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The interaction of extensional and contractional deformations in the outer zones of the Central Apennines, Italy

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Abstract

The relationships among normal faults and thrusts in the Apennines of Italy are often unclear, and the local absence of syn-tectonic stratigraphic controls have led to contrasting interpretations on the relative chronology for both classes of structures. The activity of normal faults has been variously regarded as due to pre-, syn- or post-orogenic extension, and the contrasting evidence from different sites has produced an ongoing debate on the normal fault–thrust interaction. The results of a kinematic analysis on selected composite structures of the outer zones of the Central Apennines make it possible to unequivocally establish a relative chronology of extensional and contractional deformations. Detailed mapping, outcrop-scale observations and structural overprinting relationships support a positive inversion tectonic history, where normal faults and fault-controlled escarpments formed first, and were later deformed by thrusts and related folds. All normal faults control the distribution of foredeep deposits, thus indicating that the recognised episode of positive inversion is related to the incipient stages of construction of the Apennine thrust belt. The systematic collection of structural data may help to unravel the evolution of adjacent sectors of the Apennine chain, as well as of other belt-foredeep–foreland systems whose extension–contraction relationships are poorly constrained. © 2002 Published by Elsevier Science Ltd.

Keywords: Kinematic analysis; Extensional and contractional deformations; Positive inversion tectonic history; Central Apennines

1. Introduction

The architecture of fold-and-thrust belts is dominated by contractional structures that generally display relatively simple geometrical features (Bally et al., 1966; Boyer and Elliott, 1982). However, folds and thrusts often interfere with extensional deformations producing complex, composite structures (Fig. 1). The deformation styles of thrust-related folds along former passive margins or continental rifts may be quite complicated, due to the interaction of early extensional and late contractional structures (Fig. 1a; Gillcrist et al., 1987; Butler, 1989). Other common complexities in fold-and-thrust belts generally result from the modification of contractional structures by younger normal faults developed during late- or post-orogenic extension (Fig. 1b; Wernicke and Burchfiel, 1982; Constenius, 1996). The changes from early extension to late contraction, and from early contraction to late extension, are defined as positive and negative tectonic inversion, respectively (Williams et al., 1989). Although the tectonic inversion processes are often assumed to occur by simple fault reactivation, several studies have shown that inverted structures may display complex geometries, with pre-existing fault surfaces that can be either truncated by, or reactivated as, younger faults (Butler, 1989; Hayward and Graham, 1989).

In addition to pre-, and late- or post-orogenic extension, resulting from positive or negative tectonic inversion, further complication may arise from syn-orogenic extensional structures that are kinematically linked to the growth of thrust-related folds, and that commonly consist of normal faults developed in the hanging walls of moving thrust sheets (Fig. 1c and d; Butler et al., 1987; Meyer et al., 1990; Coward et al., 1992). Therefore, in the study of orogenic belts where extensional structures occur, the relationships between thrusts and normal faults may be difficult to establish (e.g. Coryell and Spang, 1988; O'Dea and Lister, 1995). Reliable stratigraphic and structural criteria are needed to correctly unravel the local deformation histories of these settings, and hence to quantify and separate the effects of pre-, syn- and post-orogenic extension (e.g. see Holdsworth et al., 1997; Tavarnelli, 1999).

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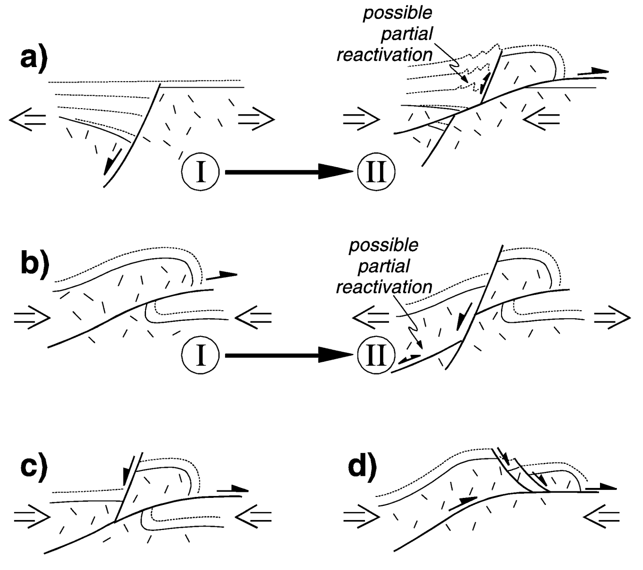

Fig. 1. Modes of possible thrust-normal fault interactions in orogenic belts. (a) Early normal fault truncated by a younger thrust (positive inversion: I–II in time). (b) Early thrust truncated by a younger normal fault (negative inversion: I–II in time). (c) Hinterland-dipping normal fault within a thrust sheet. (d) Foreland-dipping normal fault within a thrust sheet. Normal faults are pre-thrusting in (a), post-thrusting in (b) and syn-thrusting in (c) and (d).

The Apennines of Italy is an orogenic system that bears the signature of both pre- and post-orogenic extension (Elter et al., 1975; Hippolyte et al., 1995). The relationships among normal faults and thrusts are often unclear, and have led to contrasting interpretations on their relative timing of development. The aim of this paper is to provide additional constraints to help establish the chronology of extensional and contractional deformations at selected sites in the outer, i.e. eastern zones of the Central Apennines, and to describe the structural styles resulting from the interaction between normal faults and thrusts.

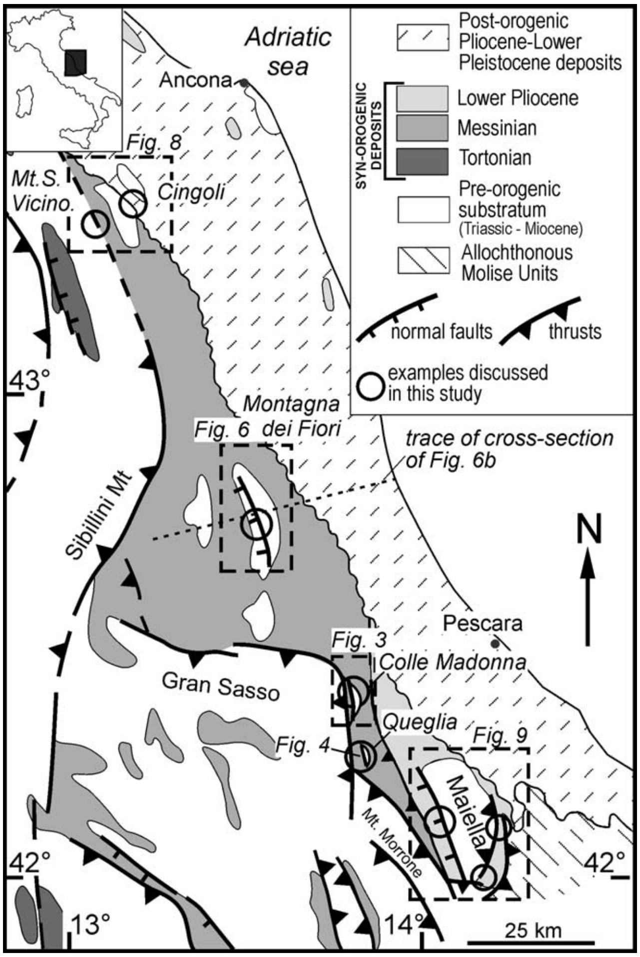

Fig. 2. Tectonic sketch map of the Central Apennines of Italy, with location of the structures described in this study.

