts) (e.g. Butler, 1989; Tavarnelli, 1996; Cortes Angel et al., 1999; Hafid, 2000; Nemkoc et al., 2001).

The Apennines belt of Italy represents one of the most suitable regions in the Mediterranean area for the study of

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foreland deformation processes prior to the onset of thrusting, because of its relatively young age, mild superimposed contractional deformation and a very well known stratigraphy (Fig. 1). The sedimentary sequences permit the reconstruction of the main extensional and contractional phases in this belt, with a well-calibrated deformation sequence: (a) the Mesozoic to Paleocene extensional break-up of Pangea; (b) the evolution of the Tethyan subduction system (Alpine subduction); (c) Oligocene–Neogene orogenic contraction with foredeep flexure, basin formation and thrust faulting (Apennine subduction); and (d) late, post-orogenic extension (Tyrrhenian back-arc opening and/or orogen collapse) (Bernoulli et al., 1979; Castellarin et al., 1982; D'Argenio and Mindszenty, 1987; Accordi et al., 1988; Patacca et al., 1990; Gueguen et al., 1997; Tavarnelli and Prosser, 2003). The orogenic contraction phase is characterized by the eastward migration of the active thrust fronts that, in turn, caused a shift of sequentially younger foredeep basins towards the 'undeformed' Adriatic foreland. The foredeep domains were subsequently involved in the deformation by stacking of different structural units in a fold-and-thrust belt.

In the Central Apennines, high relief with good exposure provides a favorable setting for the study of this deformation history as recorded in the Lazio–Abruzzi Peri-Tethyan carbonate platform (Ziegler et al., 2001). This thick (up to 6000 m) carbonate succession developed during the Late Triassic to Miocene (Parotto and Praturlon, 1975) and was involved in contractional deformation from Tortonian time, as indicated by the age of the foredeep deposits cropping out in this area (Fig. 2).

Nevertheless, irregularities of the foredeep–foreland migration system, compared with other sectors of the chain have been observed and described by different authors, based on: (i) the lack of regular eastward migration of foredeep depocenters with younger foredeep deposits in more internal positions; (ii) the lack of parallelism of the main thrusts related to the same stress field but showing a different trend in map view (Fig. 2); (iii) the occurrence of out-of-sequence thrusts. Previous workers have used strike-slip tectonics, tectonic windows related to very large displacement thrust planes, and reactivation of inner structures to explain these irregularities (Castellarin et al., 1982; Patacca et al., 1990; D'Andrea et al., 1991; Corrado et al., 1996; Ghisetti and Vezzani, 1997). Recently, pre-existing extensional structures have been offered to explain these irregularities in the external area of the Lazio–Abruzzi carbonate platform domain, while adopting a more complex paleogeography in the construction of balanced geological cross-sections (Calamita et al., 1998; Scisciani et al., 2000a, b, 2001a,b, 2002; Bigi and Costa Pisani, 2002; Mazzoli et al., 2002; Calamita et al., 2003). This study documents the occurrence of ancient normal faults largely preserved with their pre-thrusting geometry in a western sector of the Central Apennines. We present a geological section across the study area, illustrating this new interpretation. The

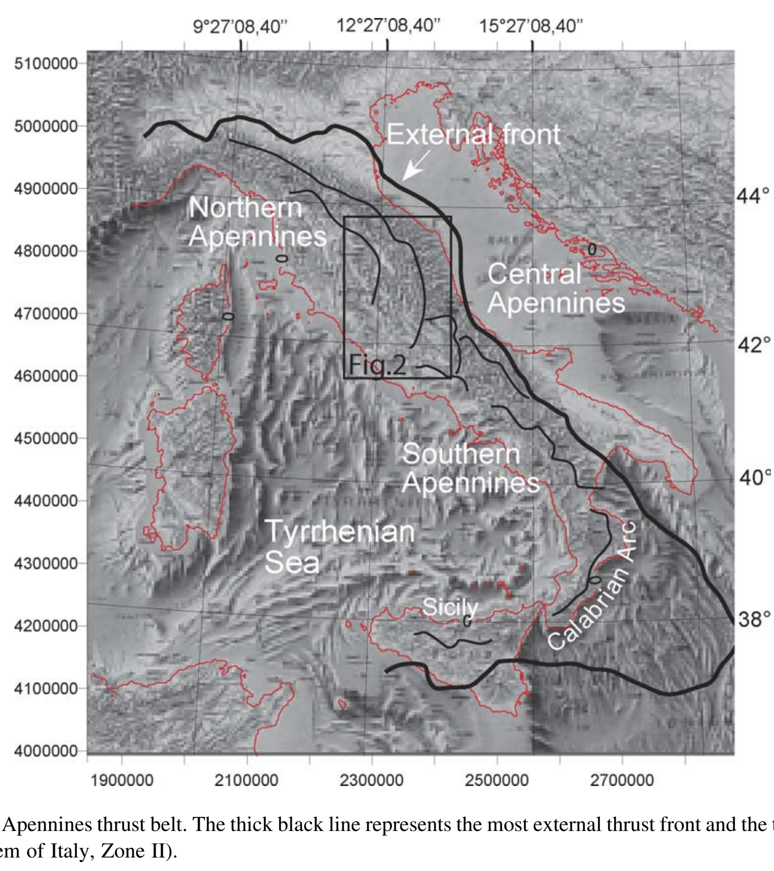

Fig. 1. Three main sectors of the Apennines thrust belt. The thick black line represents the most external thrust front and the thin black lines represent the main internal thrusts (coordinate system of Italy, Zone II).

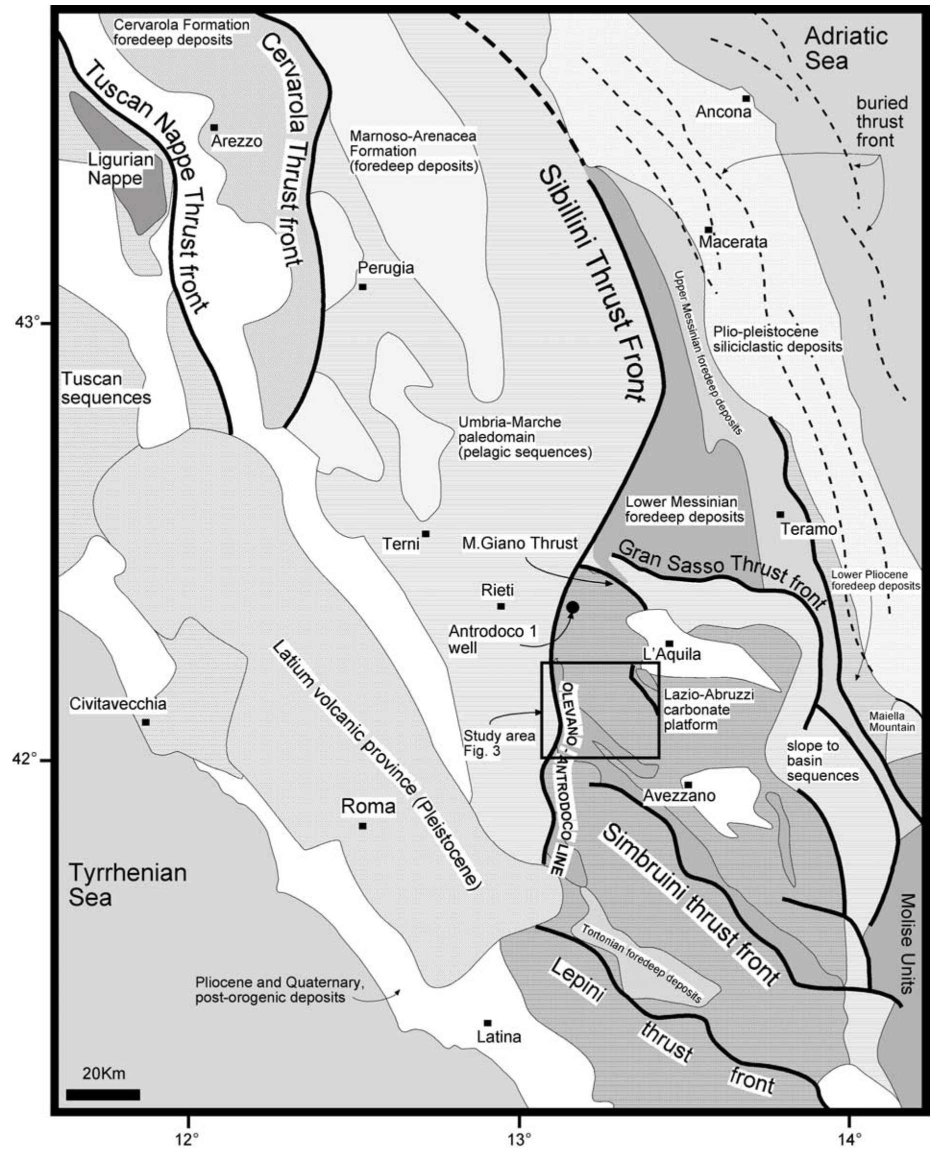

Fig. 2. Lithotectonic map of the Northern and Central Apennines with location of the study area.

cross-section and its restored template illustrate how pre-thrusting normal faults controlled the geometry and the location of thrusts during regional contractional deformation and demonstrate that the new interpretation better explain the irregularities than the previous interpretations. Therefore, this sector of the Central Apennines can be considered as a good example of the behavior of a large extensionally faulted carbonate platform system during subsequent compressional tectonic deformation.