2. Geological setting

The Apennines of Italy is a fold-and-thrust belt that developed from Oligocene time onwards, following the closure of the Mesozoic Tethys Ocean and the collision of the African and European continental margins (Carmignani and Kligfield, 1990). The stratigraphic section cropping out in the eastern zone of the Central Apennines consists of a pre-orogenic Triassic–Miocene, mainly carbonate sequence, overlain by Miocene–Pliocene syn-orogenic sediments (Fig. 2). The pre-orogenic sequence experienced significant extension during the Triassic, Jurassic and Cretaceous–Paleogene time intervals (Centamore et al., 1971; Decandia, 1982; Martini et al., 1986). From Miocene time onwards, the pre-orogenic sequence was detached from the underlying basement along Triassic evaporites (Bally et al., 1986), and was affected by ENE-verging folds and related thrusts that overprinted Triassic–Paleogene normal faults and produced complex structures (Winter and Tapponnier, 1991; Bruni et al., 1995; Tavarnelli, 1996). The main regional features of the outer zones of the Central Apennines correspond to the Mt. Sibillini, Gran Sasso and Mt. Morrone overthrusts (Fig. 2). Contractional deformation was accompanied by the development of foredeep basins filled with syn-orogenic deposits ahead of the advancing thrust structures (Ricci Lucchi, 1986). The age of syn-orogenic deposits decreases eastwards, indicating a progressive migration of the belt-foredeep system towards the foreland (Fig. 2; Boccaletti et al., 1990). From Pliocene time onwards, orogenic contraction was followed by the onset of late- or post-orogenic extension related to the opening and evolution of the Tyrrhenian Sea (Carmignani et al., 1994; Lavecchia et al., 1994) with development of structures that overprinted and/or partly reactivated pre-existing thrust surfaces as low-angle normal faults (Cooper and Burbi, 1986; Decandia and Tavarnelli, 1991).

3. Relationships among thrusts and normal faults in the Apennines

The Apennines show many situations where normal faults and thrusts interfere, and the relationship among these two classes of structures is generally clear, so that it is usually possible to determine reliably whether the normal faults predated or post-dated thrusting. However, the relative chronology of normal faults and thrusts is sometimes difficult to establish, due to the local lack of stratigraphic constraints. Three main classes of models have been proposed that alternatively consider normal faults as pre-, syn- or post-orogenic structures.

The occurrence of normal faults in the backlimbs of Apennine thrust-related anticlines has long been recognised (Lotti, 1926; Elter et al., 1975), and has been interpreted in terms of a mechanical model, the composite-wedge model (Migliorini, 1948), where a wedge-shaped tectonic unit, bounded by a gently hinterland-dipping reverse fault at its front and by a steeply hinterland-dipping normal fault at its rear, is pushed up and extruded during orogenic contraction (Fig. 1c; Migliorini, 1948; Castellarin et al., 1985). A variant of this composite-wedge model predicts that thrust-induced extensional strains are accommodated by shallow foreland-dipping (Fig. 1d; Bonini et al., 2000) or steep hinterland-dipping (Ghisetti and Vezzani, 2000) normal faults, that develop within thrust sheets as they are carried piggy-back above stepped, ramp-flat thrust surfaces. Both interpretations require a kinematic link between extensional and contractional deformations within the framework of a single event of orogenic shortening, and therefore consider normal faults as syn-thrusting features.

A different interpretation considers the normal fault–thrust interaction as resulting from a reversal of the dominant tectonic regime, either from extension to contraction (positive inversion) or from contraction to extension (negative inversion), and examples of both pre- and post-thrusting normal faults are widely documented (Elter et al., 1975; Hippolyte et al., 1995). However, normal faults in the backlimbs of given thrust-related anticlines have been interpreted alternatively as pre-orogenic (Fig. 1a; Tavarnelli, 1996; Calamita et al., 1998) or post-orogenic (Fig. 1b; Mattei, 1987; D'Agostino et al., 1998). Moreover, stratigraphic studies have shown that the shape of some foredeep basins ahead of advancing thrust fronts in the Central Apennines was controlled by syn-sedimentary normal faults active soon before thrust propagation, thus supporting the view of pre-thrusting, syn-orogenic extension (Calamita and Deiana, 1980; Alberti et al., 1996; Tavarnelli and Peacock, 1999; Scisciani et al., 2001). In the forthcoming sections we present the results of a kinematic analysis carried out along several composite structures where normal faults and thrusts occur together, and whose relative chronology is poorly constrained. We focus on the most commonly observed geometries and deformation styles of extensional and contractional structures that affect Neogene syn-orogenic deposits and their pre-orogenic substrata in the eastern province of the Central Apennines (Fig. 2). Normal faults are abundant throughout the belt; however, due to recent uplift and erosion, their relationships with folds and thrusts are best preserved in two structural positions, corresponding to the backlimbs and forelimbs of the main thrust-related anticlines, respectively.

4. The Colle Madonna structure

The Colle Madonna structure is a minor east-verging, thrust-related anticline developed east of the Gran Sasso overthrust (Fig. 2). The anticline, that extends for 4 km with a general N–S trend, affects a Cretaceous–Miocene, pre-orogenic carbonate sequence overlain by syn-orogenic, calcareous and siliciclastic deposits of Burdigalian–Early Messinian age (Fig. 3a; Ghisetti et al., 1992; Bigi et al., 1997). The anticline is thrust onto Late Messinian siliciclastic deposits along a gently W-dipping reverse fault

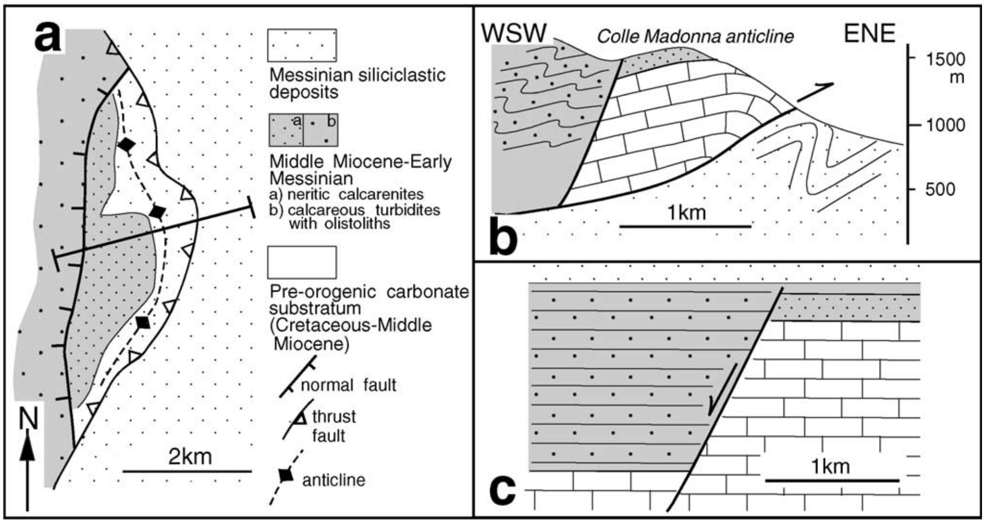

Fig. 3. The Colle Madonna structure (see Fig. 2 for location). (a) Simplified geological map. (b) Simplified cross-section (trace in (a)). (c) Schematic restoration of the pre-thrusting template.

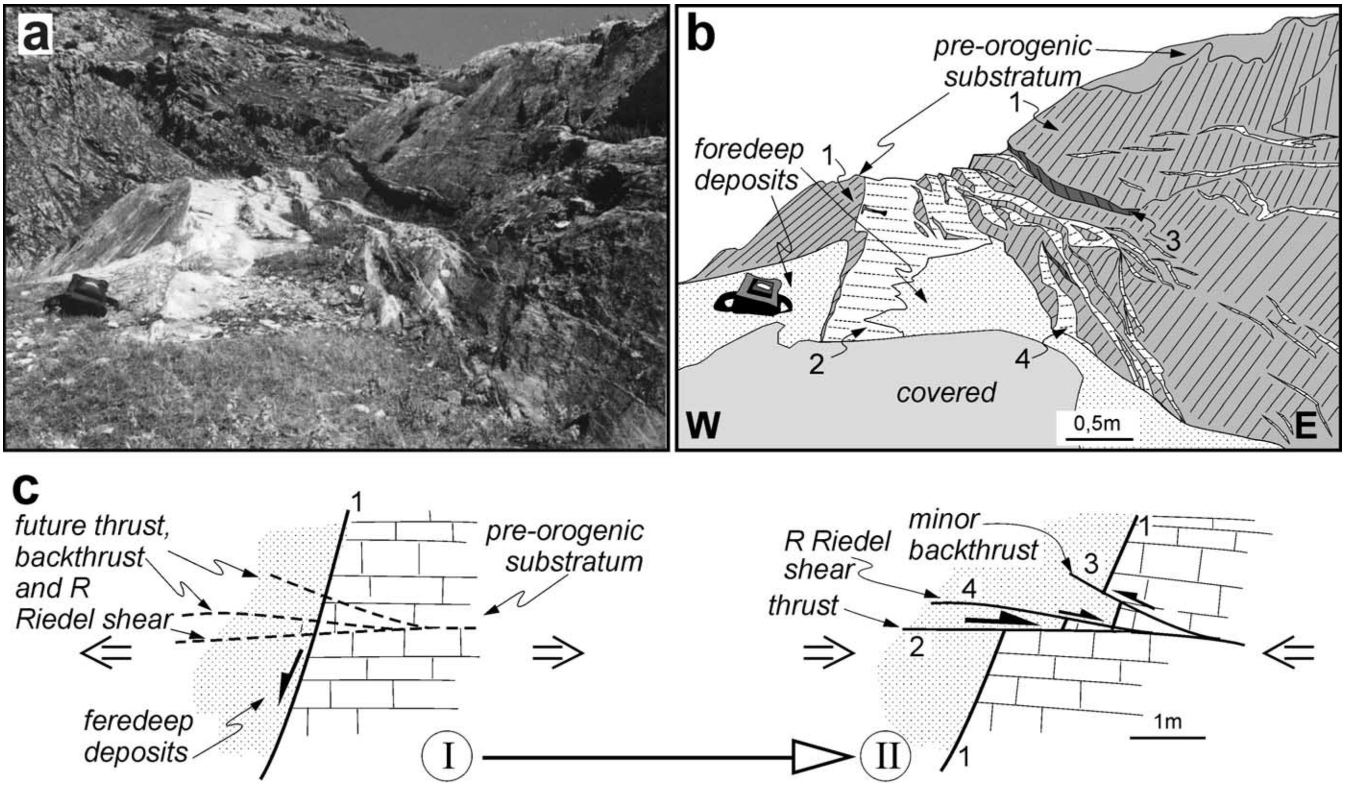

Fig. 4. Normal fault–thrust interaction in the backlimb of the Queglia anticline (see Fig. 2 for location). (a) Photograph and (b) line drawing illustrating the steeply W-dipping normal fault surface (1) truncated and offset by forethrusts (2), backthrusts (3) and R Riedel shears (4). (c) Inferred transition from early extension to late contraction (I–II in time) based on the observed overprinting relationships.

(Fig. 3b). The backlimb of the anticline is truncated by a steeply W-dipping normal fault (Fig. 3b). The syn-orogenic sequence displays significant thickness and facies variations across the normal fault, where a 100-m-thick sequence of neritic calcarenites of Tortonian–Early Messinian age in the footwall is juxtaposed with coeval, up to 800-m-thick calcareous turbidites with abundant olistoliths in the hanging wall (Fig. 3c). These stratigraphic variations across the normal fault indicate that its development occurred during deposition of the syn-orogenic sediments in Burdigalian–Early Messinian time (Fig. 3c). The normal fault is not laterally continuous, but rather terminates downwards

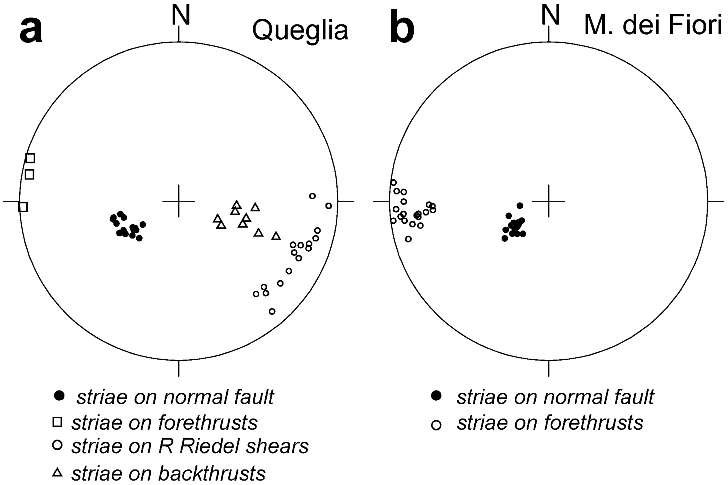

Fig. 5. Kinematic data from normal faults, thrusts and backthrusts in the backlimbs of the Queglia (a) and Montagna dei Fiori (b) anticlines (equal area projection, lower hemisphere). (a) The striations on the normal fault mean plunge 70° towards N242E. The striations on the thrusts, backthrusts and R Riedel shears are aligned along a mean N120E direction. (b) The striations on the normal fault mean plunge 75° towards N234E. The striations on the thrusts mean plunge 20° towards N265E and indicate a top-to-the-E sense of shear.

against the thrust surface. This relationship suggests that extensional deformations pre-date the onset of contraction, and that the normal fault was truncated and carried piggy-back by the upward propagating thrust during Late Messinian time.