2. The Lazio–Abruzzi carbonate platform domain in the Apennines Foredeep–Foreland migration model

The Apennines are an eastward-verging fold and thrust belt, containing several thrust sheets developed mostly during the Neogene. Generally, it can be subdivided into three domains, the Northern, Central and Southern sectors, based on differing structural styles (Fig. 1). In this contribution, we focus on the Central Apennines, which is tectonically similar to the Northern Apennines (Fig. 2).

In the west, the highest thrust sheets comprise oceanic-derived rocks, including ophiolitic bodies (Boccaletti et al., 1990a,b), and a crystalline basement. The external belt displaces Mesozoic–Cenozoic successions deposited on the southern passive margin of the Africa–Adria plate (Kligfield, 1979). These successions consist of two main paleotectonic domains that were controlled by extensional tectonics: the Sabina–Umbria–Marche basin and the Lazio–Abruzzi carbonate platform (Accordi et al., 1988, and references therein; Cooper and Burbi, 1988). These two paleotectonic domains were differentiated due to the activity of a Jurassic master normal fault whose trace now coincides with the Ancona–Anzio line (Castellarin et al., 1982), locally named the Olevano–Antrodoco Line (Calamita et al., 1987; Bigi et al., 1991; Cipollari and Cosentino, 1991, and references therein). This feature corresponds to the N–S oblique ramp of the main Sibillini thrust front, that places the Sabina–Umbria–Marche domain onto the Lazio–Abruzzi domain (Figs. 2 and 3).

The Liassic to Eocene Sabina–Umbria–Marche basin succession consists of pelagic limestones, marls and siliceous rocks with an average thickness of 3000 m. The Lazio–Abruzzi platform is a 5000–6000-m-thick pile of shallow-water carbonates, developed on a subsiding platform from Late Triassic to Late Miocene times.

Since the Oligocene, the Apennines have evolved by the eastward migration of thrust front and foredeep depocenters. This migration produced a common sequence of events: flexure of the foreland with simultaneous siliciclastic turbiditic deposition in the new foredeep, propagation of thrusts, and then thrust imbrication with thrust-top basin development (Ricci Lucchi, 1986; Royden et al., 1987; Boccaletti et al., 1990a,b; Patacca et al., 1990). The thrust fronts show an arcuate trend and are characterized by a regular hinterland-to-foreland thrust sequence. The age of the active thrust front and the onset of the foredeep basin depocenters are correlated with the age of the corresponding deposits in the thrust-top and the foredeep basins (Boccaletti et al., 1990a,b; Patacca et al., 1990, and references therein; Bigi et al., 1991).

In the Central Apennines (Figs. 2 and 3), deviations of

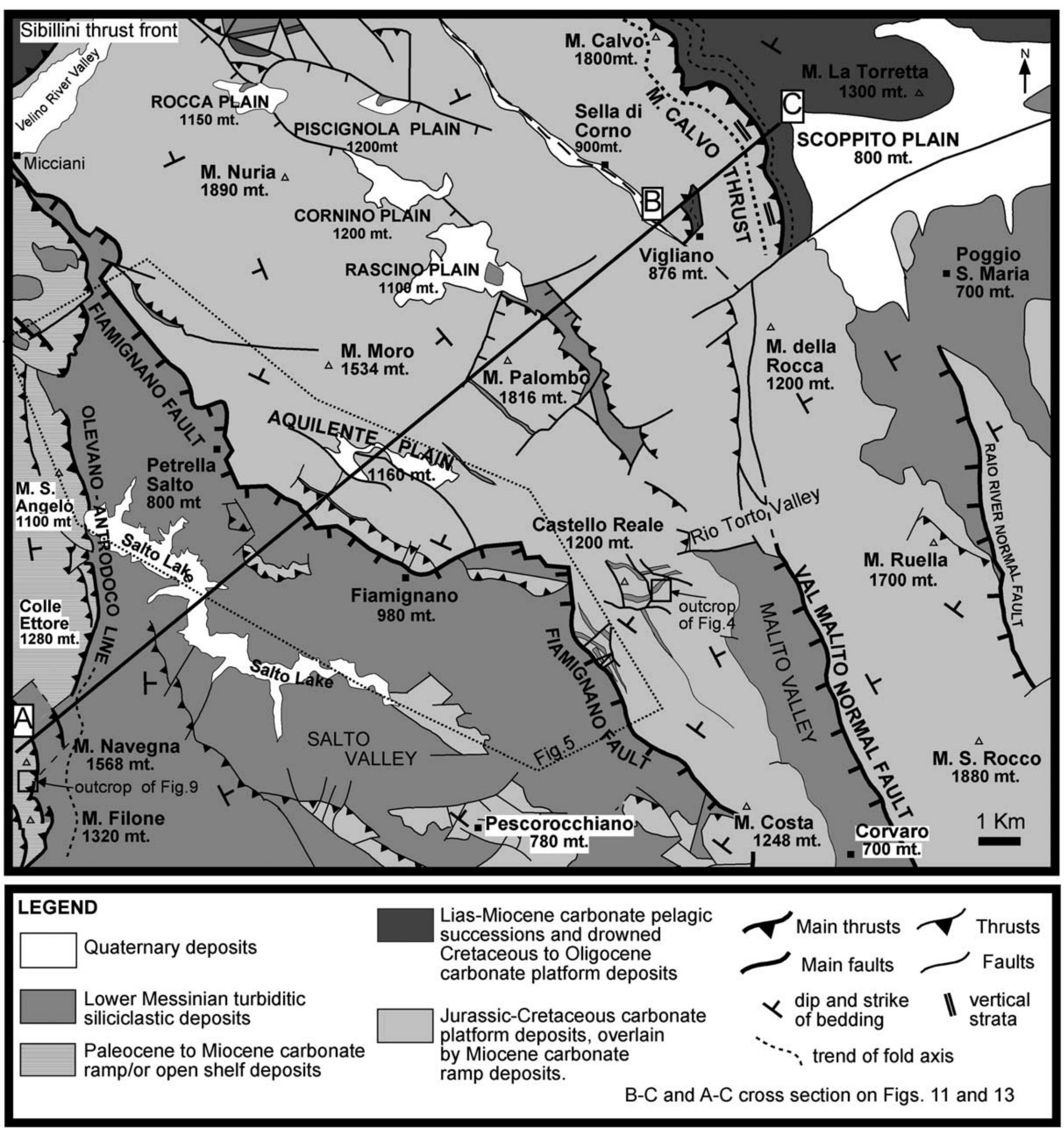

Fig. 3. Structural geology of the study area (modified from Bigi and Costa Pisani, 2002). See Fig. 2 for location.

the deformation sequence and geometry exist. Faulted and eastward-dipping monoclines of carbonate platform successions are caused by high-angle reverse faults on turbiditic beds. The bedding in the hanging-wall carbonates close to the fault planes varies from vertical to overturned toward the east, defining frontal anticlines. Also, the trends of the main thrusts range from NW–SE, N–S and E–W in map view. Interference and superposition between those differently oriented thrusts supports an interpretation of local anomalous out-of-sequence thrust propagation (sensu Morley, 1988). Moreover, the main thrusts are systematically developed in narrow areas, characterized by thickness and facies variations of Jurassic and Cretaceous platform-to-basin sequences. They usually occur along the pre-existing fault zones of the carbonate platform domains.

The fault zones associated with propagation of the main thrust fronts are characterized by dominantly brittle cataclastic features, suggesting that they developed at the very upper levels in the crust. Pressure-solutions structures and S–C fabrics (Berthè et al., 1979; Calamita, 1990), usually linked to the compressive fault zones in the Northern Apennines, are lacking along the main faults of the Lazio–Abruzzi area.

Another deviation is that stratigraphic data from the foredeep deposits suggest that depressions bounded by pre-existing normal faults controlled the depocenter location rather than the eastward migration of the flexure. Syn-sedimentary normal faults, together with distance from the source area, controlled the shape, facies and thickness of the sedimentary bodies ahead of the advancing thrust fronts (Castellarin et al., 1982; Milli and Moscatelli, 2000, 2001). In fact, the occurrence of coarse clastic carbonates (breccias and calcarenites) at the bottom of the siliciclastic sequences is interpreted to indicate the presence of active fault scarps along the foredeep basin margins (Compagnoni et al., 1991).

3. Geological and stratigraphic setting of the study area

The study area includes the northwestern margin of the Lazio–Abruzzi carbonate platform, which was affected by drowning events during the Late Cretaceous and the southeastern portion of the Umbria–Marche–Sabina basin (Salto Valley area; Figs. 2 and 3). The Lower Messinian foredeep deposits form the upper litho-stratigraphic unit of the Tertiary sedimentary succession. It is underlain by hemipelagic deposits of the Marne a Orbulina Formation (Tortonian), that lies on the Middle–Upper Miocene Calcari a Briozoi e Litotamni Formation.