5. The Queglia structure

The Queglia structure is a minor thrust-related anticline developed north of the Mt. Morrone overthrust (Fig. 2). The anticline extends for 3 km with a general N160E trend, and affects a Cretaceous–Miocene pre-orogenic calcareous sequence, overlain by syn-orogenic siliciclastic turbidites of Messinian age (Ghisetti et al., 1992; Bigi et al., 1997). These relationships are complicated in the backlimb of the thrust-related anticline (Fig. 4a), where a hinterland-dipping normal fault juxtaposes syn-orogenic deposits in the hanging wall against the pre-orogenic substratum in the footwall (Fig. 4b). The normal fault surface appears truncated by arrays of sub-horizontal or gently WSW-dipping minor thrusts and moderately ENE-dipping backthrusts that produce offsets up to 2 m (Fig. 4). These relationships indicate that the normal fault formed first, and was subsequently truncated by linked forethrusts and backthrusts, thus revealing a switch from early extension to late contraction (Fig. 4c). Sub-horizontal thrusts are also locally accompanied by gently ENE-dipping faults that produce top-to-the-ENE displacements, and that we interpret as thrust-induced, synthetic R Riedel shears (Fig. 4c). Mechanical striations collected along the normal fault surface plunge 70° towards N242E, indicating dip slip (Fig. 5a). Shearing fibres and slickenlines along the forethrusts, R Riedel shears and backthrusts are aligned along a mean N120E direction (Fig. 5a). Therefore, the slip vectors reconstructed for early extensional and late contractional structures are not coaxial, an observation suggesting a lack of kinematic consistency between normal and thrust faults.

6. The Montagna dei Fiori structure

The Montagna dei Fiori structure is a thrust-related anticline developed north of the Gran Sasso overthrust (Fig. 2). The anticline extends for over 30 km with a general N150E trend, and affects a Jurassic–Miocene pre-orogenic carbonate sequence, overlain by syn-orogenic deposits of Burdigalian–Messinian age (Fig. 6a; Giannini, 1960; Mattei, 1987; Calamita, 1990). The overall geometry is illustrated on a regional balanced section that extends for 35 km across the main contractional structures that occupy the outer zones of the Central Apennines (Fig. 6c). The section was constructed integrating available surface data (Centamore et al., 1991) with information derived from borehole data and seismic reflection profiles (Bally et al., 1986; Calamita et al., 1991; Paltrinieri et al., 1992). The restored template obtained by removing the effects of both

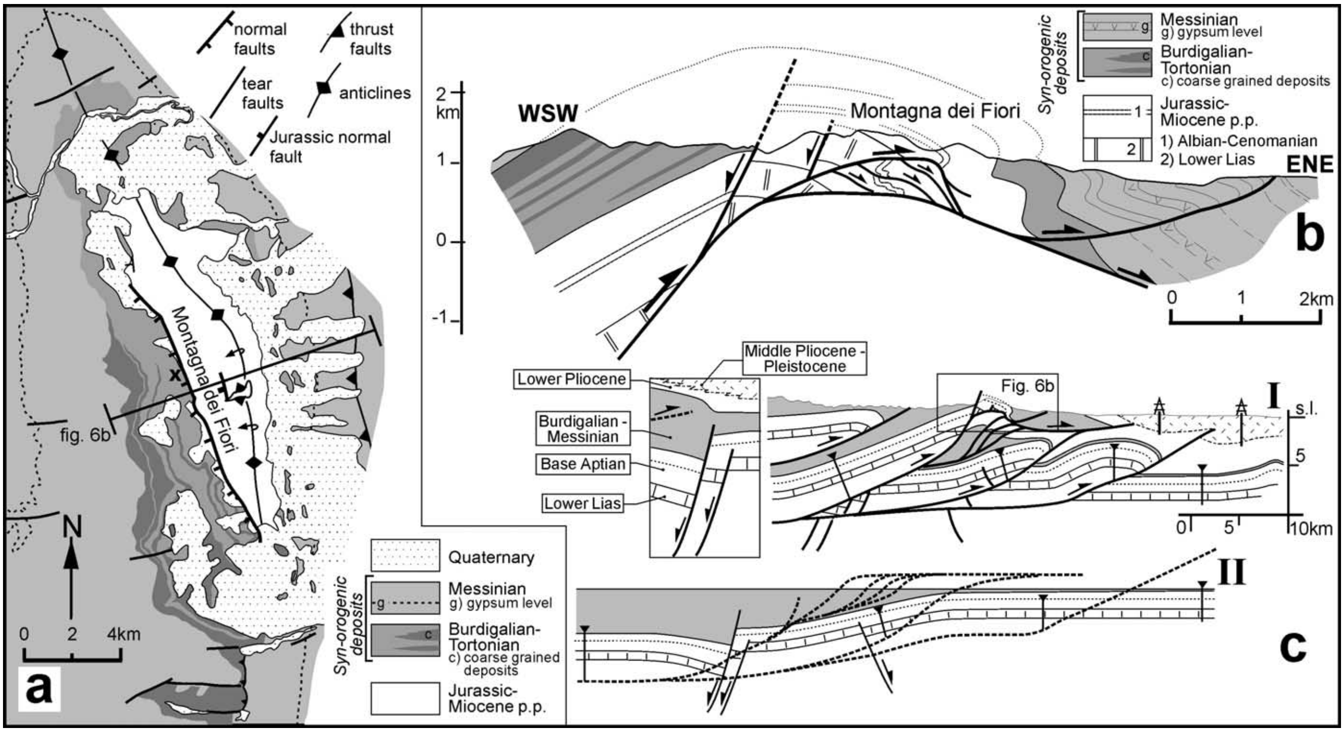

Fig. 6. The Montagna dei Fiori structure (see Fig. 2 for location). (a) Simplified geological map. (b) Detailed cross-section (trace in (a)). (c) Regional balanced (I) and restored (II) cross-section (see trace in Fig. 2), showing a major W-dipping normal fault in the pre-thrusting template. The balanced cross-section (I) is based on integrated surface and subsurface data.

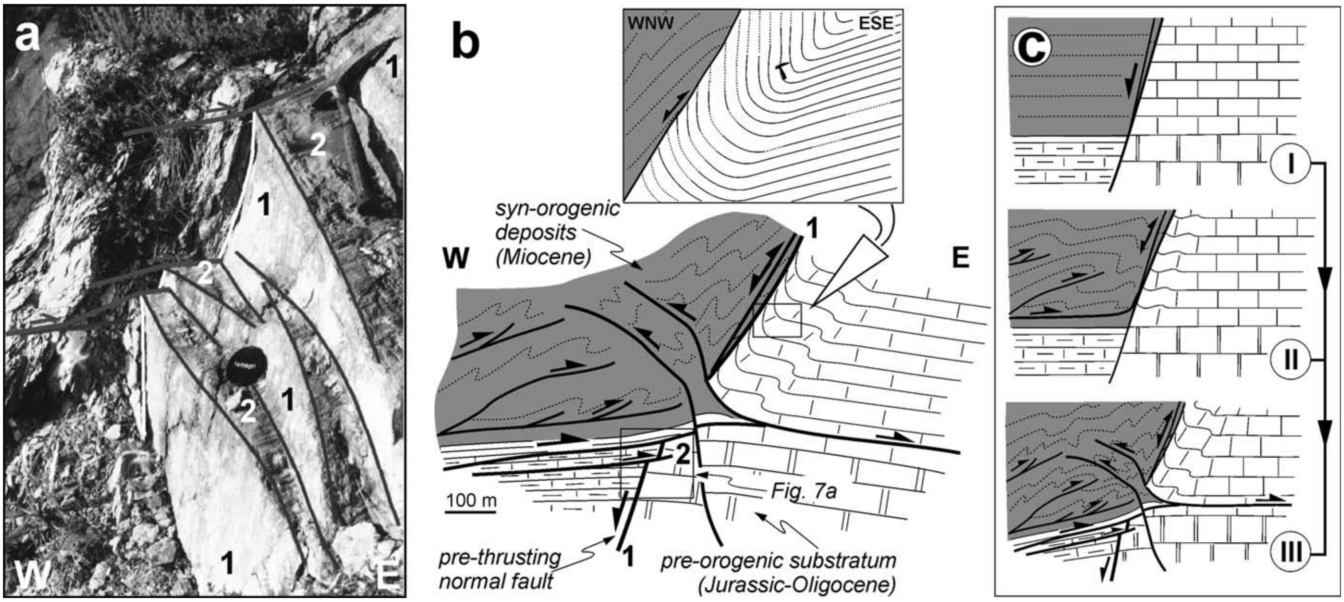

Fig. 7. Normal fault–thrust interaction in the backlimb of the Montagna dei Fiori anticline. (a) Photograph illustrating the steeply W-dipping normal fault surface truncated and offset by mesoscopic forethrusts (location X in Fig. 6a). (b) Interpretation of the relationships shown in (a); the inset shows the style of folding due to buttressing against the normal fault. (c) Proposed deformation history (I–III in time) based on the relationships shown in (a) and in inset of (b).

folding and thrusting is 63 km long (Fig. 6c). The inferred orogenic shortening is 28 km, an estimate that is highly conservative due to the lack of information on additional contraction taken up by carbonates through pressure-solution fabrics.

The main thrust surface is antiformally folded by the growth of a younger thrust-related anticline in its footwall (Fig. 6b and c; Calamita, 1990). The contact between syn-orogenic deposits and the pre-orogenic substratum in the backlimb of the Montagna dei Fiori anticline corresponds to a steeply WSW-dipping normal fault, that produces an offset of 900 m (Fig. 6b). The syn-orogenic stratigraphic sections on both sides of the normal fault display remarkable thickness and facies variations: a condensed, 500-m-thick sequence of fine-grained marls of Burdigalian–Tortonian age, in the footwall, passes to a complete, 1400-m-thick sequence of coeval marls with abundant calcarenites (Fig. 6b). Mechanical striations along the fault surface mean plunge 75° towards N234E (Fig. 5b), and record dip-slip.

The structural relationships among extensional and contractional deformations are particularly clear when observed at the outcrop scale. At location X of Fig. 6a, the steeply W-dipping normal fault surface is truncated by arrays of gently W-dipping minor thrusts that produce offsets up to 20 cm (Fig. 7a). Slickenfibres along the thrust surfaces mean plunge 20° towards N265E and indicate top-to-the-ENE displacements (Fig. 5b). Some of these thrusts are, in turn, truncated by moderately E-dipping backthrusts (Fig. 7b). Truncation of the normal fault by thrusting (Fig. 7a and b) is accompanied by local folding of both pre-orogenic and syn-orogenic sediments adjacent to the fault surface (Fig. 7b). Minor folds are tight near the fault surface and moderate to open away from it. By simple analogy with observations on thrusts developed across pre-existing extensional structures elsewhere (e.g. the French Alps; Butler, 1989), this change of minor fold geometry with respect to the normal fault is here interpreted as due to a buttressing effect. The structural overprinting relationships observed at location X (see Fig. 6a) indicate that the development of the normal fault pre-date the episode of contraction (Fig. 7c). The thickness and facies variation of syn-orogenic deposits reflect the activity of the normal fault, thus indicating its syn-sedimentary character (stage I of Fig. 7c). Contractional deformation was accommodated by gently W-dipping thrusts and by moderate folding due to buttressing of the pre- and syn-orogenic sediments against the normal fault surface. Local structural complexities, with abundant evidence for slip and shear sense reversal along the normal fault could be due to its partial reactivation as a high-angle reverse fault (stage II of Fig. 7c). Additional contraction was then taken up by moderately E-dipping backthrusts (stage III of Fig. 7c).

The history inferred from mesoscopic data (Fig. 7) make it possible to unravel the tectonic evolution of the larger, host Montagna dei Fiori structure. Restoration of the regional cross-section I of Fig. 6c, based on the inferred relative chronology of events, shows a pre-thrusting template characterised by both foreland- and hinterland-dipping normal faults of different ages, from Jurassic to Miocene (II of Fig. 6c). The major pre-thrusting normal fault, that at present occurs in the backlimb of the Montagna dei Fiori anticline (I of Fig. 6c), is shown in the pre-thrusting template as a major feature responsible for the stratigraphic variations of the syn-orogenic deposits (II of Fig. 6c). The angle between the mean N234E direction of normal fault slip and the mean N265E thrusting direction indicates that the kinematic axes for early extension and late contraction are not coaxial, thus suggesting that the two subsequent deformations are not related.

It is important to stress that most contractional displacement was taken up by thrusting and related development of the Montagna dei Fiori macroscopic anticline, whereas mesoscopic folding due to buttressing against the normal fault and its partial reverse reactivation only represent minor components of the described inversion process. This behaviour could be explained in terms of experimental models, where deformation appears diffuse around the normal faults first, and becomes localised along discrete thrust surfaces during the advanced stages of inversion (e.g. see Eisenstadt and Withjack, 1995).

7. The Mt. San Vicino and Cingoli structures

The examples described in the previous sections provide evidence for normal faults located in the backlimbs of thrust-related anticlines. However, normal faults in the Central Apennines also occur in a different structural position, namely in the anticline forelimbs. Two examples are seen in the Mt. San Vicino and Cingoli structures (Fig. 8a), whose main geometrical features are illustrated on a 20-km-long regional balanced cross-section (Fig. 8b). The section was constructed using available surface and seismic reflection data (Calamita et al., 1991), and was restored using line-length restoration techniques (Fig. 8c).

The Mt. San Vicino structure is a thrust-related anticline developed in the hanging wall of the Mt. Sibillini overthrust (Fig. 2), and extends for 50 km with a general N150E trend (Fig. 8a; Calamita et al., 1990). The Cingoli structure is a minor thrust-related anticline developed east of the Mt. San Vicino anticline, in the footwall of the Mt. Sibillini overthrust, and extends for 15 km with an arcuate trend, ranging from N130E to N170E (Fig. 8a; Calamita et al., 1991). Both structures affect a Jurassic–Miocene pre-orogenic carbonate sequence, overlain by syn-orogenic, siliciclastic turbidites of Messinian and Early Pliocene age. The Messinian and Early Pliocene sequences are locally separated by an unconformity. The anticline forelimbs, that affect the pre-orogenic sequence, dip moderately to steeply (40–70°) towards the east-northeast (Fig. 8b). They are commonly truncated by faults that also propagate across the basal strata of the overlying Messinian syn-orogenic deposits, dip steeply towards the west-southwest, and make with bedding high (60–80°) cutoff angles. These faults are associated with significant thickness and facies variations of syn-orogenic deposits (e.g. see insets X and Y of Fig. 8b). In particular, at Mt. San Vicino the WSW-dipping fault determines the superposition of a 100-m-thick, condensed sequence of sandstones and marls of Early Messinian age, onto a coeval, 400-m-thick complete sequence (see inset X in Fig. 8b). These differences across the fault are sealed by a thin