In this area, the Olevano–Antrodoco thrust places a succession consisting of Paleogene to Miocene carbonate ramp to proximal slope deposits (the M. Filone–M. Navegna succession), on a succession characterized by Meso-Cenozoic platform carbonates grading upwards to Miocene carbonate ramp deposits and early Messinian siliciclastic turbidites (the Salto–Nuria succession). In the northeastern part of the study area, the M. Calvo thrust crops out, showing a NW–SE trend. It overthrusts the Cretaceous carbonate platform deposits on the folded and faulted Cenozoic pelagic sequence (Scaglia Rossa and Scaglia Cinerea Formations). Between these two thrust fronts, the Fiamignano normal fault places Lower Messinian turbidites in the hanging-wall of the southwest side of the fault, against carbonate platform sediments in the footwall, organized in a large NW–SE-trending anticlinorium (Fig. 3).

4. Structural data

4.1. The Fiamignano fault

The Fiamignano fault trends NW–SE, between the villages of Micciani and Mt. Costa (Fig. 3) with a normal offset of about 600–1000 m. Also, the Lower Messinian deposits change facies and thickness across the Fiamignano fault. In the Salto Valley (hanging-wall), the total thickness of the Lower Messinian turbiditic succession is about 800 m and is mainly composed of a well-graded turbiditic sandstone, whereas in the Mt. Nuria–Mt. Costa ridge (footwall) the same interval consists of deposits less than 50–100 m thick of dominantly claystone and massive sandstone (Fig. 3).

At Castello Reale, as well as in a few other locations, syn-orogenic siliciclastic deposits (Lower Messinian) onlap the eroded strata of a pre-orogenic carbonate sequence on a low-angle surface interpreted as a fault escarpment, that dips gently south-westwards (Figs. 3 and 4). Although the internal geometry is not conserved, this unconformity surface is well exposed, and locally is encrusted with siliceous material and by a reddish oxidation coat. Oxidation and deposition of siliceous crusts on Jurassic paleoscarps related to Jurassic normal faults, due to contact with younger siliceous deposits, have already been documented for Jurassic carbonate platform paleoscarps (Compagnoni et al., 1991; Santantonio et al., 1996). In the present case, the same feature is interpreted as being due to contact with the siliciclastic sequence. Moreover, carbonate gravitational-sliding deposits (Capotorti and Mariotti, 1991; Bigi and Costa Pisani, 2003) unconformably resting on the sandstone in the hanging-wall of the Fiamignano normal fault (Fig. 5) support an interpretation of syn-depositional fault motion with scarp creation and erosion.

Collectively, these observations are used to interpret that the exposed Castello Reale surface as an ancient fault scarp related to the Fiamignano normal fault activity during Lower Messinian deposition.

At the map scale, the Fiamignano fault is buried northwestward by the Sibillini thrust front (Fig. 5). This relationship suggests that: (i) normal faults predated the

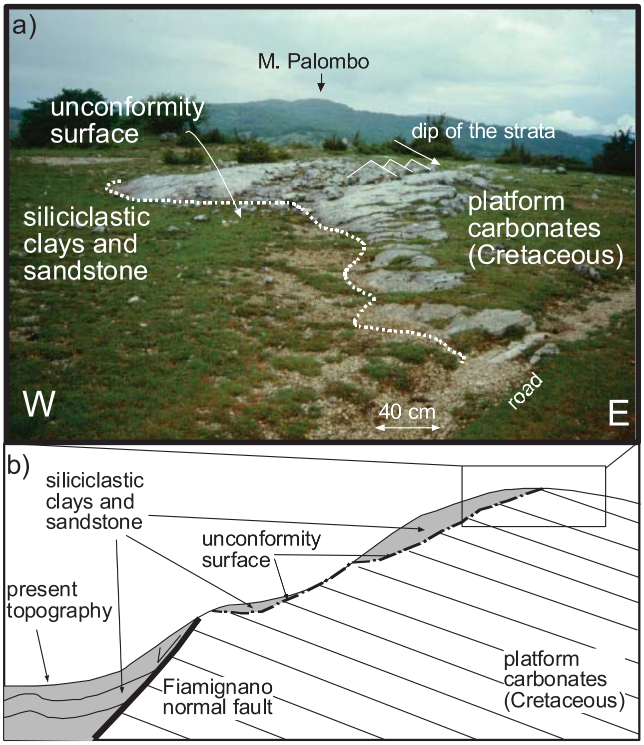

Fig. 4. Castello Reale area with view looking north. (a) W-dipping paleoscarps related to the Fiamignano normal fault. The picture shows the unconformity surface between the Lower Messinian clays and sands on the Cretaceous platform carbonates. See Fig. 3 for location. (b) Sketch illustrating the relationship between Miocene and Cretaceous rocks at Castello Reale outcrop, and along the Fiamignano fault.

onset of contraction, and (ii) the normal fault was truncated by an upward propagating thrust.

The Fiamignano fault plane changes dip angle and dip direction along strike with an average dip angle value of 40–45° for southwestward-dipping segments, and 65–80° for northeastward-dipping segments, where it locally displays back-thrust geometry (Fig. 5). In contrast, the fault plane maintains a constant cutoff angle within the carbonate strata in its footwall (Fig. 5). This constancy of cutoff angle is interpreted to indicate that the Fiamignano fault had a constant dip and cutoff geometry along its length prior to contractional deformation.

The hanging-wall and the footwall of the Fiamignano fault, respectively, contain E-dipping minor thrusts and high-angle (80°) reverse faults. Both groups of structures are parallel to the main fault and show a wide dip range. The E-dipping thrusts form flats to their hanging-walls; the Miocene carbonate ramp and the Lower Messinian turbidite deposits, respectively, occur in their hanging-wall and footwall (Fig. 5). The occurrence of E-dipping minor thrusts just at the hanging-wall sector closest to the normal faults suggests a strong stress concentration developed immediately ahead of the normal fault plane caused by the contraction. These minor contractional features testify that the normal fault planes acted as a buttress against thrust propagation. No evidence for reverse reactivation of the main normal fault surface is documented, because the attitude of the main fault plane (steeply nearly perpendicular to the regional compression tectonic transport) should not allow inversion (Jeager and Cook, 1976; White et al., 1986) (Fig. 5). Stress concentration against the pre-existing Fiamignano normal fault is also documented by the occurrence of folds, involving the Lower Messinian clays and sandstone at its hanging-wall. The fold axes (NW–SE) trend parallel to the direction of the main normal fault. Locally the Fiamignano fault is offset by tear faults that are parallel to the direction of maximum shortening (Fig. 5); in these cases the fold axes are orthogonal to the main fault plane system.

Analysis of mesoscopic brittle structures, observation of their cross-cutting relationships and collection of kinematic data along the Fiamignano fault make it possible to infer a relative chronology of deformation (Fig. 5). On the main fault plane, the oldest kinematic indicators record pre-thrusting normal slip along the NW–SE-trending segments and oblique left-lateral to strike-slip along the NE–SW transfer segment.

Mesoscopic conjugate fault systems, either with strike-slip, or with oblique- and reverse-slip, truncate or offset the main fault plane. Fault geometry and kinematic indicators are consistent with a NE–SW direction of maximum shortening, responsible for the development of the Apennines, as recognized and documented by many authors (Bigi et al., 1996, and references therein).

Dips of 40° or less for the Fiamignano fault are associated with evidence for layer-parallel slip on the footwall strata. The reverse kinematic indicators on bedding surfaces exhibit top-to-NE slip directions, again consistent with the direction of maximum shortening in the Apennines (NE–SW). In these sites, the steeply-dipping fault is offset by gently dipping or sub-horizontal shear surfaces to produce a staircase geometry and is folded toward the top of the topography (Fig. 6). The Tortonian Marne a Orbulina Formation and the Lower Messinian sandstone cropping out in the hanging-wall are passively translated north-eastward over the platform carbonates by layer-parallel slip processes, producing apparently anomalous, local, younger-on-older thrust relationships.

Mechanical striations and shear-related vein fibres collected along the Fiamignano fault plunge about 60° southwestward, while shear-related vein fibres and slickenlines from backthrusts, high-angle reverse faults and mesoscopic conjugate systems, indicate two main slip vectors, toward N20°E and N50°E, with a noticeable dispersion. The cross-cutting relationships persistently indicate that contractional structures postdate the normal faults around the Fiamignano fault (Fig. 5).

A later extensional kinematic reactivation (sensu Holdsworth et al., 1997) affected the Fiamignano fault when normal and oblique high-angle fault systems cut and offset the fault surface and the Quaternary deposits (mostly

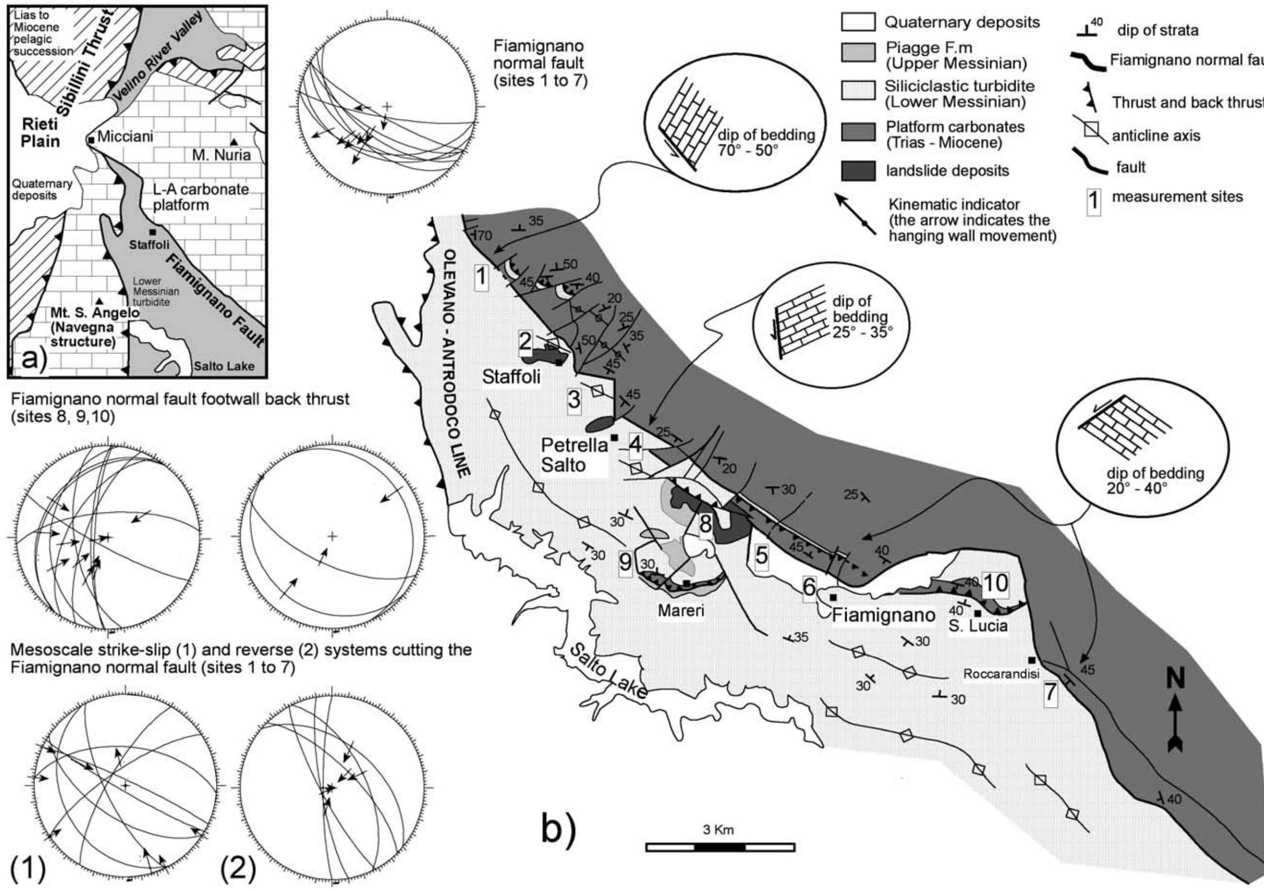

Fig. 5. The Fiamignano normal fault. (a) Structural map illustrating the cross-cutting relationship between the Fiamignano normal fault and the western thrust fronts (Sibillini and Mt. Navegna thrust fronts). (b) Detailed structural map. The relationships between bedding dip and the fault plane attitude are highlighted. Projection of structural data (Daisy 3.0; Salvini et al., 1999) showing the coaxial deformation between contractional and extensional events.

breccias). These structures are interpreted to be the result of post-orogenic uplift during late extension in the Apennines chain (Barchi et al., 1998). This activity during the Holocene, linked with the Fucino normal fault system to the south, triggered about 10 m of offset on the Fiamignano fault (Morewood and Roberts, 2000), which is minor when compared with a total offset of ca. 800 m from pre-thrusting displacement.

4.2. The Val Malito fault

The Val Malito fault crops out over a length of about 8 km from the Torrente Rio Torto Valley, where it is cut by a SW–NE-trending fault, to the village of Corvaro in the south (Fig. 3). This fault separates the Malito Valley to the west from the M. Ruella–M. S. Rocco ridge to the east. In the west, the M. Costa summit is underlain by a NE-dipping monocline that youngs eastward from Lower Cretaceous platform carbonates to Lower Messinian siliciclastic turbidites in the valley. The fault trends NNW–SSE with irregular exposure, juxtaposing Lower Messinian sandstones in the hanging-wall, with Lower Cretaceous–Miocene platform carbonates in the footwall (Fig. 7).

Although syn-displacement sediment areas are absent in the footwall, preventing assessment of fault kinematics with them, the relative age of extensional and contractional elements are preserved in the Val Malito fault zone (Fig. 7). Extensional indicators in the primary fault zone are here the oldest and include shear planes filled with fibrous calcite and dissolution cleavage defining lithons with 1–2 cm spacing (S–C fabric; sensu Calamita, 1990). The mean intersection between shear surfaces and cleavage trends N160°E, and indicates a N60°E direction of extension. The main fault zone is offset by smaller reverse faults that displace up to 40 cm with a top-to-N40°E displacement, and locally by strike-slip faults. Striations with strike-slip kinematic indicators generally are also superimposed on extensional calcite fibres in the shear planes of the fault zone. This structural overprinting indicates that the normal displacement of the Val Malito fault preceded later thrusting.

4.3. Rascino plain structures

Small intramountain basins are located on top of the main mountains, at elevations of about 1000 m and contain sub-horizontal, massive and poorly cemented Lower

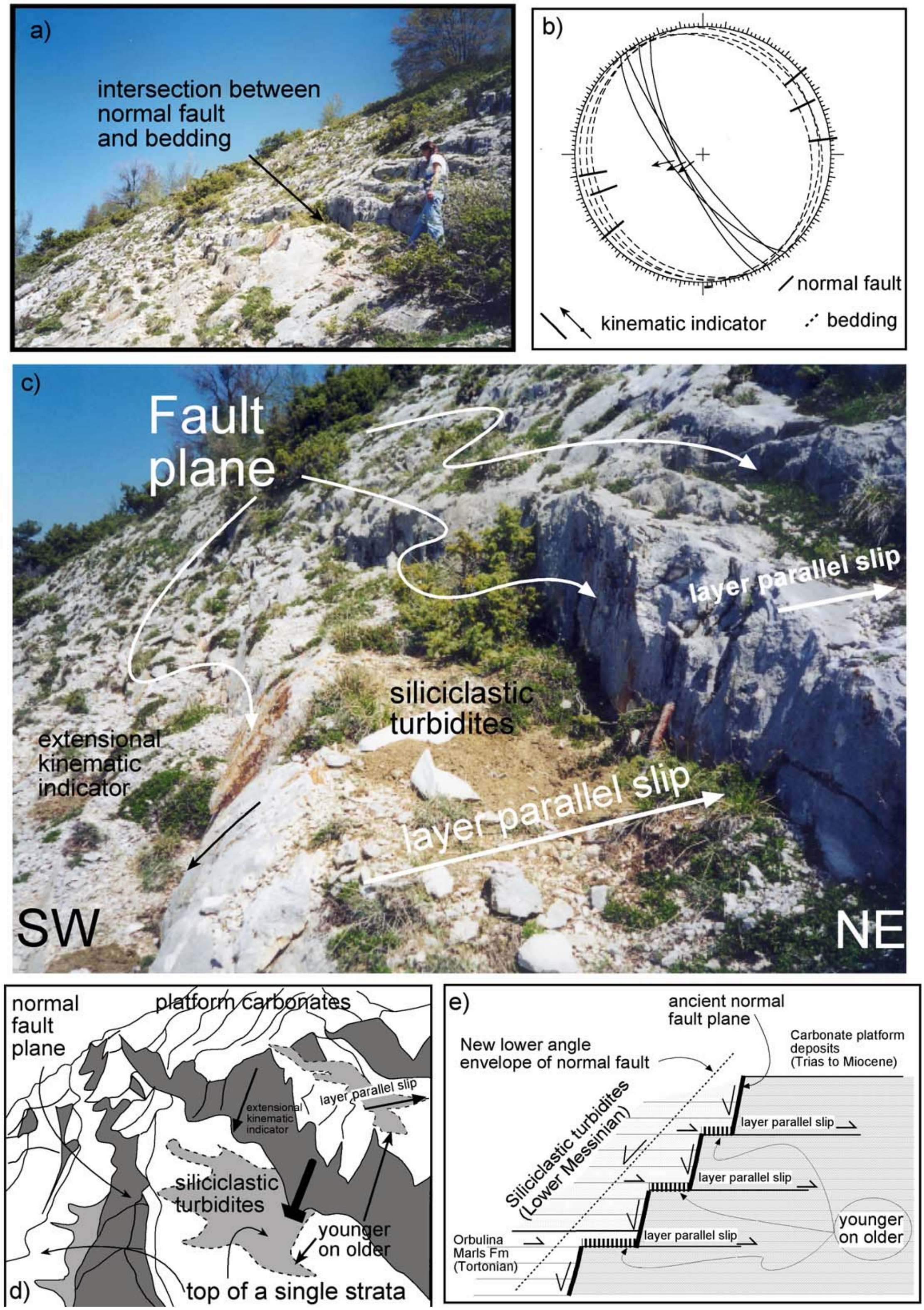

Fig. 6. Staircase geometry of the Fiamignano normal fault (site 5-6 on Fig. 5). Photographs (a) and (c) and line drawing (d) illustrate the E-dipping normal fault surface (dark grey) offset by layer-parallel slip. (b) Stereographic projection of bedding planes and normal fault plane. The kinematic data indicate a top-to-NE transport for slip along bedding and a top-to-SW transport for the normal fault. (e) Interpretation of observation.