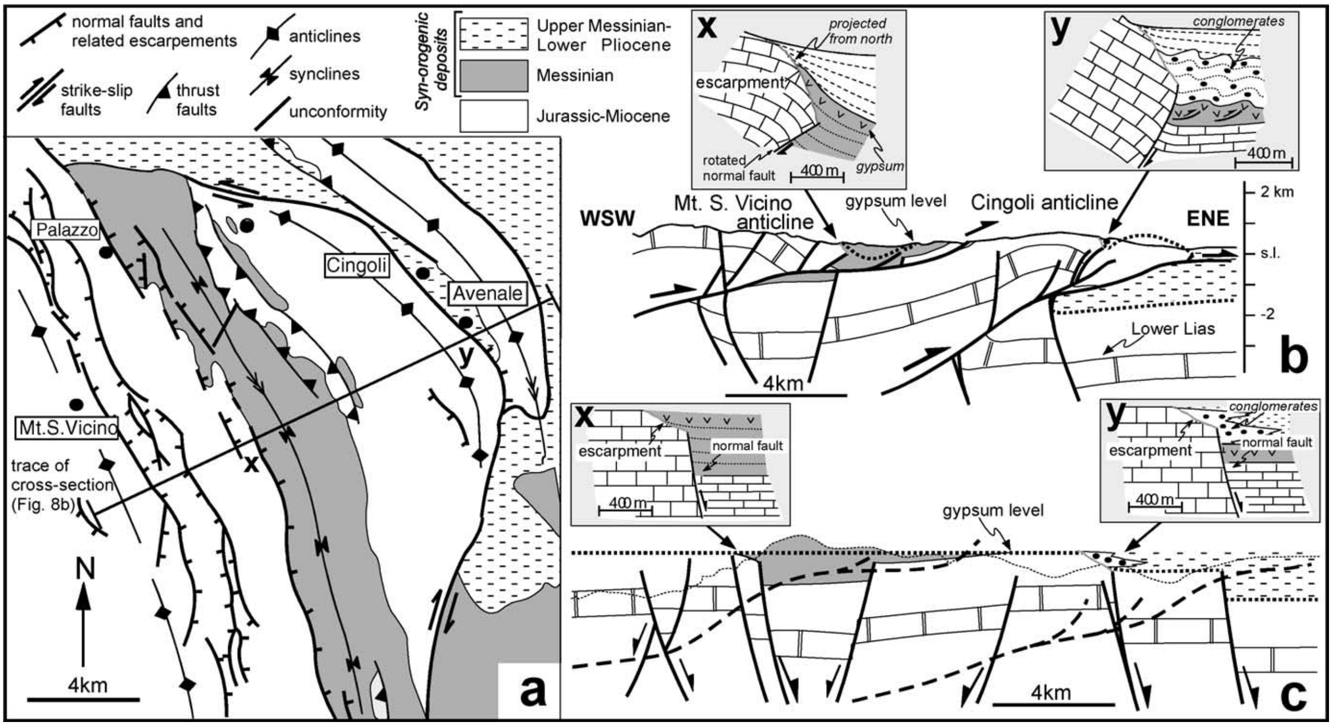

Fig. 8. The Mt. San Vicino and Cingoli structures (see Fig. 2 for location). (a) Simplified geological map. (b) Balanced cross-section (trace in (a)), constructed using available surface and subsurface data (Calamita et al., 1990). The insets X and Y show the relationships between faults, escarpments and syn-orogenic sediments seen at Mt. San Vicino and Avenale, respectively. (c) Restored template, showing the pre-thrusting normal faults, and the inferred original relationships seen at Mt. San Vicino (X) and Avenale (Y).

layer of gypsum, that constrains the fault activity to Messinian time.

The activity of WSW-dipping faults was accompanied by intense erosion of their uplifted blocks, so that it is locally possible to recognise fault-related escarpments. At Mt. San Vicino and Avenale, syn-orogenic deposits of Messinian age onlap the eroded, moderately ENE-dipping strata of pre-orogenic carbonates along steeply ENE-dipping escarpments (see insets X and Y in Fig. 3b). The recognition of the fault-related escarpments is a critical feature, because it allows for a correct restoration of the topographic surface during faulting. Several studies have shown that the original dip of most Apennine fault-related escarpments range from 25 to 35° (Bice and Stewart, 1985; Alvarez, 1990): therefore we assume for the Mt. San Vicino and Avenale escarpments an average, original 30° dip. Once the effect of tilting is removed, and the escarpments are restored to their presumed original dip, the restored fault surfaces dip steeply towards the east-northeast, and exhibit a remarkable extensional character (see insets X and Y of Fig. 8c). The normal faults and the fault-related escarpments are, in turn, sealed by unconformably overlying siliciclastic deposits of Early Pliocene age. These relationships provide a key for restoration of the regional cross-section of Fig. 8b. The normal faults were active in a steeply ENE-dipping attitude during Messinian time, and were tilted to their present WSW-dipping attitude during the growth of the Mt. San Vicino and Cingoli anticlines in Early Pliocene time (Fig. 8b and c).

8. The Maiella structure

The folds described so far display evidence for pre-thrusting extension in their backlimbs or forelimbs; however, it is locally possible to recognise anticlines whose limbs are both affected by normal faults. The clearest example is provided by the Maiella anticline, a thrust-related fold that extends for 25 km with an arcuate trend, ranging from N130E to N200E, whose development is referred to Middle Pliocene time (Fig. 9a; Casnedi et al., 1981). The geometry of the structure was reconstructed using available surface, borehole and seismic reflection data (Casnedi et al., 1981) integrated in a regional balanced cross-section (Fig. 9b and c). The Jurassic–Miocene pre-orogenic sequence within the moderately (25–45°) WSW-dipping backlimb is truncated by a steeply WSW- to SW-dipping normal fault (Fig. 9a), that abuts 500-m-thick Messinian siliciclastic sediments with olistoliths and slumps in its hanging wall, against a coeval 50-m-thick, condensed mudstone sequence in its footwall (Fig. 9b). These relationships indicate for the