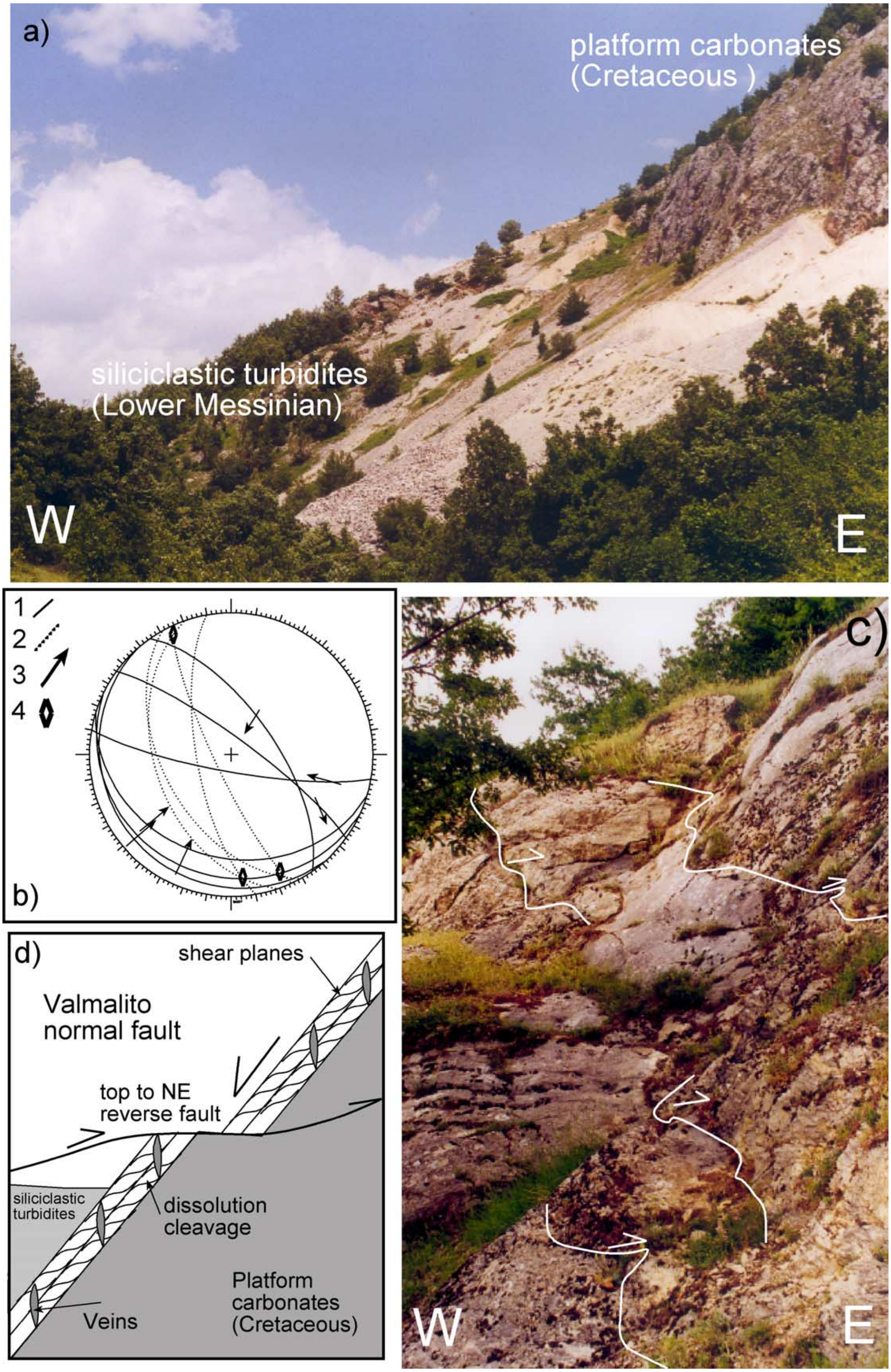

Fig. 7. (a) The Val Malito fault surface; (b) structural elements measured along the fault: 1—reverse fault cutting the normal fault plane; 2—shear planes and dissolution cleavage in the normal fault zone; 3—reverse kinematic indicators and 4—intersection between shear planes and cleavage; (c) photograph showing the normal fault cut by reverse low-angle reverse faults; (d) sketch illustrating the relationship between normal fault and the younger low angle reverse fault.

Messinian sandstones (Fig. 3). The northern and eastern basin margins are usually bounded by low-angle southward- and westward-dipping normal faults, respectively, whereas their southern and western margins are usually bounded by steeply dipping (80° dip) reverse faults. In some cases, faults placing hanging-wall sandstones in contact with footwall Cretaceous platform carbonate deposits have associated breccias with Miocene clasts (Fig. 8). These breccias have been interpreted as depositional rather than tectonic, but are still fault scarp related, indicating that the basin-bounding faults moved prior to sandstone deposition.

4.4. The Navegna–Colle S. Angelo ridge structures and the Olevano–Antrodoco Line

In the western part of the study area, the Navegna–Colle S. Angelo ridge occupies the hanging-wall of the thrust known as the Olevano–Antrodoco Line (Fig. 3). The ridge consists of left-stepping, en-échelon anticlines with N–S axial trends, in a 500-m-thick Lower Miocene carbonate ramp succession, which is locally overlain by the Marne a Orbulina Formation (Tortonian) and Lower Messinian sandstones. Near the thrust, which dips SW 50–60°, hanging-wall strata are subvertical. The footwall is mainly composed of the Marne a Orbulina Formation, which is also vertical near the thrust, forming the western limb of a wide footwall syncline. This geometry and the reduced stratigraphic displacement on the thrust in proximity to the fold suggest that the structure first originated as a fault-propagation fold, and later was cut by thrust, producing a final geometry similar to the breakthrough model (Suppe and Medwedeff, 1990; Capotorti and Mariotti, 1991, and references therein).

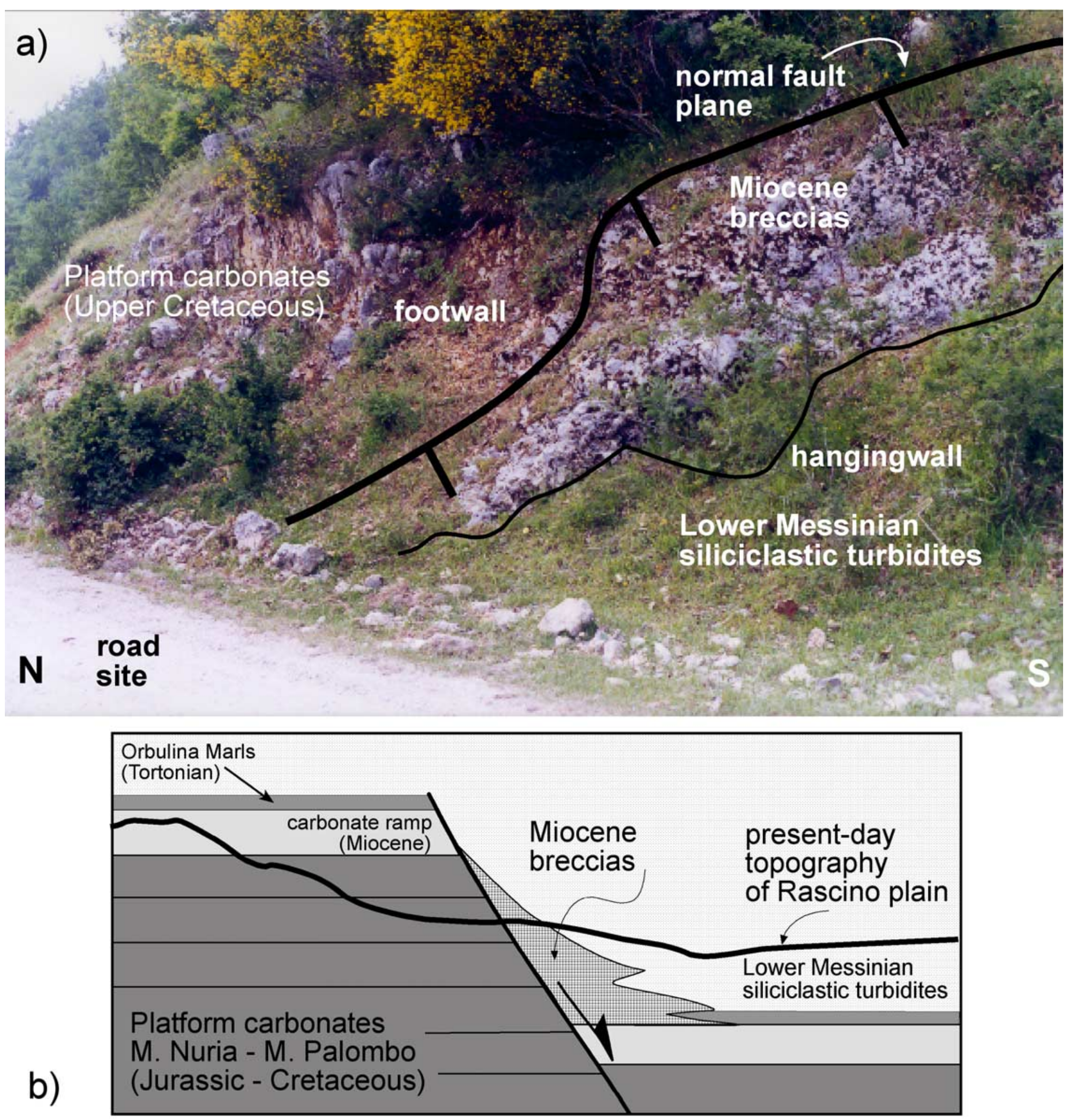

Fig. 8. Rascino Plain. (a) Normal fault with breccias of Miocene rocks. (b) Relationships among the normal fault, breccias of Miocene rocks and Messinian sandstones at Messinian time.

This thrust-related fold contains a system of conjugate normal faults throughout its domain, and these faults have consistent cutoff angles to bedding at all locations (Fig. 9). In the present geometry, these conjugate systems comprise high-angle reverse faults, which displace the top of the carbonate succession about 30–50 cm and low-angle normal faults with a top-to-SE displacement; a few metres of Marne a Orbulina Formation crop out in these small rotated graben. The intersection line of these conjugate systems is parallel to the bedding, while the acute bisector is normal to the bedding. This geometric relationship is maintained even in the crest and backlimb of the anticline, suggesting that normal faulting of the strata occurred before formation of the thrust-related fold.

These structures support the presence of Miocene normal faults even in this area. Also the footwall contains conglomerates and breccia deposits interbedded in the Marne a Orbulina Formation and Lower Messinian sandstones, indicating proximity to the source areas, possibly as the result of pre-thrusting normal faults occupying the Olevano–Antrodoco line (Milli and Moscatelli, 2000, 2001; Bigi and Costa Pisani, 2002). In this interpretation, an E-dipping, pre-thrusting normal fault would here been rotated during regional thrusting (Tavarnelli, 1996) (Fig. 10).

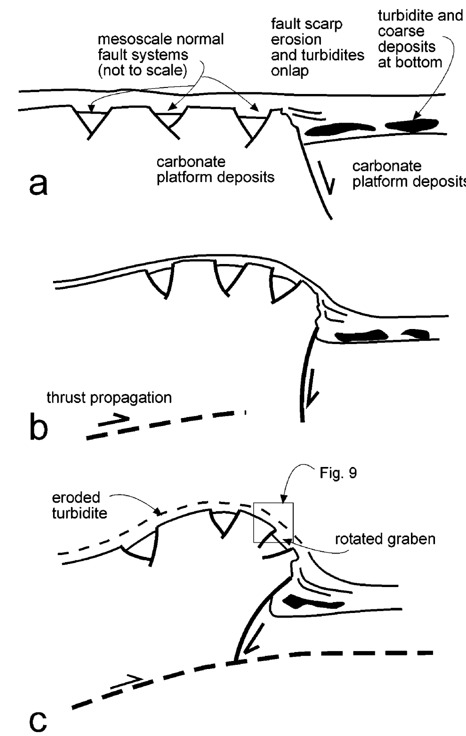

Fig. 10. Sequential schematic model showing the effects of thrust development across a stratigraphic sequence with preexisting normal faults.

4.5. The Micigliano fault, the Vigliano structures and the M. Calvo thrust

The N–W-trending M. Calvo thrust crops out in the northeastern corner of the study area, juxtaposing Upper Cretaceous platform margin carbonates onto deformed Cenozoic pelagic rocks of the Scaglia Rossa and Scaglia Cinerea Formations, whereas the same pelagic sequence crops out in tectonic contact with the carbonate platform sequence in the Vigliano area (Figs. 3 and 11). The Antrodoco 1 well, located farther to the north (Fig. 2), penetrated Triassic dolostones overlying the Cretaceous pelagic carbonates at a depth of 2742 m below the surface (Parotto and Praturlon, 1975).

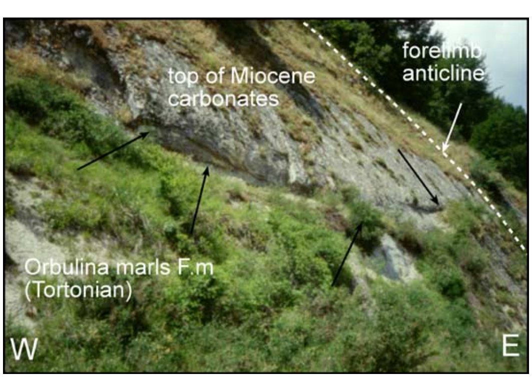

Fig. 9. Forelimb of the M. Navegna anticline (see Fig. 3 for location). Black arrows indicate location of rotated normal fault juxtaposing two stratigraphic units. This normal fault belongs to conjugate normal fault systems distributed throughout the anticline.

These data constitute one of the main constraints in the interpretation on the structural style of this part of the Central Apennines. Based on these data, the footwall of the M. Calvo thrust, the Cretaceous rocks at the bottom of Antrodoco 1 well and also the Vigliano outcrop have been interpreted as the footwall of the same thrust, which is considered to accommodate ca. 15 km of displacement (Parotto and Praturlon, 1975; M. Giano thrust in Bally et al., 1986) (Fig. 3).

A key relationship for this region in the interpretation of the main contractional elements is the coincidence between them and the carbonate platform margins, several lines of stratigraphic evidence support the idea that first Cretaceous, and later Oligocene, normal faults allowed a gradual drowning phase of the carbonate platform peripheral sectors. This coincidence is suggested by thickness variations of the drowning sequence (constituted by the Scaglia rossa and Cinerea Formations) across the M. Calvo thrust and the Vigliano area. In the hanging-wall of the Mt. Calvo thrust, 10–20 m of Oligocene Scaglia Cinerea Formation fill the small graben, unconformably overlying the Cretaceous platform margin carbonates (Figs. 11 and 12), whereas the same formation has a thickness of ca. 300 m in the Vigliano area and 600 m in the footwall of the M. Calvo thrust. Here the deposits of the Umbria–Marche succession contain considerable amounts of strata consisting of calcarenites and breccias, attesting the proximity of

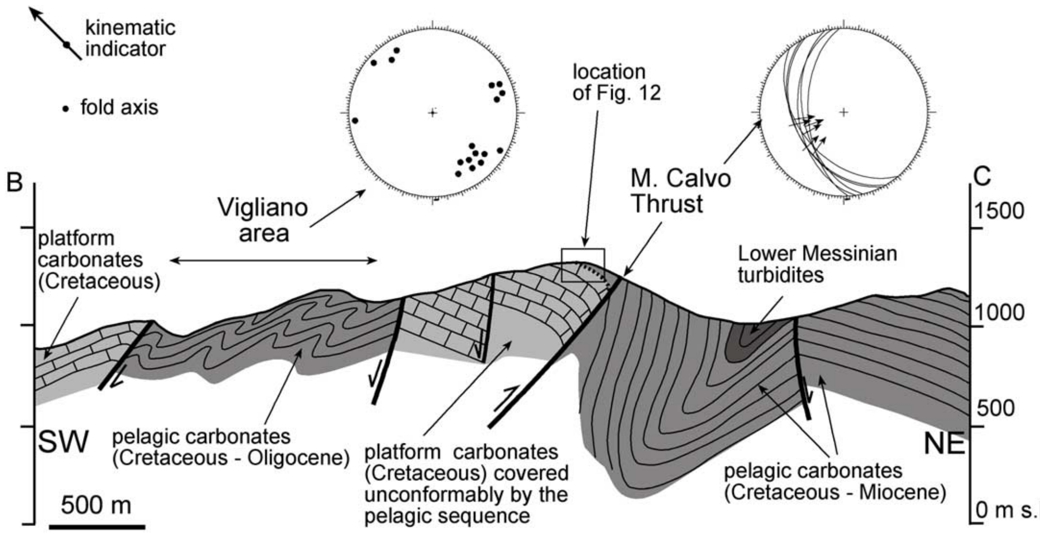

Fig. 11. Geological cross-section across Vigliano–M. Calvo (B–C) located in Fig. 3, illustrating: (i) the location of the unconformity surface of Scaglia Cinerea on the carbonate platform deposits in the hanging wall of M. Calvo thrust; (ii) the cutoff angle in the footwall of M. Calvo thrust.

the source areas. The lithofacies, age and grain shape characteristics of the calcarenites and breccias deposits indicate M. Calvo as the most probable source area. These stratigraphic relationships are used to infer the movements of normal faults that created intra-platform basins in the Vigliano area during Upper Cretaceous–Oligocene times, as already proposed based on stratigraphic evidence (Sabina gulf: Capotorti et al., 1997).