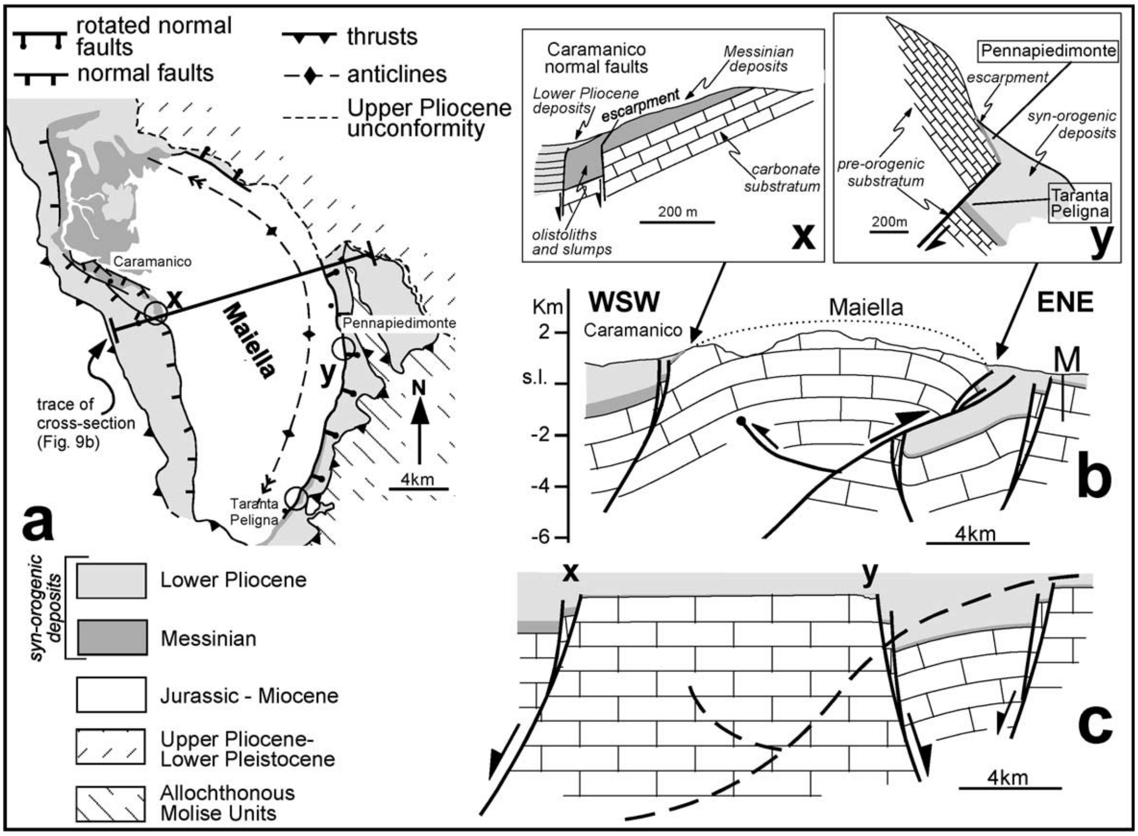

Fig. 9. The Maiella structure (see Fig. 2 for location). (a) Simplified geological map. (b) Balanced cross-section (trace in (a)). the insets X and Y show the relationships between faults, escarpments and syn-orogenic sediments seen at Caramanico and Taranta Peligna–Pennapiedimonte, respectively. (c) Restored template, showing the pre-thrusting normal faults. Note that the eastern fault at Caramanico has a Messinian age, whereas the western fault has an Early Pliocene age.

normal fault a Messinian age and a syn-sedimentary character. Relicts of a related, WSW-dipping fault-controlled escarpment are seen at Caramanico (inset X in Fig. 9b). The Messinian deposits are, in turn, truncated and offset by a younger, parallel normal fault, that is sealed by Lower Pliocene deposits (inset X in Fig. 9b). The forelimb of the Maiella anticline dips 60–70° towards ENE, and is truncated by a moderately WNW-dipping fault, that makes high (ca. 70°) cutoff angles to bedding. At Pennapiedimonte and Taranta Peligna (location in Fig. 9a), this fault is sealed by Lower Pliocene syn-orogenic deposits (see inset Y in Fig. 4b). At Pennapiedimonte, the fault activity produced a steeply ENE-dipping erosional escarpment, similar to those seen at Mt. San Vicino and Avenale. When the effects of tilting due to folding are eliminated, and the fault-induced escarpment is restored to its presumed 30° ENE-dip, the restored fault surface dips steeply towards the foreland (Fig. 9c). The relationships seen on both limbs of the Maiella anticline indicate that the structure had the features of a normal fault-bounded horst in Early Pliocene time (Fig. 9c), and that it was subsequently affected by folding and thrusting, with rotation of the foreland-dipping normal fault to its present WNW-dipping attitude, during Middle Pliocene time (Fig. 9b). Moreover, the relationships seen at Caramanico, where the WSW-dipping normal fault of Early Pliocene age developed in the vicinity of an older, parallel Messinian normal fault, indicate that extensional deformation was active in the area since Late Miocene time.

9. Discussion

Syn-thrusting extension is known to occur in the hanging walls of moving thrust sheets (e.g. see Meyer et al., 1990), and post-orogenic extension related to the opening and evolution of the Tyrrhenian Sea has severely modified the contractional architecture of the Apennine fold-and-thrust belt (Carmignani et al., 1994; Lavecchia et al., 1994). It is perhaps for these reasons that many previous accounts on the structure of the outer zones of the Central Apennines consider most normal faults affecting syn-orogenic deposits as synchronous with (e.g. Bonini et al., 2000; Ghisetti and Vezzani, 2000), or subsequent to thrusting (e.g. see Mattei, 1987; D'Agostino et al., 1998). The data presented in this study, instead, provide new structural constraints that make it possible to establish a reverse chronology, with early extension followed by late contraction in the Colle Madonna, Queglia, Montagna dei Fiori, Mt. San Vicino, Cingoli and Maiella structures. In all these localities, normal faults examined in scattered outcrops appear truncated, or modified by younger contractional structures, namely thrusts and/or backthrusts and related folds. We consider these relationships as unequivocal structural evidence for an episode of extension prior to thrusting. All normal faults truncated and/or modified by thrusting and folding, control the distribution of foredeep deposits. This observation indicates that the extensional episode closely preceded the onset of contractional deformation, and must have occurred during the incipient stages of construction of the Central Apennines fold-and-thrust belt. On the other hand, the possibility that some of the investigated pre-thrusting normal faults have later been reactivated as post-orogenic extensional structures during the advanced stages of evolution of the Central Apennines cannot be ruled out, although no kinematic evidence at the investigated sites supports this interpretation.

Particular care is required for the interpretation of interacting faults, erosional surfaces and stratal architectures, such as those seen at Mt. San Vicino, Cingoli and Pennapiedimonte, because these combined features are generally used to constrain the age of growing folds and related thrusts in contractional environments, rather than that of structures resulting from tectonic inversion. Detailed field studies in orogenic settings (Burbank and Vergés, 1994; Ford et al., 1997) and physical models (Poblet et al., 1997) have shown that the growth of anticlines may be accompanied by erosion in their crest regions, and by extensive deposition of syn-orogenic sediments in their limbs (Fig. 10a). The fold-related erosional surfaces commonly dip less steeply than bedding of the pre-growth

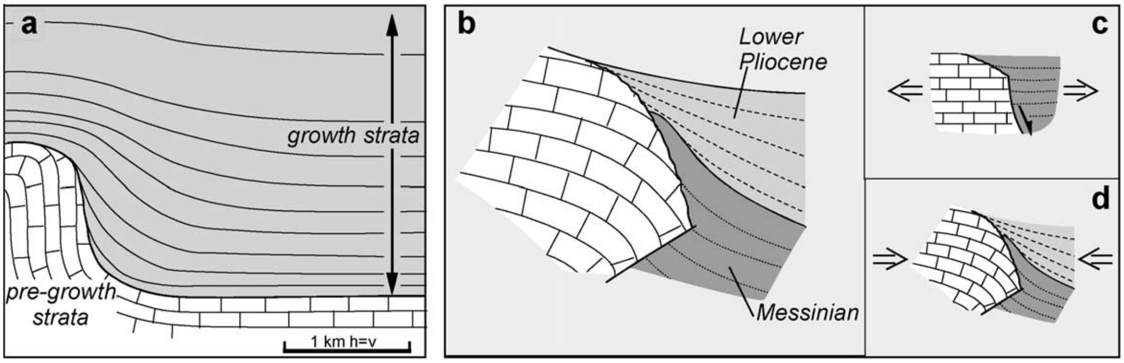

Fig. 10. (a) Typical relationships between growing folds, erosional escarpments and growth strata in contractional environments (inspired by Poblet et al. (1997), Ford et al. (1997) and Suppe et al. (1997)). (b) Relationships between faults, erosional escarpments and growing strata as seen at Mt. San Vicino and Avenale. (c) and (d) Inferred deformation history, with an early episode of extension followed by a late episode of contraction.