Structural data collected along the main tectonic contact in the Vigliano outcrop demonstrate that the pelagic sequence Scaglia Rossa–Scaglia Cinerea Formations is bordered by a combination of high-angle W-dipping reverse (in the south) and normal faults (in the north) and is intensely folded, with an axial trend of N70° and N140° (Fig. 11). These folds have been regarded to be the result of a strong concentration of stress developed against the northern normal fault, due to the propagation of a minor splay of the main M. Calvo thrust. This high angle splay created a gentle north-eastward dipping monocline in the hanging wall (Jurassic–Cretaceous margin sequence); in the footwall, the cutoff angles of the Umbria–Marche sequence can be reconstructed along the thrust fault, showing the development of a main footwall syncline. The occurrence, both in the hanging wall and in the footwall of a high angle ramp structure and the lateral continuity of the platform–margin–slope deposits, constrain the geometry of the thrust plane and strongly suggest that the structural elevation of M. Calvo is due mainly to Cretaceous–Oligocene normal faulting active before thrusting.

As a consequence, the displacement of M. Calvo thrust is significantly reduced with respect to the previous interpretation, as proposed in the geological section in this paper (Fig. 13).

5. Discussion of structural data

Structural geometries in the study area support an interpretation of normal faulting with syntectonic sedimentation preceding propagation of the Apennines foreland fold-and-thrust-belt (Table 1). The Cretaceous–Oligocene and Miocene normal faults show limited or no younger reverse slip, but are rotated and segmented by the subsequent, younger thrusts. Also, some geometries are consistent with post-thrusting extension from the Pliocene on, creating normal faults that offset both the pre-orogenic normal faults as well as the thrusts. This latter extension is recognized in the Apennines and is related to the Tyrrhenian back arc opening (Gueguen et al., 1997, and references therein) and/or to the orogen collapse (Decandia et al., 1998). Our data set also demonstrates the role played by pre-orogenic paleogeographic features in the development of the Apennines fold-and-thrust-belt of Central Italy.

The oldest extensional structures (Cretaceous–Oligocene) characterized narrow, weak zones that inhibited the localisation of subsequent contractional structures (thrust ramps and back thrusts; Fig. 13). A possible explanation is that normal faults produced a more complex paleogeography on the monotonous carbonate platform, with several 'competent' sectors (carbonate platform successions) separated by less competent domains (pelagic successions). The restored template of Fig. 13 shows that normal fault locations controlled the position of thrust ramps that systematically placed platform margin carbonates over pelagic intra-platform basin successions.

The Miocene normal faults controlled sedimentation during the Tortonian–Lower Messinian time interval as documented both by thickness and facies variation of foredeep deposits, and by structural evidence described

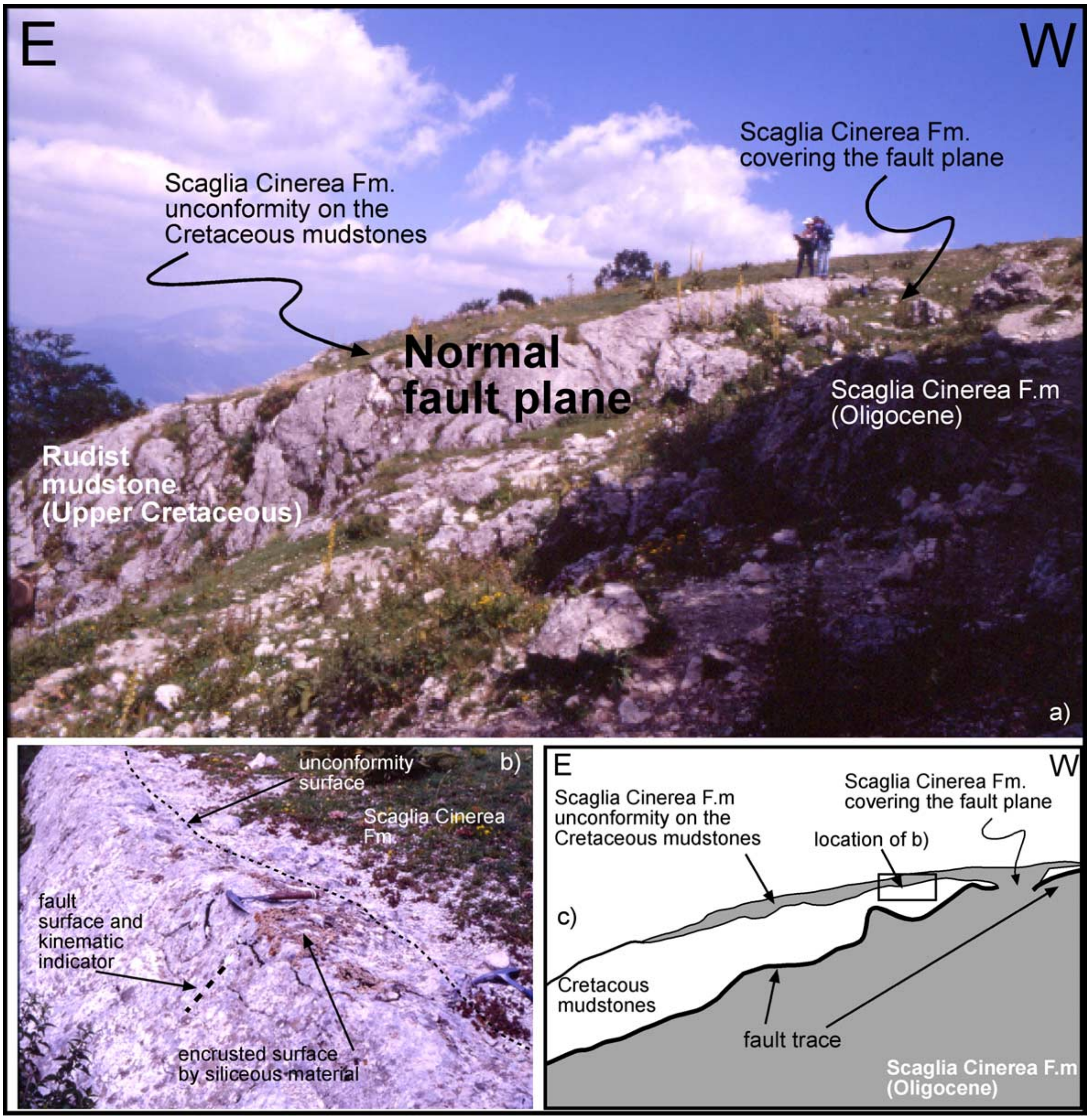

Fig. 12. Hanging-wall of M. Calvo Thrust (location on Fig. 11). (a) SW-dipping normal fault covered by deposits of Scaglia Cinerea Formation (Oligocene); (b) detail of the unconformity surface resting parallel to the top of the Upper Cretaceous Rudist mudstones; (c) sketch showing their geometric relationship.

Table 1
Table of events with key observations and interpretation from Cretaceous to Holocene in the study area

Age	Event	Structures	Kinematics
Late Cretaceous–Oligocene	Normal faulting	Thickness and facies variation of Scaglia Rossa and Scaglia Cinerea Formations (Fig. 11); normal fault closed by Scaglia Cinerea Formation (Fig. 12)	Extension?
Tortonian–Early Messinian	Normal faulting	Thickness and facies variation of siliciclastic turbidite (sandstones and clays). Onlap of turbidite on eroded platform carbonate substratum (Fig. 4)	Extension; NW–SE
Late Messinian–Early Pliocene	Thrusting	Contractional structures cutting the normal faults at meso- and macro-scale. Rotated normal fault. Normal fault plane acting locally as buttress against the thrust propagation.	Contraction; NW–SE; WNW–ESE
Late Pleistocene–Olocene	Normal faulting	Continental deposits (mostly breccias) displaced by extensional structures with reduced amount of displacement	Extension; NW–SE

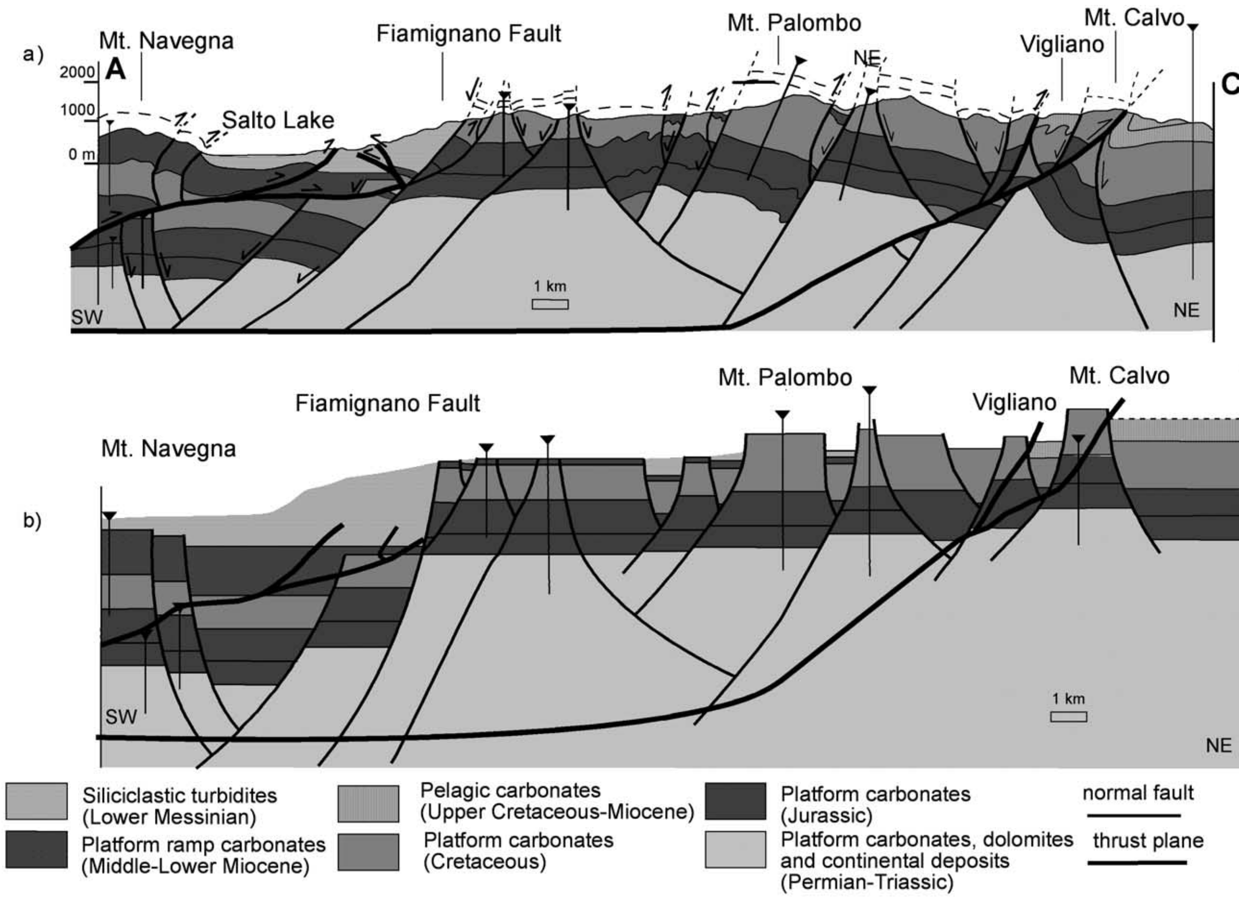

Fig. 13. (a) Balanced cross-section between M. S. Angelo–M. Calvo and its restored section (b). The section trace is shown in Fig. 3.

above for each structure. Faults such as the Fiamignano and the Val Malito structures produced most of the accommodation space for siliciclastic deposits in their hanging-walls, whereas, in the structurally elevated footwall areas (M. Nuria–M. Palombo), the Lower Messinian sandstones often directly overlie the substratum (Castello Reale); normal faults with minor offset bound small depressions corresponding to the present day intramountain basins (from Rocca to Rascino plains).

Later positive inversion of the Miocene extensional structures was quite limited, and generally the hanging-wall sequences are not uplifted above the regional. In this paper a large number of elements are proposed, collected along the main normal faults cropping out in the study area, supporting that the normal faults form first and are then cut by contractional structures.

6. Geological section

The stratigraphic and structural data described above provide geometric and kinematic constraints that were used to restore a SW–NE balanced cross-section from Mt. Navegna to the L'Aquila Plain (Fig. 13). The section is parallel to the thrust transport direction, and the restoration was conducted for the Liassic–Lower Messinian part of the succession. Both line-length and equal-area balancing techniques (Woodward et al., 1989) were used to obtain a restoration (Fig.13). The top of the Liassic and Cretaceous carbonates were used as key-horizons to estimate the shortening magnitude for the sedimentary cover. The thrust trajectories in the section cut through the sedimentary sequence from Triassic to Miocene rocks, while the basal detachment is not represented, due to a lack of subsurface data. Therefore, crystalline basement below the Apennine floor thrust is not included in the section and the sole thrust is located in the Permo-Triassic sequence.

The section is based on a kinematic model for thrusting across pre-existing normal faults. Similar models have been proposed for the Western Alps (Butler, 1989) and the external part of the Apennines, in the Gran Sasso and Mt. Maiella structure (Scisciani et al., 2000a,b).

In the eastern part of the section, the M. Navegna thrust propagates across the Miocene carbonates until it reaches the Fiamignano normal fault. The front of this thrust crops out in the Salto Valley, where the upper part of the Miocene carbonates is placed on the Lower Messinian sandstones (in the south; Fig. 3). This geometry is interpreted in the section considering that at the contact with the Fiamignano fault, the thrust plane was unable to propagate into the carbonate platform succession that acted as a buttress. Back-thrusting occurred as a result of the forward migration of the thrust detachment.

The total length of the section is about 26 km, while the shortening displacement for the section is 1.6 km, calculated between the tip lines located in the Jurassic and Cretaceous layers of M. Navegna structure and in the footwall of M. Calvo thrust, respectively. This displacement is entirely accommodated by contractional structures, and is significantly lower than the values obtained by Parotto and Praturlon (1975) and Salvucci (1997) for the M. Calvo thrust and by Bally et al. (1986) for the M. Navegna–M. S. Angelo structure.

7. Conclusions

The present day structural setting of the Lazio–Abruzzi platform is an example of the style of deformation of a Peri-Tethyan carbonate platform developed and extended during its foreland stage and then affected by contraction during the development of the Central Apennines fold-and-thrust-belt. Stratigraphic (e.g. Milli and Moscatelli, 2000, 2001) and structural data (this paper) indicate that the carbonate platform was affected by normal faulting during the Cretaceous–Oligocene and Tortonian–Early Messinian time intervals. The oldest normal faults controlled the drowning portion of the carbonate platform, determining thickness and facies variation in the Cretaceous–Oligocene sedimentary successions. The restored position of these normal fault systems, within the pre-thrusting template of Fig. 13 coincides with the location of the younger contractional structures, such as thrusts and back thrusts. However the most evident pre-thrusting normal faults were mainly active during Tortonian–Early Messinian times, i.e. during deposition of syn-orogenic siliciclastics. This is recorded by the foredeep sequence, which exhibits thickness and facies variations across the hanging-walls and the footwalls of these normal faults. These structures produced tectonic depressions at their hanging wall where clastic sediments were deposited. This conclusion is consistent with sequence stratigraphic studies that indicate deposition within a fault-confined basin (Milli and Moscatelli, 2000, 2001). Structural analysis and overprinting criteria along the normal faults also highlight the time relationships between extensional and contractional deformations: these indicate that normal faults formed first and were later deformed by younger contractional structures.

During the subsequent orogenic contractional stage, pre-thrusting normal faults were not reverse-reactivated. No evidence of kinematic inversion has been collected along the investigated structures, which are generally rotated and/or folded by contractional structures. The deposits occurring in the hanging wall of the pre-thrusting normal faults are highly deformed, indicating a high stress concentration against the main fault surface. These structural features (fold trains and back-thrusts) are characteristic of structural settings dominated by buttressing processes.

Although a contractional event usually overprints earlier structures, most of the Miocene normal faults are still preserved in this sector of the Central Apennines, allowing the reconstruction of a Lower Messinian paleogeography. The geometric and time relationships between the tectonic features provided by the structural analysis and interpretation, used to constrain the balancing and restoration of a geological section crossing this sector of the carbonate platform domain, yields a structural style very different from the ones so far applied. Also the total amount of shortening (1.6 km) is an order of magnitude lower than the previously calculated shortening (15 km) in the same area.

The extensional tectonics documented in this study, possibly related to foreland deformation and peripheral bulge uplift, was followed by a contractional event that probably involved the whole Lazio–Abruzzi carbonate platform in a very short time span (Middle–Upper Messinian), producing folding and synchronous thrusting. The results of this study shows how a complex paleogeography, corresponding to a foreland plate organized in a horst and graben geometry, could control the structural setting and the geological evolution of the subsequently evolving Central Apennines fold and thrust belt. The comparison between the structures described in the Apennines and the structures from other areas could provide critical information for a better understanding of the mechanisms linked to the initial stages of the orogenic processes.

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