substratum (Fig. 10a; Poblet et al., 1997; Suppe et al., 1997), whereas the erosional escarpments at Mt. San Vicino, Avenale and Pennapiedimonte dip more steeply than bedding in the pre-orogenic substratum (Figs. 8b and 10b). Moreover, the depositional architecture of syn-orogenic deposits adjacent to growing folds appears characterised by a general thinning of the growth strata towards the anticline crest regions (e.g. Fig. 10a). This geometry is quite different from the architecture of syn-orogenic deposits reconstructed in the forelimbs of the Mt. San Vicino and Cingoli anticlines, whose Miocene strata onlap steeply hinterland-dipping faults and the related erosional escarpments (Fig. 10b). These structures could alternatively be interpreted as blind-thrusts, or as rotated normal faults. Fortunately, the recognition of the fault-related escarpments and their angles to the substrata make it possible to distinguish between these mutually exclusive interpretations. Restoration of the escarpments to their presumed original attitudes (Fig. 10c) shows that the faults are, in fact, steeply foreland-dipping extensional structures, rather than blind-thrusts. On the other hand, the internal architecture of younger, unconformably overlying deposits of Early Pliocene age, that thicken away from the fold crest zone, closely resembles that of classical growth strata (e.g. compare Fig. 10a and b). Based on the stratal relationships reconstructed at Mt. San Vicino and Cingoli, we propose that the lower sequence of Messinian age was deposited during an early episode of extension, with development of syn-sedimentary, steeply ENE-dipping normal faults (Fig. 10c), and that these were subsequently deformed by folding during Early Pliocene time (Fig. 10d). A similar history is also recorded by the erosional escarpment at Pennapiedimonte (inset Y in Fig. 9b). The onset of later contractional deformation, with development of thrusts and related folds, caused the subsequent tilting of the normal fault surfaces to their present hinterland-dip, and of the normal fault-induced erosional escarpments. The growth of the thrust-related anticlines also controlled the architecture of Lower Pliocene deposits, which define a wedge thickening away from the fold crest.

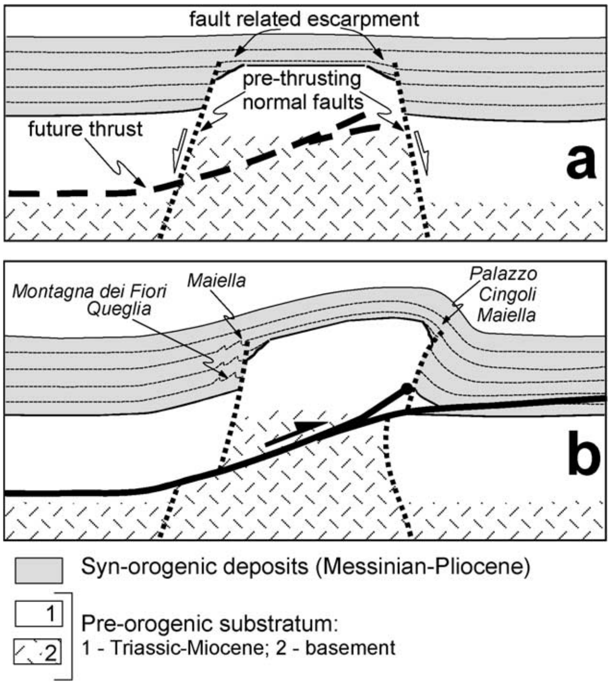

Fig. 11. Schematic, ideal 2D deformation model for the composite structures described in this study. The restored template (a) shows the pre-thrusting arrangement of normal faults affecting syn-orogenic deposits. The deformed situation (b) shows the positions of the analysed structures within the ideal composite, thrust-related anticline. The proposed evolution (a–b in time), in agreement with the results from cross-section restoration, suggests that the investigated anticlines reflect the distribution of the normal fault-bounded structural highs.

Cross-section restoration across the investigated anticlines shows that the pre-thrusting templates are characterised by important, syn-sedimentary normal faults (Figs. 6, 8 and 9). This inference is broadly consistent with the documentation of extensional deformation based on independent stratigraphic evidence from the main Central Apennines foredeep basins (Calamita and Deiana, 1980; Alberti et al., 1996; Tavarnelli and Peacock, 1999; Scisciani et al., 2001). A 2D conceptual deformation model for a typical anticline of the Central Apennines, based on the results of cross-section restoration, is shown in Fig. 11. Cross-section restoration shows that the present location of the examined anticlines reflects the distribution of normal-fault bounded structural highs within the syn-orogenic basins. This coincidence suggests that pre-thrusting normal faults constituted an important mechanical anisotropy, that was effective in controlling the localisation and spacing of propagating thrust ramps and related folds. Pre-thrusting normal faults were commonly deformed by late thrusts, whereas little evidence seems to support their entire reactivation as high-angle reverse faults. This peculiar mode of inversion, at odds with conventional assumptions of fault reactivation (e.g. see Williams et al., 1989), but in agreement with field investigations across inverted structures (e.g. see Butler, 1989), might be explained by the non-coaxial directions of early extension and late contraction (Fig. 5), although other mechanical and rheological controls cannot be ruled out.

In summary, the time relationships among extensional and contractional features within the fold limbs indicate that the anticlines examined in this study are, in fact, composite structures, which bear the signature of an episode of Neogene pre-thrusting extension. The distribution of normal faults over the outer zones of the Central Apennines indicates that pre-thrusting extension must be regarded as a regional, rather than local, phenomenon. Moreover, the progressive eastward decrease in age of normal faults, inferred from their relationship to foredeep sediments, indicates that the pre-thrusting extensional process was not episodic, but rather was diachronous and characterised the entire evolution of the Apennine belt-foredeep system.

10. Conclusions

The most commonly observed geometries of structures preserved in the limbs of several anticlines in the Central Apennines include foreland- and hinterland-dipping normal faults of Neogene age that were steepened, rotated about horizontal axes, and truncated by thrusts, with local development of minor folds due to buttressing against the fault surfaces. Many of these features are geometrically similar to those widely reported from inversion of older (i.e. Triassic, Jurassic and Cretaceous–Paleogene) normal faults within Apennine thrust-related folds (Winter and Tapponnier, 1991; Bruni et al., 1995; Tavarnelli, 1996), as well as from other fold-and-thrust belts developed at expenses of passive continental margins (e.g. see the French Alps; Gillcrist et al., 1987; Butler, 1989).

A main difference with the results from previous work is that the structures described in this study affect not only pre-orogenic substrata, but also syn-orogenic deposits within foredeep basins, thus showing that their development occurred soon (i.e. one million years or less) before folding and thrusting. Another relevant difference is that, due to the generally mild overprint of contractional deformation, the described normal faults preserve some originary features, such as fault-controlled escarpments, that may be lost in other belts due to stronger uplift and erosion. Fault-related escarpments provide critical information for a correct cross-section restoration, and for the definition of the pre-thrusting architecture of syn-orogenic basins.

The documentation of normal faults within syn-orogenic deposits, and of their relationship with thrusts and folds of the Central Apennines of Italy, provides useful constraints for correctly separating the effects of old, pre-orogenic (i.e. passive-margin) extension, from those produced by positive inversion of syn-orogenic foredeep basins. These results may ultimately help improve our understanding of the time–space evolution of complex belt–foredeep systems, and of their migration toward undeformed forelands.

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